

ISSN 0917-3706
CODEN : TOTREH



TOYOTA Technical Review

Apr. 1998
208

Vol. 47 No.2
Special Edition
**Prevention of
Global Warming**
— CO₂ Reduction —

Cover design M. Mochizuki : Design Div.

Paint designed to protect automotive bodies from acid rain, dust and scratching, not to mention change the vehicle's image, is being featured (in this picture of imaginary soup). Environmentally friendly looking green is used as the base, with impressing points highlighted in white.

Contents

▷ Special Edition for Prevention of Global Warming -CO₂ Reduction-

• Not Only as a Businessman, but as a CitizenBy Akio Matsubara	4
• CO ₂ Reduction in Automotive DevelopmentBy Naoto Kushi	6
• Fuel Efficiency Improvement of Gasoline Engine VehicleBy Nobutaka Morimitsu	12
• Development of Fuel Economy 5W-20 Gasoline Engine OilBy Kenyu Akiyama/ Hiromi Kawai/ Shinichi Sugiyama	18
• Contributions of Automatic Transmission to Fuel EconomyBy Sinya Nakamura/ Masahiro Kojima/ Katsumi Kohno	23
• Development of D-4 EngineBy Zenichiro Mashiki/ Souichi Matsushita/ Takeshi Gouno	29
• Electric Vehicle "RAV4 EV"By Masao Kinoshita/ Sadahiro Kimura	36
• Introduction of EV Commuter "e-com"By Makoto Yamada/ Keiji Kogaki/ Toshiyuki Sekimori/ Tetsuhiro Ishikawa	43
• A Development of Toyota Hybrid SystemBy Shinichi Abe/ Takeshi Kotani/ Ryuji Ibaraki/ Kazuo Tojima/ Sumikazu Shamoto/ Akira Sakai	47
• A High-Expansion-Ratio Gasoline Engine for the TOYOTA Hybrid SystemBy Toshifumi Takaoka/ Katsuhiko Hirose/ Tatehito Ueda/ Yasushi Nouno/ Hiroshi Tada/ Hiroshi Kanai	53
• Production Engineering Development for EV, HV UnitsBy Ken Tanoue/ Hiroshi Miyazaki/ Yasutomo Kawabata/ Toshiaki Yamamoto/ Takao Hirose/ Hajime Nakagawa	61
• Development of Electric Vehicle Powered by Fuel CellBy Yasuhiro Nonobe/ Yoshio Kimura	67
• CO ₂ Reduction Activities in TMC Production ProcessBy Hidehiro Ono/ Wataru Sato/ Tomoki Nakagaki/ Takeo Sakai	73

▷ Technical Paper

• An Automatic Offsetting Method of Composite SurfacesBy Hiroyuki Kawabata/ Yukitaka Fujitani/ Junji Ishida/ Hiromi Morisaki	79
• Development of TOYOTA New BEAMS 1UZ-FE EngineBy Kenji Watanabe/ Tetsuji Asahi/ Minoru Iwamuro/ Kunihiro Satou/ Tsutomu Hiyoshi/ Shigeo Kikori	85
• A Development of Easy-Column ShiftBy Yoshitaka Sato/ Harumi Minoshima/ Minoru Makiguchi	92
• Development of Catalyst for Diesel EngineBy Hideaki Ueno/ Toshinobu Furutani/ Tetsuo Nagami/ Norihiko Aono/ Hideyuki Goshima/ Kouichi Kasahara	98
• Molecular-Level-Analysis on Water Behavior Concerned to Degradation of Paint FilmBy Nobuaki Takazawa/ Yoshihiro Yamamura/ Ryuji Shimazaki	104
• Construction and Implementation of Internal Management System for Hazardous SubstancesBy Kengo Ando/ Yoshihisa Nakagawa/ Yuji Kiyono/ Chikashi Ogura	111

▷ Topics	118
----------------	-----

▷ Technical Award News	125
------------------------------	-----

▷ Recent Publications by Toyota Authors (January – June, 1997)	129
--	-----

▷ Awards (January – June, 1997)	135
---------------------------------------	-----

TOYOTA Ecocar (ELECTRIC & HYBRID VEHICLES)

RAV4 **EV** ELECTRIC VEHICLE



PRIUS -Hybrid EV-





FCEV

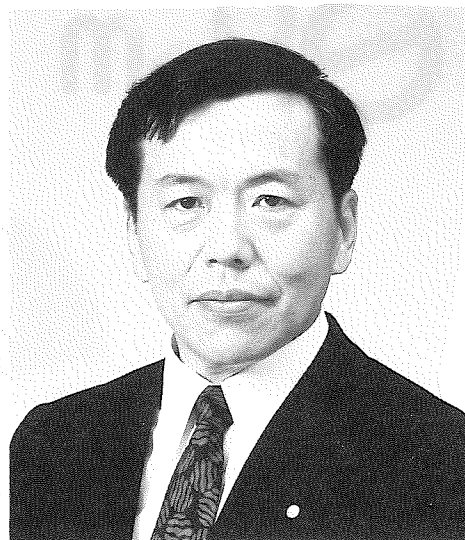
Fuel Cell Electric Vehicle



Not Only as a Businessman, but as a Citizen

Akio Matsubara

Akio Matsubara, Director



In his preface to the previous issue of the Toyota Technical Review, "A Nation and A Company Raised on Eco Challenges", Mr. Akihiko Saito summarized the environmental problems faced by the automobile industry.

The recognition of those problems underlies the contents of this special issue. Still, it must be acknowledged that the problem of global warming, particularly the question of measures to reduce CO₂ that lies at its heart, poses a challenge more difficult than any the human race has confronted to date.

As automobile makers, we have been grappling with the problem of exhaust emissions since the mid-1960s, and we have done our utmost to make our vehicles environmentally clean. Our efforts continue without pause to this day, and must continue in the future, but now the CO₂ problem has also become important.

Whatever one's views concerning hydrocarbons, carbon monoxide, nitrogen oxides, and particulates, the emissions components that are the main problem in urban areas, everyone agrees that in high concentrations they are harmful to human health. CO₂, on the other hand, is created even when fuel is burned completely, and although it is harmless in itself, some fear that increased amounts may cause the Earth to grow warmer, leading to worldwide climatic changes that could raise ocean levels and threaten the continued existence of terrestrial ecosystems.

If I may be permitted a little black humor, I would note that the phenomenon of rising ocean levels reminds me of the story of Noah's Ark in the Book of Genesis.

Using the gift of fire that Prometheus brought down from the heavens, human beings have created a high-level civilization. But one cost that comes with this "civilization of fire" is the CO₂ problem.

Taking this point a step further, I would point out that we human beings ourselves live by burning a fuel we call food in a mechanism called the body, emitting CO₂ in the form of breath. To that extent, therefore, every aspect of life in a civilized society is related to CO₂ emissions.

In December of last year, the Third Conference of Parties of the United Nations Framework Convention on Climate Change (COP3) was held in Kyoto. Each participating nation presented a plan outlining its concept of the efforts necessary to reduce CO₂, and the participants then debated the direction in which the world as a whole should move.

The problem is what sort of effort each individual country should make, given the dilemma in developing nations of wanting to suppress CO₂ emissions while maintaining economic balance in the face of an exploding population.

It is only natural to say that the efforts of each country must be carried out fairly and equitably. Yet this is actually terribly difficult.

What it boils down to, I believe, is that the effect of environmental measures will be determined by whether or not they are carried out fairly and equitably. That is because tackling the issue by agreeing on general goals, but opposing individual measures, is not a fair way to go about the task.

One measure by which we may overcome this ordeal that the human race faces is unquestionably

technological innovation.

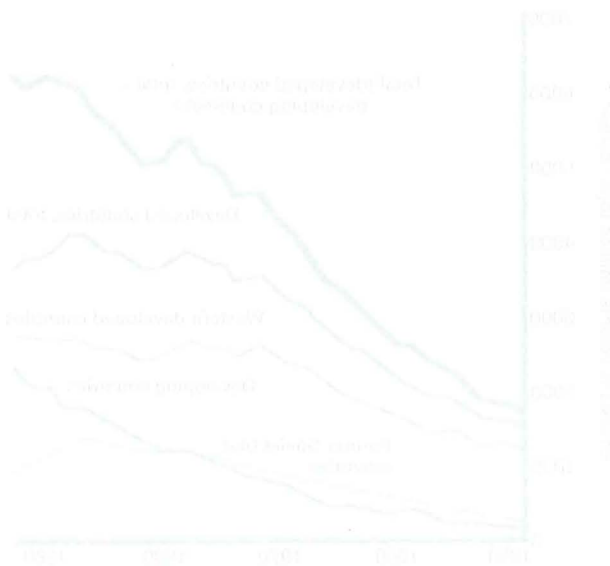
History provides us with any number of cases where technological progress has opened the door to a brighter future.

As someone who works in the field of technological development at Toyota, and also as one of those responsible for dealing with environmental problems, I can say with confidence that Toyota intends to do its share as a company to respond effectively to these challenges. The specific environmental efforts we are making are described in the papers presented in this issue, which I commend to your attention.

But I feel that effort is demanded of me as an individual as well.

Earlier, I mentioned that the CO₂ problem is deeply rooted in our civilization. This deeply rooted problem is something that I must address constructively, not only as a businessman, but as a citizen living on planet Earth.

In his preface to the previous issue, Mr. Saito discussed the Environmental Household Account Booklet. I, too, feel it is necessary for me as a citizen to speak and act responsibly with regard to the environment, not only by using my car in a way that is not wasteful, but also by urging my neighbors to make their own modest efforts in the same direction.



CO₂ Reduction in Automotive Development

Naoto Kushi*

Abstract

With regard to global warming, it is necessary to improve fuel efficiency, and to use low CO₂ emission alternative fuels. The creation of smooth traffic flow also effectively reduces CO₂ levels. The improvement of conventional engine and transmission efficiency, and vehicle weight reduction are the main approaches to improve fuel efficiency. Concern about global warming has also accelerated the development of new power-train systems such as hybrid vehicles, electric vehicles and fuel cell electric vehicles.

From the viewpoint of the best use of resources and global CO₂ reduction, we do our utmost to develop genuinely clean and available automobiles.

Keywords: prevention of global warming, CO₂ emissions reduction, fuel economy improvement, energy efficiency, power train

1. Introduction

1.1 Worldwide Efforts to Prevent Global Warming

Greenhouse gases such as carbon dioxide (CO₂), methane, chlorofluorocarbons (CFCs), and water vapor are contained within the atmosphere and by their action help to maintain a livable atmospheric temperature for human beings and for plants and animals. However, in recent years, larger amounts of greenhouse gases such as CO₂ and methane have been emitted into the atmosphere as a result of human activity. (Fig. 1)

In the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), adopted in December of 1995, the fact that global warming is definitely progressing due to human activity was confirmed scientifically. According to the report, the Earth's average air temperature has risen 0.3 – 0.6°C over the last hundred years. Moreover, should the quantity of greenhouse gases continue to increase at the current rate, the average air temperature is forecast to rise an additional 2°C by the end of the 21st century, and sea levels would rise approximately fifty centimeters. It is feared that these changes will be accompanied by far-reaching and serious effects on the living environment of human beings and all living things. Further, the report suggests that in the future, in order to stabilize the concentrations of greenhouse gases, the total volume of emissions worldwide, including the developing countries, must at the very least be reduced to a level far below that of 1990.

At the United Nations Conference on Environment and Development (also known as the "Earth Summit") in June, 1992, 155 countries signed the United Nations Framework Convention on Climate Change, which set a target of reducing

CO₂ emissions to their 1990 level by the end of the decade. The convention took effect in March of 1994. Following up on that commitment, the First Session of the Conference of Parties (COP1) was held in Berlin in March, 1995, with the Second Conference of Parties (COP2) being held in Geneva in July, 1996. However, it was clear by that time that the goal of achieving 1990 emissions levels by the year 2000 was already beyond reach. With regard to the reduction of CO₂ emissions after the year 2000, there were problems of scientific uncertain-

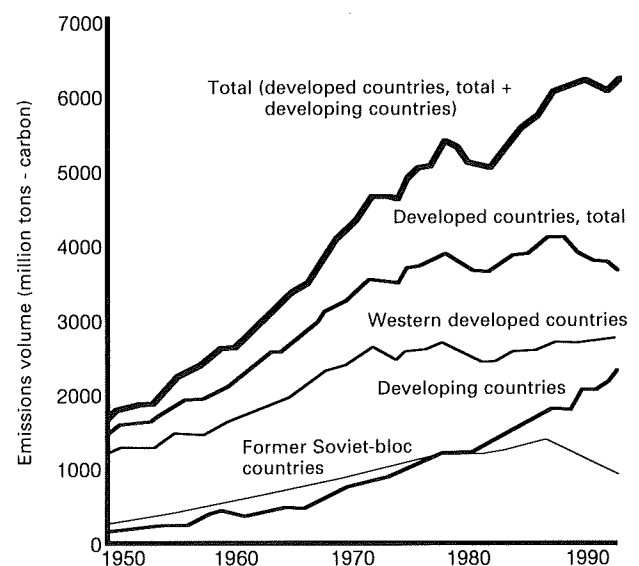


Fig. 1 World Carbon Dioxide Emissions

Source: Estimates by Oak Ridge National Laboratory, Carbon Dioxide Information Analysis Center

* Research & Advanced Development Planning Div.

ty and the effects on economic growth in the participating countries, so the adoption of specific reduction targets was put off until the Third Conference of Parties (COP3), held in Kyoto in December, 1997.

The reductions adopted at COP3 for the major industrialized nations specify that the average emissions level during the five-year period 2008 to 2012 must be 6% lower than the 1990 level for Japan, 7% lower for the United States, and 8% lower for the European Union. This is an international agreement with legally binding targets, and with the advanced nations leading the way, it constitutes an important step by every country in the world toward effective preservation of the global environment.

1.2 Reduction of Automobile-related CO₂ in Different Countries

Against this background, reductions in CO₂ emissions from automobiles are also being sought. In Japan, policies that have been adopted include the implementation of fuel consumption regulations for gasoline-powered passenger cars by the year 2000 and for gasoline-powered light-duty trucks by 2003, as well as the promotion of alternative-fuel vehicles with low CO₂ emissions, based on fundamental principles established by the cabinet for the introduction of new energy sources. Other measures under consideration include the introduction of a carbon tax and the restructuring of the vehicle tax from categories based on engine displacement to ones that take fuel efficiency into account.

In the United States, the public/private Partnership for a New Generation of Vehicles (PNGV) project is aiming to develop a Camry-class vehicle with three times the current fuel efficiency. In Europe, such measures as tax exemptions for ultra-fuel-efficient (3 liters/100 km) vehicles have been established.

2. Reducing Automobile CO₂ Emissions

2.1 Approaches to CO₂ Reduction

As shown in **Fig. 2**, CO₂ is the cause of about half of the greenhouse effect, and almost 80% of the effect is said to come from the consumption of fossil fuels. **Fig. 3** shows the trends in CO₂ emissions in Japan from 1965 to 1993. The volume of emissions increased 2.7 times during that period, and the percentage emitted by the transportation sector rose from 13.9% to 19.4%.

According to a study (the Life Cycle Assessment) that estimates the extent of CO₂ emissions from an automobile over the course of its entire life cycle from manufacture and use to disposal, emissions during vehicle operation account for 80% of

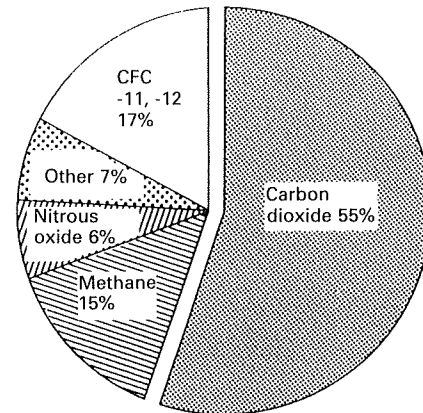


Fig. 2 Contribution of Greenhouse Gases to Global Warming Due to Human Activity in the 1980s

Source: IPCC Report

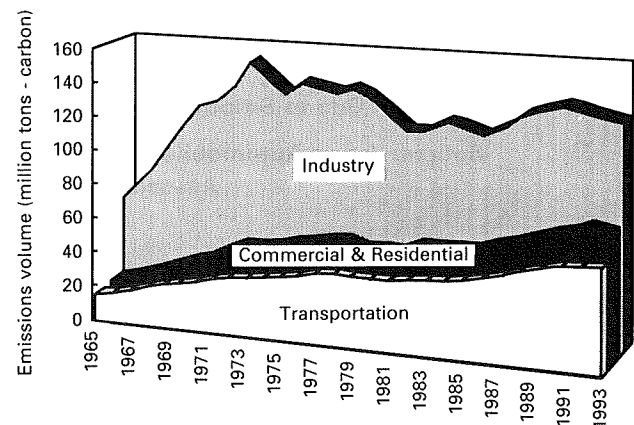


Fig. 3 Carbon Dioxide Emissions per Sector in Japan

Source: Environment Agency estimates

the total. Therefore, to reduce the total volume of CO₂ emissions from automobiles, it is necessary to reduce the emissions when a vehicle is running.

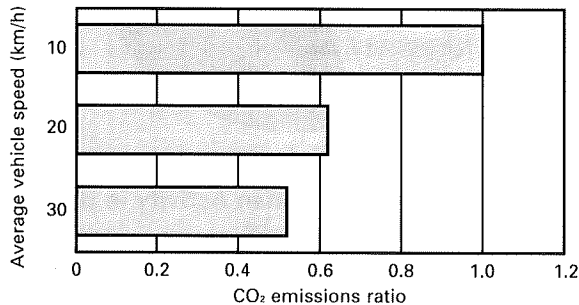
There are three ways to reduce CO₂ emissions during vehicle operation.

The first is to improve automobile fuel economy. For both gasoline and diesel-powered automobiles, reducing the amount of fuel consumed during operation by improving the fuel economy can definitely reduce the volume of CO₂ emissions.

The second way to reduce CO₂ emissions is to encourage the use of vehicles burning fuels that produce little CO₂. For example, if the fuel is natural gas, the volume of CO₂ emissions can be reduced by about 20%.

The third approach is to improve the traffic environment, smoothing out the flow of traffic and eliminating excessive concentrations of traffic and bottlenecks. If the average vehicle

speed were to rise as shown in **Fig. 4**, the volume of CO₂ emitted would be reduced. Research and development is under way on Intelligent Transport Systems (ITS), such as navigation systems compatible with the Vehicle Information & Communication System (VICS), the Automated Vehicle/Highway System, and the Electronic Toll Collection System. All of these systems contribute to smoother traffic flow.



- Emissions ratio 1 corresponds to average vehicle speed of 10 km/h.
- Results shown are for 2000 cc gasoline-powered passenger car.

Fig. 4 CO₂ Reduction Due to Smoother Traffic Flow

Source: Japan Automobile Manufacturers Association (JAMA)

2.2 Automobile Technologies for Improving Fuel Economy and Reducing CO₂

Incorporating new technology into automobiles in one or more of the five areas described below would help to improve fuel economy and reduce the volume of CO₂ emissions associated with driving.

2.2.1 Fuel Economy Improvements to the Vehicle Itself

Reducing vehicle weight, rolling resistance, and aerodynamic drag are generally effective measures for improving fuel economy, regardless of the type of power train.

With traditional gasoline and diesel-powered vehicles, the energy required for acceleration cannot be recovered, so reducing vehicle weight contributes greatly to improved fuel economy. By contrast, electric and hybrid vehicles are able to use regenerative braking during deceleration to recover some of the energy required for acceleration, so in these cases, the contribution of reduced rolling resistance and aerodynamic drag becomes greater.

Measures such as improving the efficiency of the air conditioning system are also effective for improving actual fuel economy.

However, measures taken to improve fuel economy must be compatible with the maintenance of such features as passive

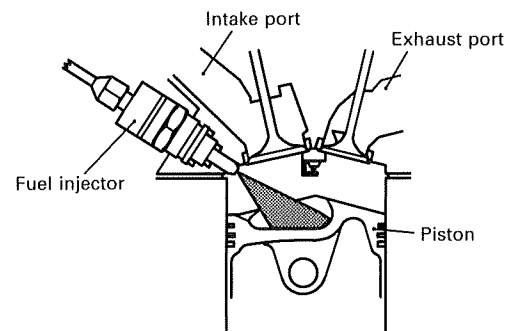
safety, stability, controllability, and comfort.

2.2.2 Drive System Fuel Economy Improvement Measures

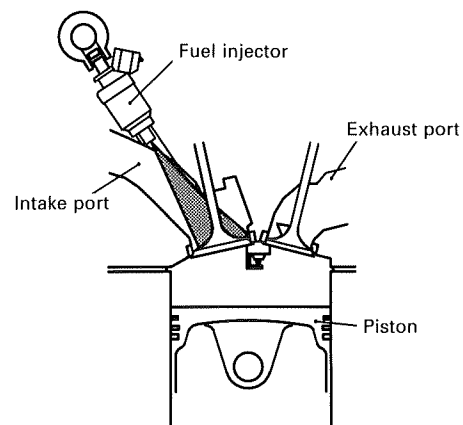
The next generally effective technique is to improve fuel economy through changes in the drive system. Regardless of the engine to which it is connected, if the transmission's efficiency is improved, CO₂ emissions can be reduced. Automatic transmission lock-up control is one example.

2.2.3 Engine Fuel Economy Improvement Measures

The measures receiving the most attention are improvements in the fuel economy of the engine itself. Improving combustion helps to raise the compression ratio and reduce friction loss. For gasoline engines, the technologies include the use of continuous variable valve timing (VVT-i: Variable Valve Timing-intelligent) and the lean burn engine, as well as the direct-injection Toyota D-4 engine shown in **Fig. 5**, which injects fuel directly into the cylinders. In diesel engine technology, the traditional Indirect Injection (IDI) type is being replaced by the more efficient Direct Injection (DI) engine, which is being developed into a small diesel engine.



(a) Toyota D-4



(b) Conventional engine

Fig. 5 Direct Injection Gasoline Engine

2.2.4 Fuel Economy Improvement Measures for the Combination of Engine and Drive System

The technologies described up to this point all act independently to improve fuel economy. The focus from this point on, however, will be on technologies that improve fuel economy even more and reduce CO₂ for the vehicle as a whole.

For example, combining the Continuously Variable Transmission (CVT) with a special engine creates a low fuel-consumption package technology. The CVT can select the gear ratio freely, so the engine operating conditions (engine load and engine speed) during driving can be maintained within a certain range. Therefore, if that operating range is maintained, and the transmission is combined with an engine with improved efficiency, a revolutionary improvement in fuel economy can be expected.

2.2.5 Using New Power Trains to Improve Fuel Economy and Reduce CO₂ Emissions

New power trains developed for even greater fuel economy are now at the stage where they are being put to practical use. For example, the Toyota Hybrid System, shown in **Fig. 6**, is a hybrid vehicle combining the advantages of a gasoline-powered car and an electric vehicle. It runs on a combination of gasoline engine power and electric motor drive. By means of innovations such as stopping the engine automatically when the car stops and regenerating energy during deceleration, the technology greatly reduces energy loss and dramatically improves fuel economy.

At the same time, power trains that use fuels with low CO₂ emissions have already been commercialized and their use is spreading. For example, the natural gas vehicle, which burns natural gas instead of gasoline, not only lowers CO₂ emissions, but is also one of the stronger alternative candidates to vehicles burning petroleum fuels.

Because the electric vehicle itself does not emit any CO₂

when it runs, as a vehicle per se it is an ideal measure for reducing CO₂. (**Fig. 7**)

Research and development is also progressing for the Fuel Cell (FC) electric vehicle as a promising power train for the future. It is an electric vehicle that runs on electricity generated by a chemical reaction between hydrogen and atmospheric oxygen. Because its only emission is water, it is an extremely clean automobile. (**Fig. 8**)

However, unlike the problem of localized air pollution, CO₂ emissions must be reduced on a global scale to have any effect on the prevention of global warming. Thus, in discussing the reduction of CO₂ emissions involved in the operation of automobiles, the focus must be not only on CO₂ emitted directly from vehicles, but also on CO₂ that is generated in the manufacturing and transport of the fuels that vehicles use.

This means that in countries such as France and Japan, where a high proportion of electrical power generation is nuclear and hydroelectric, and thus relatively little CO₂ is emitted in the process of generating electricity, the use of electric vehicles would have a great impact on the reduction of total CO₂ emissions, even when the manufacture and transport of fuels

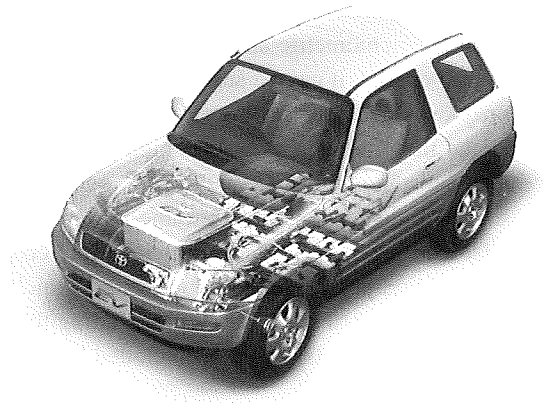


Fig. 7 Electric Vehicle (RAV4L EV)

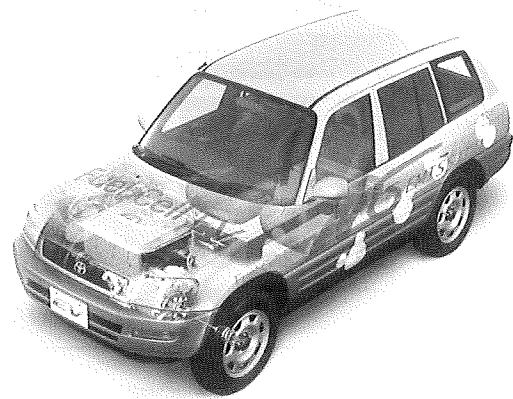


Fig. 8 Fuel Cell Electric Vehicle (Experimental Vehicle)

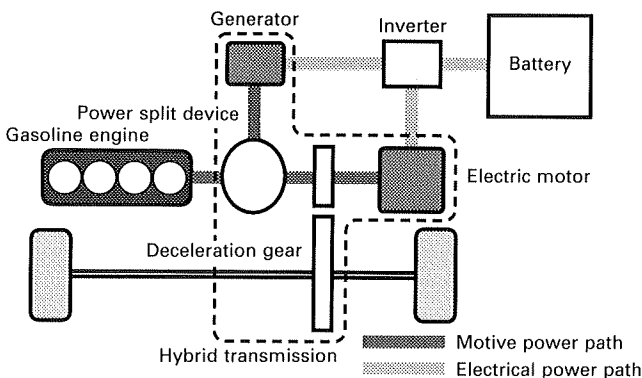


Fig. 6 Toyota Hybrid System

are taken into account. However, reports have also noted that in a country such as Germany, where a high proportion of electricity is thermally generated in coal-fired plants, power generation itself produces large amounts of CO₂, and once factors such as losses during battery charging are taken into account, no significant effect on CO₂ reduction can be anticipated⁽⁶⁾.

2.3 Comparing Fuel Economy and CO₂ Emissions of Different Power Trains

The previous section described some power trains that are effective for improving fuel economy and reducing CO₂ emissions. The effects of using these power trains are shown in **Figs. 9 to 11**. The driving mode was assumed to be the 10-15 mode, and the effects of vehicle weight were taken into consideration. Also, the ability of the hybrid vehicle, the electric vehicle, and the fuel cell electric vehicle to recover energy through regenerative braking has been factored into the calculations. The calculation of CO₂ emissions for the electric vehicle is based on the proportional mix of power generation systems in Japan.

Fig. 9 shows the energy consumption (fuel economy) of various vehicles in comparison with a gasoline-powered automobile running on a stoichiometric air-fuel ratio. Converting fuel consumption into energy, it can be seen that the electric vehicle consumes only one-fourth as much energy as a gasoline-powered vehicle and that the vehicle itself is highly efficient. The hybrid vehicle is also a highly efficient system, consuming only half the gasoline of the conventional gasoline-powered vehicle.

Fig. 10 also compares energy consumption (fuel economy) with that of a gasoline-powered automobile with a stoichiometric air-fuel ratio, but here the total energy, including the manufacture and transport of fuels, has been included. The electric

vehicle's advantage diminishes to the point where it is more or less the same as that of the hybrid vehicle. This is because the efficiency of electrical power generation is low, outputting as electricity only 35% to 40% of the energy contained in fuel resources such as petroleum and natural gas. By contrast, even considering the losses incurred in the course of drilling for oil, refining it into gasoline, and transporting the gasoline by tank truck, a gasoline-powered vehicle is able to use about 85% of the energy contained in the original crude oil.

In discussing the problem of energy and resources, it is important to consider not only simple vehicle efficiency, but also how the energy contained in resources can be used without waste.

Fig. 11 compares the CO₂ emissions of various vehicles with those of a gasoline-powered automobile with a stoichiometric air-fuel ratio, including the CO₂ emitted in the manufacture and transport of resources. Using the D-4 gasoline engine or the DI diesel engine brings a reduction in CO₂ emissions that is proportionate to the reduction in energy consumption. In much the same way, the hybrid vehicle can cut CO₂ emissions in half. Because all of these systems can use the existing fuel-supply infrastructure, the fuel economy improvement technologies for the gasoline and diesel systems, as well as the hybrid vehicle technology, can be expected to gain public acceptance rapidly.

The natural gas vehicle shows almost no reduction in energy consumption (improvement in fuel economy), but because natural gas generates little CO₂ when it is burned, the vehicle achieves better than a 20% reduction in CO₂ emissions. However, in order for the technology to gain wide acceptance, the means of storing natural gas on board the vehicle must be improved and made less expensive. A natural gas-supply infrastructure must also be established.

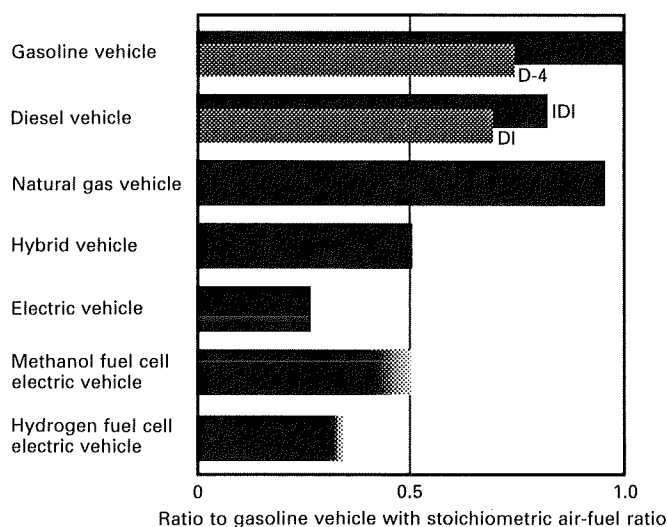


Fig. 9 Comparison of Energy Consumption in Vehicles

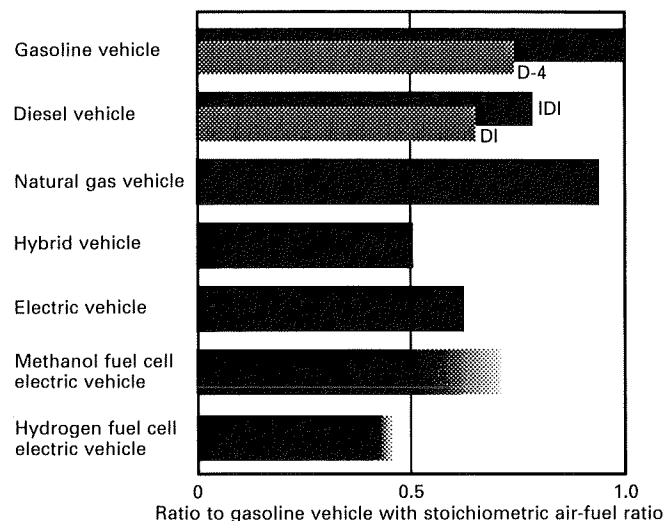


Fig. 10 Comparison of Energy Consumption Including Manufacture and Transport of Fuels

Given the proportional mix of power generation systems in Japan, the electric vehicle can be expected to reduce CO₂ significantly. Its advantage as a vehicle that emits no exhaust gas is expected to lead to its acceptance by the public.

The fuel cell electric vehicle also greatly reduces CO₂, and expectations are especially high for the hydrogen fuel cell. However, numerous problems remain to be solved, including the establishment of a hydrogen supply infrastructure and the development of a practical means for storing hydrogen on board the vehicle.

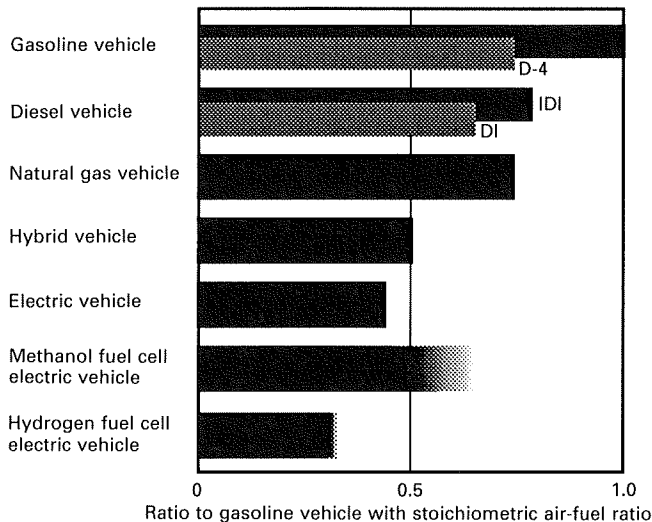


Fig. 11 Comparison of CO₂ Emissions Including Manufacture and Transport of Fuels

3. Conclusion

Starting with the problem of localized air pollution in the 1970s, the automobile has constantly faced new environmental problems such as noise and recycling. And today, the new global issue of cutting CO₂ emissions has been raised as a way to prevent global warming.

Efforts to improve fuel economy have been continuing for some time, but technologies that improve fuel economy have generally been adopted in order to enhance product appeal by reducing the burden of fuel cost (vehicle running cost) on customers. From now on, we must approach fuel economy improvement and new power train technologies from the higher standpoint of preserving the global environment, applying the collective wisdom of various fields and resolutely tackling the challenge of higher targets.

Fig. 11 compares power trains in terms of CO₂ emissions, but this question must be addressed in a manner consistent with numerous other issues, including exhaust emissions other than CO₂, reliability, durability, and lower cost. Also, if development does not take into account the vehicle performance issues

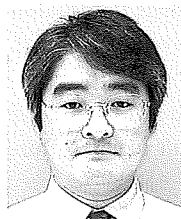
that influence customers' perception of convenience, such as cruising range, power, and interior space, then widespread acceptance can not be expected. It is also important to coordinate development with and to promote social trends like the establishment of a fuel supply infrastructure and fuel pricing system, and the implementation of systems for smoother traffic flow.

This special edition on the prevention of global warming features papers on engine and drive system technologies to improve fuel economy, and new power trains for the hybrid, fuel cell, and electric vehicles. At Toyota, we want to look at the mutual advantages of the different technologies and work even harder in a spirit of friendly competition to promote the sort of technical development that will provide our customers the world over with convenient and easy-to-drive automobiles that contribute to the preservation of the global environment.

References

- (1) Environment Agency of Japan: Quality of the Environment in Japan, 1997 Edition, Ministry of Finance Printing Bureau, 1997
- (2) Environment Agency of Japan: Quality of the Environment in Japan, 1996 Edition, Ministry of Finance Printing Bureau, 1996
- (3) Agency of Natural Resources and Energy: Natural Resources and Energy Yearbook, 1995/96 Edition, Tsusan Shiryō Chosakai, 1995
- (4) Sumio Ito: Survey of Environmentally Friendly Engine Technology, Journal of the Central Japan Chapter, Society of Automotive Engineers of Japan, No. 2, P. 52-55, 1997
- (5) Nobuyuki Kobayashi: The Engine Development Toward 21st Century, Toyota Technical Review, Vol. 47, No. 1, P. 6-7, 1997
- (6) Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF): Erprobung von Elektrofahrzeugen der neuesten Generation auf der Insel Rügen. DAUG, 1996

Author



N. KUSHI

Fuel Efficiency Improvement of Gasoline Engine Vehicle

Nobutaka Morimitsu*

Abstract

Improvement of fuel efficiency is one of the most important subjects for the automobile. The efficiency of the gasoline engine has been improved in recent decades, and is still being improved. In this paper, the process of energy conversion in the automotive power train and related new technologies are described. The important viewpoint for further improvement is cooperation with the drive train system.

Keywords: gasoline engine, fuel efficiency, theoretical thermal efficiency, indicated thermal efficiency, brake thermal efficiency

1. Introduction

In recent years, responses to global environmental issues have been strongly demanded, and improving the fuel efficiency of automobiles (reducing the volume of CO₂ emissions) has become an important issue. Fuel-saving technologies such as lean burn, gasoline direct injection, and variable valve timing have been reported in this journal. This paper approaches the issue of fuel efficiency from a slightly different viewpoint, the process of energy consumption in automobile operation.

Fuel efficiency is an indicator of exactly how much fuel is required to make an automobile go, or of how far an automobile can go on a given amount of fuel. In looking closely at just what that involves, it is useful to trace through the processes by which the fuel's chemical energy is converted into mechanical energy, transmitted, and used to make the vehicle go.

Fig. 1 shows the typical efficiency of each of these processes for a typical vehicle in the Japanese fuel economy test procedure (10·15 mode).

The theme of this issue, fuel economy improvement, is first a matter of decreasing the work required, next a question of improving the efficiency of each process, and finally, reducing as much as possible the attendant waste in energy consumption.

- (1) The starting point is the chemical energy of the fuel. The engine burns it in the cylinder and converts it into the pressure of the combustion gas. The higher the compression ratio and the specific heat ratio of the combustion gas, the higher is the theoretical thermal efficiency.
- (2) The combustion pressure is borne by the piston and converted into mechanical energy. The less heat is radiated from the cylinder wall on the expansion stroke, the better the efficiency, and it is preferable that combustion be completely finished in the shortest possible time after top dead center. Also, pumping loss occurs as a result of the difference

ence between the pressure at which the exhaust gas is expelled on the exhaust stroke and the pressure at which the air-fuel mixture is drawn in on the intake stroke.

The efficiency of the gas pressure work relative to the chemical energy of the fuel in one round of the combustion cycle is the indicated thermal efficiency.

- (3) In the course of transmitting to the output shaft the force borne by the piston, losses occur due to the sliding friction of parts and the friction of the rotating shaft bearing, as well as in the auxiliary drive for devices such as the valve train and the oil pump. These are mechanical losses, and the efficiency of these parts is mechanical efficiency. Multiplying the indicated thermal efficiency by the mechanical efficiency gives the ratio of the effective shaft output to the chemical energy of the fuel, which is to say, the brake thermal efficiency.

The brake thermal efficiency changes according to the engine operating range. When one thinks of improving the fuel efficiency of a vehicle, one must either improve the brake thermal efficiency of the engine operating range used during driving or use an engine operating range in which the brake thermal efficiency is better.

- (4) Energy consumption during idling and deceleration also affects fuel efficiency.

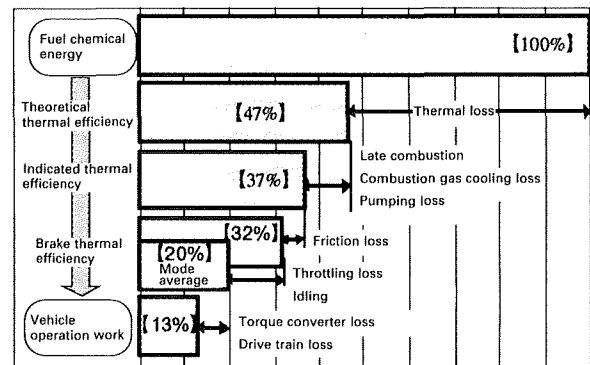


Fig. 1 Components of Engine Efficiency

* Engine Engineering Div. I

This paper traces the above processes sequentially and notes the implications and effects of fuel-saving techniques.

2. Improvement of Theoretical Thermal Efficiency

Theoretical thermal efficiency is a function of the compression ratio ϵ and the specific heat ratio κ . Theoretically, a high compression ratio is good, but in a gasoline engine, it is set at only around 10:1, because higher ratios lead to combustion abnormalities such as knocking and pre-ignition. As knock sensing devices have become more common and combustion has improved, gasoline engine compression ratios have gradually risen, but even now they are only as high as 11:1, even when premium gasoline is used. Knocking and pre-ignition have long been problems for gasoline engines, to the extent that they are even said to be eternal problems, and progress is still not being made on these issues. The latest technologies include a dual cooling system that improves cooling of the cylinder head and a combustion chamber design that minimizes end gas volume.

Another concept is the high expansion ratio engine, which raises thermal efficiency by enlarging the expansion ratio while maintaining the compression ratio of an ordinary engine. Atkinson's cycle engine is well known. **Fig. 3** shows Atkinson's No. 2 engine of 1887, which achieved a low compression ratio and high expansion ratio by means of an ingeniously complex linkage, and which exhibited exceptionally high efficiency for its time. The engine used in the Toyota Hybrid System (THS) achieves a quasi-Atkinson cycle by manipulating the valve timing. By raising the expansion ratio (the mechanical compression ratio) to 14:1, it recovers much of the energy of the combustion gas, and at the same time, by delaying the closing timing of the intake valve, it reduces the effective compression ratio to less than 10:1, thereby suppressing knocking. The efficiency of this system is high, but because the effective displacement is smaller, output is less, and that reduces its commercial potential as an engine for ordinary vehicles. To achieve high output simultaneously with high efficiency and a high expansion ratio requires variable compression ratio technology. This is a field in which unprecedented advances are anticipated.

Another method for raising theoretical thermal efficiency is to raise the specific heat ratio κ . Theoretically, the maximum specific heat ratio κ of oxygen (O_2) is 1.4, and the question is how to approach that value. Lean mixture combustion, such as that achieved by the lean burn engine and the gasoline direct-injection engine, is an effective measure for increasing the ratio of oxygen and raising the specific heat ratio κ .

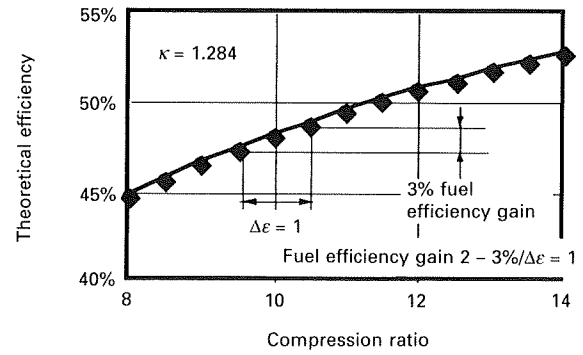
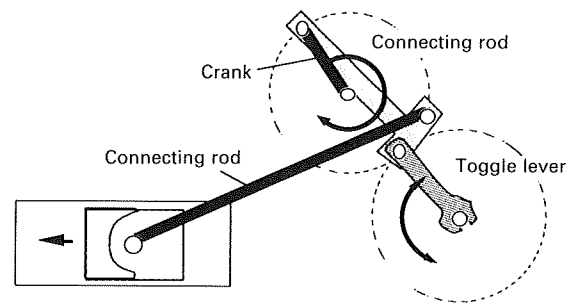


Fig. 2 Compression Ratio and Theoretical Efficiency



Atkinson's Cycle Engine No. 2
(James Atkinson, 1887)

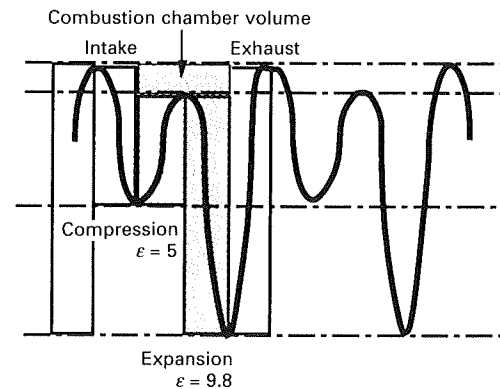


Fig. 3 Atkinson Cycle Engine

3. Improvement of Indicated Thermal Efficiency

It is said that good combustion is achieved by a good air-fuel mixture, good compression, and a good spark.

A good air-fuel mixture is achieved by using electronic fuel injection (EFI) to control the air-fuel ratio precisely and a four-valve combustion chamber to shape the mixture. A good spark is achieved by steady ignition and reduction of spark noise, and by promoting distributor-less (direct) ignition systems for easi-

er installation. **Fig. 4** shows Toyota's progress in installing Toyota Direct Ignition (TDI).

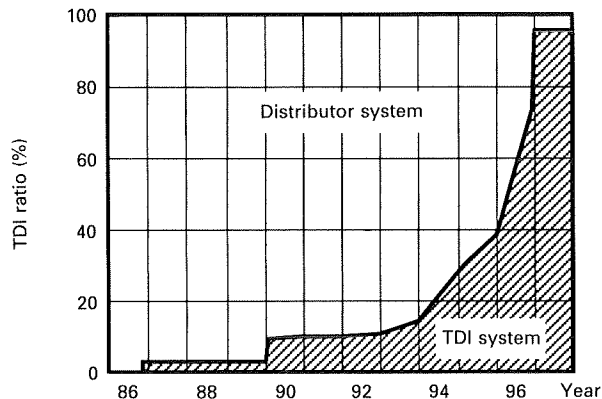


Fig. 4 TDI Installation Ratio

The key to ignition timing is to advance ignition slightly, so that maximum pressure is obtained at top dead center, but if ignition occurs too soon, it raises the pressure on the compression stroke and reduces the output. Generally, the value to which ignition timing is set incorporates a certain safety margin for preventing knocking and pre-ignition. In actuality, the minimum spark advance for best torque (MBT) can not be used in some cases, due to knocking.

What is needed to raise the indicated efficiency is a combustion chamber design that inhibits knocking, appropriate combustion chamber cooling, and the shaping of the air-fuel mixture to increase combustion speed. There is room for improvement even in the most fundamental areas.

Reducing pumping loss is also effective in raising the indicated thermal efficiency. **Fig. 5** is a pressure-volume diagram for a four-cycle gasoline engine. The compression and expansion strokes form a cycle that creates output in a clockwise loop. In contrast, the exhaust and intake strokes consume ener-

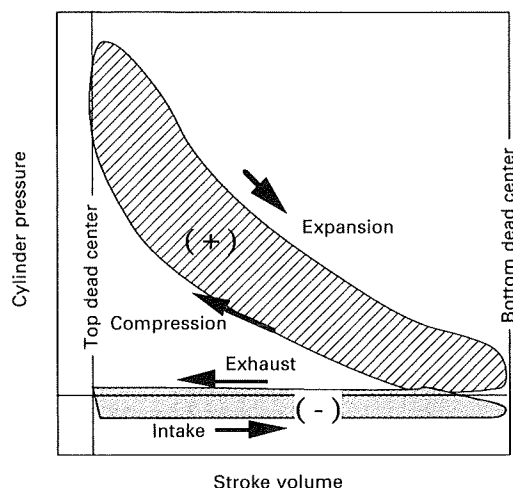


Fig. 5 Pressure-Volume Diagram (Simplified)

gy in a counterclockwise loop. Looking at pumping loss on the macro level shows that on the intake side, the work consists of drawing in the air-fuel mixture using the manifold vacuum, while on the exhaust side, the work is the expulsion of gases into the back pressure of the exhaust system. Reducing this work means either (a) reducing throttling loss on the intake side or (b) reducing the restriction and the back pressure of the exhaust system. On the micro level, it is necessary to consider (c) the passage flow resistance of the ports and valves where gas enters and leaves the engine.

In comparatively light load operation, such as in city driving, reducing throttling loss is an effective measure, as are variable valve timing (VVT) and the lean mixture combustion of the lean burn and D-4 engines. In high-speed driving, back pressure reduction is effective, and development is proceeding of variable muffler systems that allow for both higher output and lower engine noise. VVT controls the exhaust system without regard to the intake system, and expectations are growing for the ultimate cam-less valve train that will select the optimum valve timing in response to the engine speed and load.

4. Improvement of Mechanical Efficiency

The reduction of friction loss in every part of the engine is also important. Friction loss takes various forms: (a) sliding resistance in the pistons, piston rings, piston pins, etc.; (b) inertial work due to the reciprocating motion of the pistons and connecting rods; (c) friction loss in the bearings; (d) inertial work due to the reciprocating motion of the valve train; (e) friction loss in the cam and cam follower; and (f) the loading of the valve springs. Various improvement efforts have been undertaken to reduce these losses. Coating the sides of the pistons with resin and reducing the tensile strength of the piston rings have helped to reduce type (a) loss. Using skeleton-type pistons to reduce weight, converting to four-valve cylinders to make valves smaller, and implementing directly cam-driven valve trains have reduced type (b) and (d) losses. With respect to type (e) loss, the development of titanium nitride-coated shims for the valve lifters has made it possible for the cam and cam follower to achieve the same low friction as the roller follower. **(Fig. 6)**

With respect to the reduction of bearing friction, reducing both the width and diameter of bearings has proven effective. However, from the standpoint of vibration noise countermeasures and reliability, it is thicker and more rigid shafts that are required instead. Although it is very difficult, steadfast efforts are proceeding to improve both materials and designs.

In the lubrication field, the quality of lubricants is improving. Maintenance-free lubricants are anticipated in the future that will show low resistance in the high-speed range and still

sustain the oil film under the demanding conditions of low-speed operation.

In the engine operating ranges used in everyday driving, these measures are effective improvements and make a relatively large contribution to reducing energy consumption from friction loss.

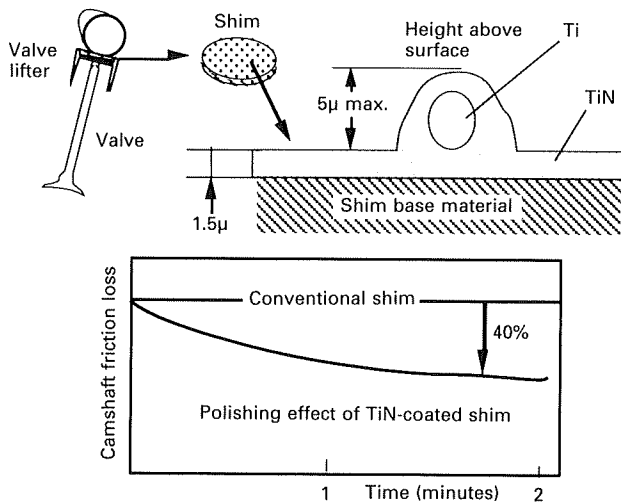


Fig. 6 Friction Reduction by TiN-coated Shim

5. Improvement of Brake Thermal Efficiency

The ratio of the work actually obtained from the engine output shaft in relation to the consumed fuel energy is called the brake thermal efficiency. Although it is generally expressed as specific fuel consumption (g/kWh), here it will be expressed as a percentage to facilitate comparison with other types of efficiency.

Brake thermal efficiency differs according to the engine operating range. As Fig. 7 shows, this can be expressed by a contour map of efficiency, or of specific fuel consumption. The most efficient range is that of medium speed and medium load. This is because under low loads, pumping loss increases due to throttling of the intake air, and at high speed, friction loss increases. The most efficient range for fuel consumption is called the bull's eye. As Fig. 8 shows, the maximum brake thermal efficiency has risen steadily over the years for a variety of engine models. Improvements in theoretical thermal efficiency and indicated thermal efficiency have contributed greatly to this rise. The gasoline engine of the future that will exceed 35% efficiency and challenge the supremacy of the diesel engine is no mere dream.

Because a gasoline engine throttles the intake air to adjust the output, pumping loss is large under low loads. The lean burn and gasoline direct-injection engines do not throttle the air even in the low-load range and therefore operate under very lean mixture conditions. This extends their high-efficiency range (the bull's eye of the fuel consumption contour map) into

the low-load operating range. As a result, their fuel efficiency in ordinary urban driving improves dramatically. Because the gasoline direct-injection engine in particular is able to achieve both increased output and higher efficiency, it will become the mainstream technology of the next generation. From now on, every company will be putting gasoline direct-injection engines on the market one after another. However, numerous issues remain to be addressed. Many new parts, such as high-pressure injection parts and lean NOx catalysts, must be developed, reliability must be improved even more, costs must be lowered, and emissions must be further reduced.

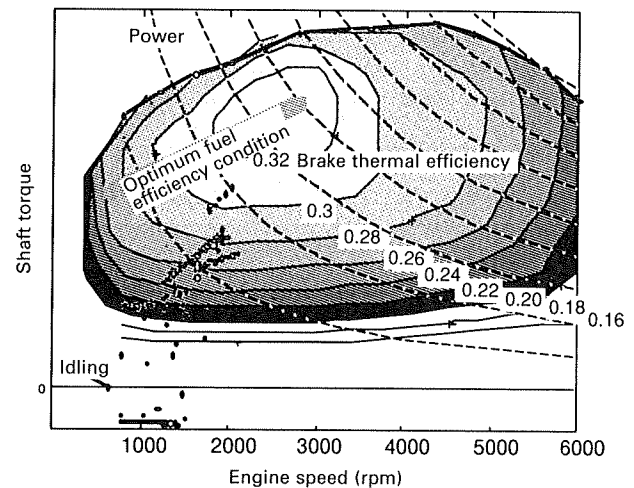


Fig. 7 Engine Brake Thermal Efficiency Map

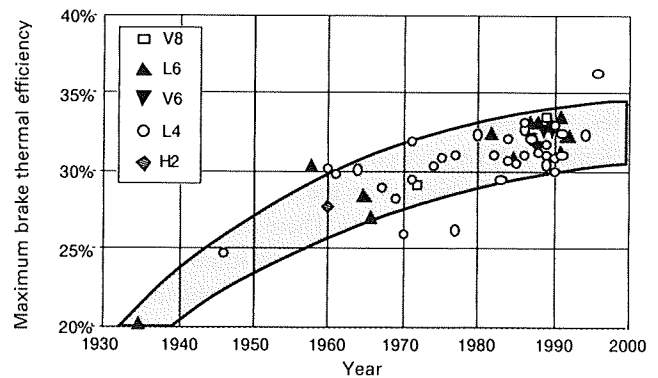


Fig. 8 Brake Thermal Efficiency of Gasoline Engines

6. Improvement of Idling

Idling is responsible for a fairly large proportion of fuel consumption in urban driving, accounting for 10% of the fuel consumed by a manual transmission vehicle, and 15% of that consumed by an automatic transmission vehicle, in the 10·15 mode. In idling, the minimum amount of fuel required to keep the engine running on its own at a certain speed is used. Therefore, measures such as reducing friction loss are effective,

but the most effective measure is to reduce the engine idle speed itself. A decade ago, the idle speed was around 800 rpm, but in recent years it has dropped to 500 – 600 rpm. **Fig. 9** shows reductions in idle speed and the effects on fuel efficiency. It can be seen that the larger the engine displacement, the greater is the effect.

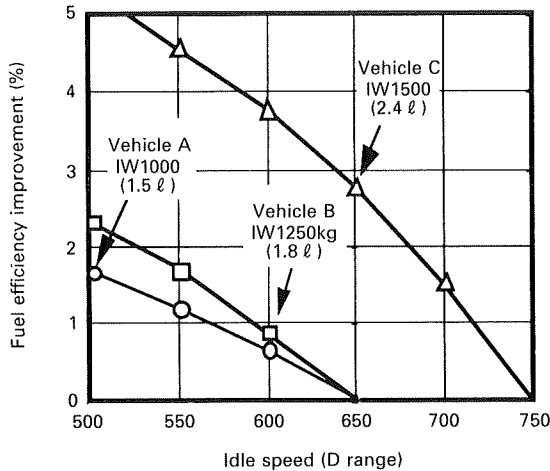


Fig. 9 Idle Speed Reduction and Fuel Efficiency Effect (10·15 Mode)

However, lowering the idle speed brings with it a variety of problems. Engine vibration becomes worse, the engine stalls easily, and the alternator's generating capacity becomes insufficient, upsetting the electricity balance. Therefore, ample caution is required when lowering idle speed.

Some have offered the opinion that rather than lowering the idle speed, the engine should just stop when the vehicle stops. However, this can not be achieved so simply with the current vehicles. Stopping the engine every time the vehicle stops for a red light is a heavy psychological burden, and the so-called Eco-Run System, which stops the engine automatically, failed to gain acceptance in the end. There are many parts, such as power steering and air conditioning, that are driven by the engine, and vibration and noise are also a problem. It is not that easy to just stop the engine.

The next-generation Eco-Run System will solve those problems and will probably make its appearance as some form of hybrid system in combination with energy regeneration.

7. Fuel Efficiency Improvement for the Vehicle

7.1 Power Train Efficiency

The fuel efficiency a vehicle gets in stop-and-go urban driving is considerably worse than when it runs at constant speed on a highway. This is because, in contrast to highway driving's

use of the range where the brake thermal efficiency of the engine itself is good, in urban driving, (1) the amount of inertial work during acceleration is large, and (2) much of the driving is done in the low-speed, low-load range where brake thermal efficiency is poor.

Because the engine displacement for the typical passenger car is determined in order to satisfy vehicle performance requirements, in urban driving the engine is not used in the high-efficiency range represented by the bull's eye on the fuel consumption contour map. Although the maximum brake thermal efficiency of the engine as shown in **Fig. 1** is 30% or more, the average brake thermal efficiency for the mode drops to 20%.

This paper uses power train efficiency as an indicator of just how efficiently the engine is used, and defines it as the ratio of the energy necessary for vehicle operation versus the fuel energy consumed in mode driving. The power train efficiency expressed in **Fig. 1** as vehicle operating work averages only about 13% for an automatic transmission vehicle. This drop in efficiency is due to slippage loss in the torque converter and friction loss in the drive train, so it is these costly areas that are the focus of attention for improving fuel efficiency.

7.2 Vehicle Running Resistance, Optimum Displacement, and Variable displacement

To reduce vehicle energy consumption, it is necessary to make smaller and lighter cars and drastically reduce their energy consumption, while at the same time raising the efficiency of the power train. Great care must be taken in determining the trade-offs between fuel efficiency and vehicle performance. If an engine's displacement is not changed, even when its energy consumption has been reduced, then it has more power to spare and vehicle performance improves, but it ends up being used mostly in the low-load range where its efficiency is poor. On the other hand, if the engine displacement is reduced, the power train's efficiency in urban driving can be raised, but it brings with it a drop in performance, and the inadequacy of drive power at high speed leads drivers to shift to lower gears, making fuel efficiency worse. Therefore, it is extremely important in the vehicle planning stage to make sure of the vehicle's required characteristics and to select the optimum displacement.

Variable displacement is a way to achieve optimum displacement in response to the vehicle's operating conditions. Thus far, systems that rely on deactivating one or more cylinders have appeared on the market, but because of problems with vibration noise and emissions, among others, they have failed to gain much acceptance, and product planning is considered difficult. In the future, the development of unique mechanisms such as variable stroke and variable compression ratio is expected.

7.3 Using the Drive Train to Improve Power Train Efficiency

The development of a drive train system that is not just a simple power transmission device, but that will more actively select the engine operating conditions to match the vehicle's required output, is important for broadening the possibilities for fuel efficiency improvement.

Because the torque converter's slippage loss is large, systems that lock up the torque converter in the high speed range where torque fluctuation is small are the current mainstream approach. However, if the converter is locked up at low speed, torque fluctuation is transmitted to the body, creating a problem with booming noise, so lock-up can not be used in the operating conditions of urban driving. Thus, not only does slippage loss continue unabated in urban driving, but even if the differential gear ratio is raised to try to shift the engine operating range to the low-speed, high-load range where efficiency is high, the engine operating range does not change just by changing the slippage in the torque converter. Expanding the range where lock-up is feasible to the low-speed range requires a damper mechanism to suppress engine torque fluctuation.

The flex-lock-up automatic transmission is a technology that employs a leading-edge control principle to slightly slip the lock-up clutch, thus making it possible both to reduce booming noise and to extend high-efficiency engine operation to the low-speed range. This is thought to be the mainstream technology of the future.

7.4 Expectations for New Drive Trains

A very different product concept, but one for which expectations are also high, is the continuously variable transmission (CVT). **Fig. 10** shows the engine operating range with a conventional four-speed automatic transmission versus the operating range with a CVT that conforms to the minimum fuel consumption curve. The CVT is the ideal power transmission mechanism, because it has the freedom to select a gear ratio that matches the required output, as well as an engine operating range where the brake thermal efficiency is highest. It is preferable for the engine to have an electronically controlled throttle, because the throttle must be adjusted to the operating range that is calculated by the system's internal computer.

Those who have tried driving CVT vehicles have indicated that the CVT feels odd, because it adjusts the engine speed to fit the required output, not the vehicle speed. However, with an electronically controlled throttle and the latest control principles, the system has the potential for control that responds quickly and precisely to the driver's intentions.

Because of the limitations on the belt's ability to transmit torque, implementation of the CVT is currently restricted to small vehicles, but the future development of versions compati-

ble with high torque would probably spur broader use. The issue for engine development, then, is to improve performance to match the characteristics of this new drive train system that is expected to be the mainstream technology in the future.

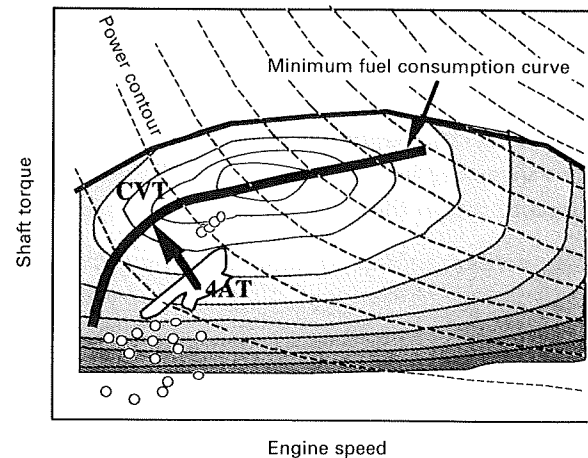


Fig. 10 Concept of Fuel Efficiency Improvement by CVT

8. Conclusion

The internal-combustion engine has made considerable progress in its 100-year history. And now there are those who say that everything that can be done with the technology has been done and that the internal combustion era is coming to an end. But if we consider the substantial fuel-supply and vehicle-service infrastructure, as well as the degree of refinement of internal-combustion technology and the ease with which it can be used, we do not find any other power source that can serve as an alternative. Moreover, as this paper has demonstrated, this is a technology that is still being developed. The internal-combustion engine is expected to continue as the mainstream power source for a relatively long time. For that very reason, we must make a sincere effort to deal with the issues of the global environment, the urban environment, and resources. At the same time that we evolve the essential functions of the automobile, we must continue our unceasing effort to achieve a better environment by means of the various technologies described in this paper.

■ Author



N. MORIMITSU

Development of Fuel Economy 5W-20 Gasoline Engine Oil

Kenyu Akiyama*
Hiromi Kawai**
Shinichi Sugiyama***

Abstract

A 5W-20 gasoline engine oil which improves vehicle fuel efficiency by more than 1.5% relative to a conventional 5W-30 gasoline engine oil was newly developed. Its high fuel economy performance lasts 10,000 km. The viscosity was optimized to satisfy both the fuel economy and antiwear performances. Thiadiazole was used to retain the initial fuel economy performance provided by MoDTC.

Keywords: engine oil, fuel economy improvement, 5W-20, friction modifier, gasoline engine, tribology

1. Introduction

From the standpoint of preventing global warming and protecting resources, the improvement of automobile fuel efficiency is an important issue. Fuel economy gasoline engine oils have been mentioned as one means of improving vehicle fuel efficiency. The usual techniques for improving the fuel efficiency of engine oil are to lower the viscosity and to reduce friction by the addition of friction modifiers. The cost per unit of fuel efficiency improvement is significantly lower for fuel economy engine oil than for improved engine design. The use of fuel economy engine oil for factory fill is rapidly becoming the standard practice worldwide. Low-viscosity 5W-30 oil is becoming popular for factory fill use. Also, the amount of 5W-30 oil consumed in the market is increasing, as opposed to 10W-30 oil.

However, the advantages of further viscosity reduction are unclear, with respect to both the fuel efficiency improvement effect and functional problems such as increased piston ring wear and oil consumption. To address this issue, fuel economy, wear, and oil consumption have been evaluated for all the various low-viscosity oils in modern engines. The purpose is to seek an optimum viscosity level that can improve fuel efficiency without increasing wear and oil consumption. Also, additives have been studied and selected for their friction-reducing effects and material compatibility. By setting the optimum viscosity level, and by combining organo-molybdenum compounds with sulfur compounds, a 5W-20 engine oil was developed that gave 1.5% better fuel efficiency than conventional 5W-30 oil. The improved fuel efficiency lasted for 10,000 km.

2. Selection of Viscosity Setting and Friction Modifiers

2.1 Determination of Optimum Viscosity

The relationship of viscosity to fuel efficiency, engine wear, and oil consumption was investigated, and the optimum value was sought.

2.1.1 Relationship of Viscosity and Fuel Efficiency

Fig. 1 shows the relationship between high-temperature, high-shear (HTHS) viscosity and fuel economy improvement in a vehicle with a 2.2-liter engine.

It is known that lowering HTHS viscosity from 3.3 mPa·s to 2.6 mPa·s improves vehicle fuel efficiency, but that at 2.4 mPa·s fuel efficiency drops⁽¹⁾. The reason for this is thought to be that the oil film breaks down on the frictional surfaces of the engine.

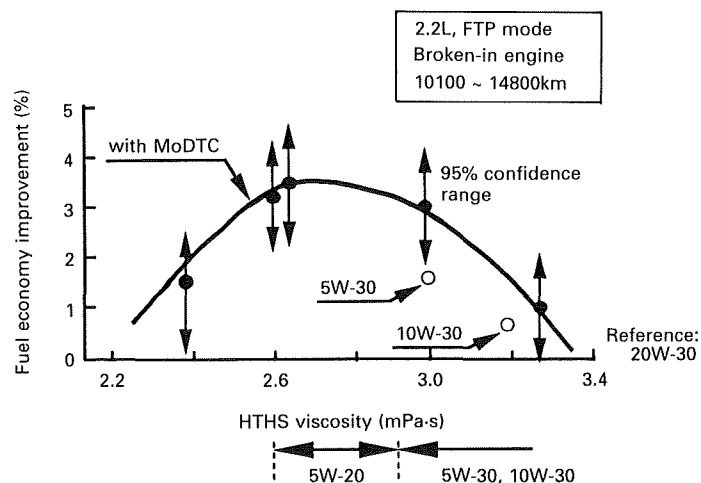


Fig. 1 Relationship between HTHS Viscosity and Fuel Economy Improvement

* Material Engineering Div. I

** Engine Engineering Div. I

*** Engine Engineering Div. II

2.1.2 Relationship of Viscosity and Engine Wear

Fig. 2 shows the relationship between viscosity and the amount of wear on the piston top ring, as measured with the radioisotope tracer technique. The results indicate that wear does not increase with an HTHS viscosity as low as 2.6 mPa·s, but that it does increase with viscosities of 2.4 and 2.2 mPa·s. The same kind of study was made of the wear on valve train cams and connecting rod bearings, but viscosity had almost no effect⁽²⁾.

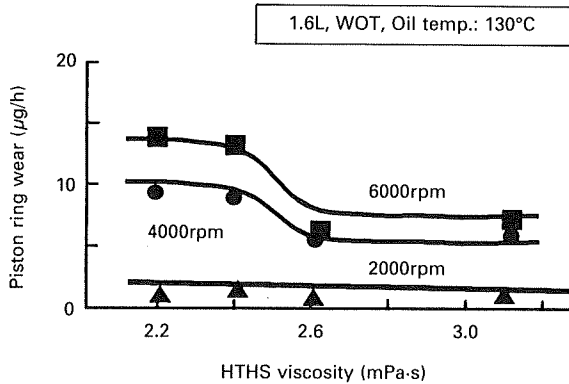


Fig. 2 Effect of HTHS Viscosity on Piston Ring Wear

2.1.3 Relationship of Viscosity and Oil Consumption

Fig. 3 summarizes the results of measurements of oil consumption and Noack volatility. In this test, specially blended experimental oils with differing HTHS viscosity levels were used. The results indicate that oil consumption depends only slightly on viscosity, but that it correlates strongly with Noack volatility.

The above results suggest that the optimum HTHS viscosity is 2.6 mPa·s and that an engine oil with that viscosity can be

expected to improve fuel efficiency without adversely affecting engine wear and oil consumption. The 2.6 mPa·s HTHS viscosity corresponds to an SAE viscosity grade of 5W-20.

2.2 Selection of Friction Modifiers

Friction reduction has been mentioned along with lower viscosity as a technique for improving fuel efficiency⁽³⁾. The use of friction modifiers was studied as one such technique.

2.2.1 Tested Additives

Table 1 lists the test oils and friction modifiers which they were used. Four types of molybdenum dithiocarbamate (MoDTC) and three types of molybdenum dithiophosphate (MoDTP) were tested for their friction-reducing effects. Five types of sulfur compounds were also tested for their ability to sustain the friction reduction effects⁽⁴⁾⁽⁵⁾. TH-0 is an API SJ grade additive with no organo-molybdenum compounds or sul-

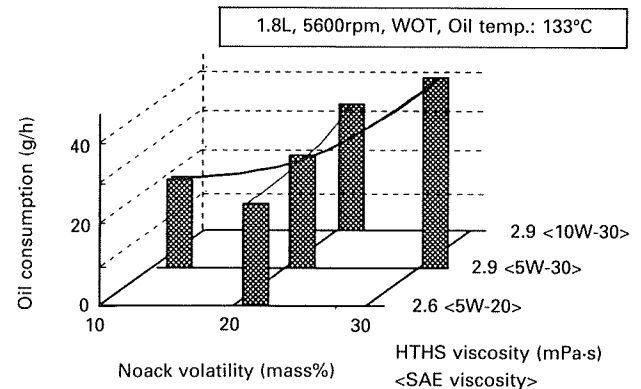


Fig. 3 Effect of Noack Volatility and HTHS Viscosity on Oil Consumption

Table 1 Material Compatibility of Friction Modifiers

Oil Code	Friction Modifier	SRV μ	Bearing *1	ACM *2	FKM *3	Nylon *4	FIPG *5
TH-0	None	0.16	Base	Base	Base	Base	Base
TH-1	MoDTC	0.06	○ No effect	○	○	○	○
TH-2	MoDTC	0.05	○	○	○	○	○
TH-3	MoDTC	0.06	○	○	○	○	○
TH-4	MoDTC	0.05	—	○	○	○	○
TH-5	MoDTP	0.07	○	○	○	○	○
TH-6	MoDTP	0.06	—	○	○	○	○
TH-7	MoDTP	0.08	○	○	○	▲ Large effect	▲
TH-12	Carbamate	0.16	○	○	▲	○	○
TH-13	Carbamate	0.16	○	○	▲	○	○
TH-14	Disulfide	0.16	○	○	○	○	○
TH-15	Sulfurized olefin	0.16	—	○	○	○	○
TH-16	Thiadiazole	0.16	○	○	○	○	○

*1; Oil temp. 130°C×500h, *2; Oil temp. 150°C×500h, *3; Oil temp. 175°C×500h, *4; Oil temp. 150°C×240h, *5; Oil temp. 120°C×240h

fur compounds added. TH-1 to TH-7 contain organo-molybdenum compounds with a molybdenum content equal to 0.05 mass %. TH-12 to TH-16 contain sulfur compounds with a sulfur content equal to 0.1 mass %.

2.2.2 Friction Modifier Selection

Friction modifiers were selected by measuring their friction coefficients (SRV μ) at 100°C in an SRV friction tester and by means of material compatibility tests. The test results are shown in **Table 1**. Organo-molybdenum compounds reduced SRV μ from 0.16 (for TH-0 with no additives) to the range of 0.05 – 0.08. It was also confirmed that sulfur compounds did not reduce SRV μ .

The material compatibility tests checked the corrosion of overlay kelmet bearings and aluminum bearings. They were also used to evaluate the physical property changes in organic materials such as acrylic rubber (ACM), fluoroethylene rubber (FKM), 6 nylon, 6.6 nylon, and Formed in Place Gaskets (FIPG) when immersed in each of the tested oils at high temperatures. The results were compared with TH-0 (the no-additive oil). The tests indicated that almost all of the organo-molybdenum compounds had little effect on other materials. However, TH-7, with MoDTP, did have considerable negative effect on both nylon and FIPG. Also, among the sulfur compounds, the carbamate in TH-12 and TH-13 seriously affected FKM. The causes and the effects on parts are currently under study, but ample care must be exercised in the use of these compounds⁽⁶⁾.

Based on the above results, effective friction modifiers with good material-compatibility characteristics were selected.

3. Formulation of Developed Oil

Using the selected friction modifiers, a formulation was developed as shown in **Table 2**. The noteworthy points about the formulation are : 1) the base oil has a high viscosity index (VI) and low Noack volatility; 2) two types of MoDTC, TH-1 and TH-2, are used as friction modifiers; 3) TH-16 thiadiazole is used to sustain the friction-reduction effect. The quality features of this oil are API SJ, ILSAC GF-2, and SAE 5W-20, an HTS viscosity of 2.65 mPa·s, low volatility, and a low friction coefficient.

Table 2 Formulation and Properties of Developed 5W-20 Oil

Formulation	Base oil	High VI
	Friction modifier (mass%)	MoDTC Mo; 0.065 Thiadiazole S; 0.07 Added
Properties	DI additive package	Added
	API ILSAC SAE	SJ GF-2 5W-20
Properties	Flash point (°C)	218
	Kinematic viscosity (mm ² /s) 40°C	42.1
	100°C	8.3
	VI	177
	Sulfated ash (mass%)	1.0
	HTS viscosity (mPa·s)	2.65
	Noack volatility (mass%)	14
	SRV μ , 100°C	0.05
	Element analysis (mass%) Mo	0.065
	S	0.37
	P	0.095

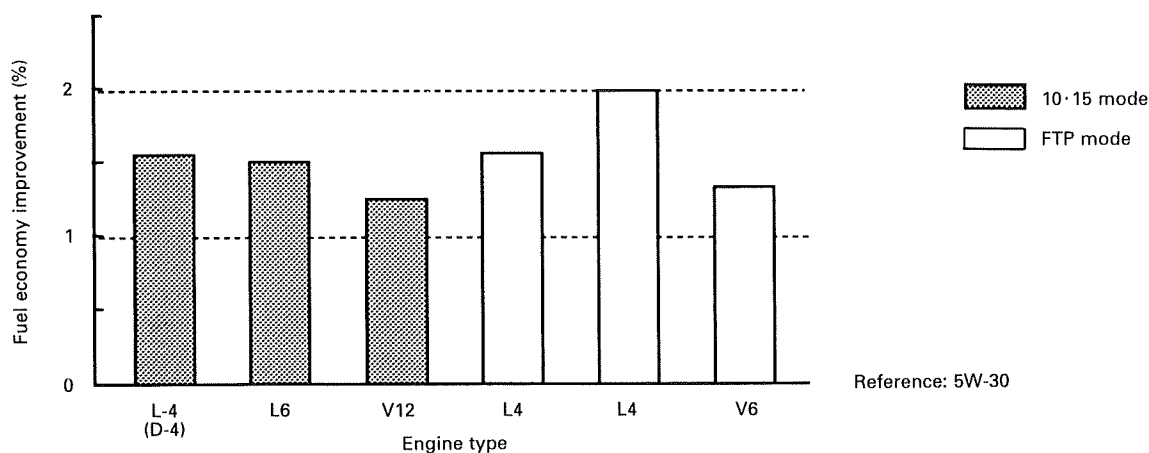


Fig. 4 Fuel Economy Improvement of Developed 5W-20 Oil

4. Fuel Economy Effects of Developed Oil

The fuel economy effects of the developed 5W-20 oil were measured on actual vehicles.

4.1 Fuel Economy Effect

The fuel economy effect of the developed 5W-20 oil was measured using six broken-in vehicles in the Japanese 10·15 mode and the federal test procedure (FTP) mode, using the results for a 5W-30 oil with no MoDTC or sulfur compounds as a baseline for comparing fuel economy improvement. The results are shown in **Fig. 4**.

The results made clear that the developed 5W-20 oil improves fuel economy from 1.2% to 2.0% in comparison with 5W-30 oil. The average improvement for all six vehicles was 1.5%.

The result is consistent with the result shown in **Fig. 1**, a 2.0% advantage for 5W-20 with MoDTC over 5W-30.

4.2 Retention of Fuel Economy Improvement

The data in **Fig. 1** and **Fig. 4** were measured in engines whose metal surfaces had already been smoothed by running. It was also necessary, however, to evaluate fuel economy performance during the first 10,000 kilometers of an engine's life to take into account the actual situation on the road until the first oil change. Using new engines, fuel consumption was first measured at almost zero kilometers, then again after the vehicles had been operated in the 11-lap/55 mode to age the oil.⁽⁴⁾

4.2.1 Test Oils

Three oils were tested: the developed 5W-20 oil, a prototype 5W-20 oil with MoDTC but without any sulfur compounds, and a conventional 5W-30 oil without MoDTC or sulfur compounds.

4.2.2 Retention of Fuel Economy Improvement

The results are shown in **Fig. 5**. In initial operation, both the prototype and the developed 5W-20 oils showed a large improvement of 3.5% over the 5W-30 oil. As operation continued, the prototype oil lost some of its effect. However, the developed oil retained its effect for as long as 10,000 kilometers. From these results, it can be said that the combination of MoDTC and thiadiazole is effective for the retention of fuel economy improvement. The reason is thought to be that the thiadiazole acts as a source of sulfur for the formation of a low-friction film of molybdenum sulfide (MoS₂) on the frictional

surfaces⁽⁴⁾⁽⁵⁾.

4.2.3 Changes in HTHS Viscosity of Used Oil

The HTHS viscosity of the developed 5W-20 oil remains stable at 2.6 mPa·s. This is in contrast to the 5W-30 oil, whose viscosity tends to drop and then rise somewhat over distance. (**Fig. 6**)

4.2.4 Changes in SRV μ of Used Oil

It has been confirmed that the SRV μ of the developed 5W-20 oil remains low for as long as 7,500 kilometers. (**Fig. 7**)

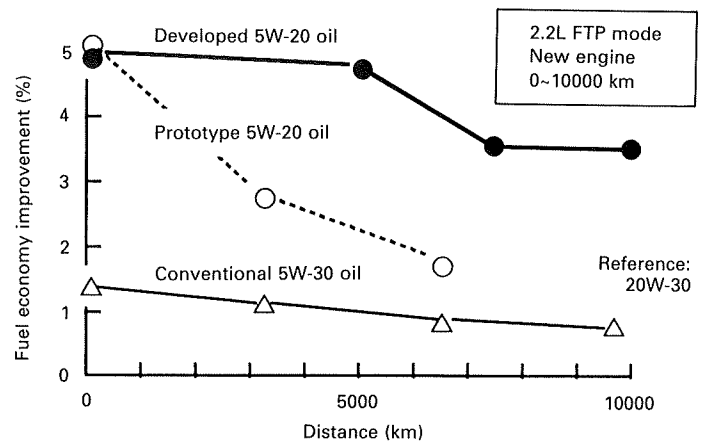


Fig. 5 Retention of Fuel Economy Improvement of Developed 5W-20 Oil

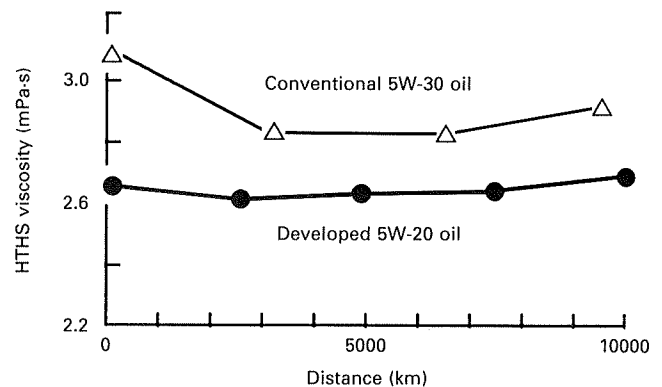


Fig. 6 HTHS Viscosity Change

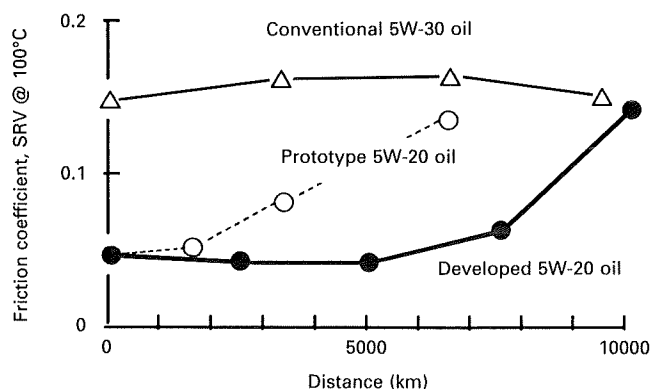


Fig. 7 Friction Coefficient Change

5. Conclusions

The results of studies conducted with various types of modern engines made the following points clear:

- (1) In fuel economy tests with six types of broken-in vehicles, the fuel economy improvement effect of the developed 5W-20 oil averaged 1.5% better than that of 5W-30 oil without MoDTC or sulfur compounds.
- (2) In a 10,000 kilometer fuel economy test using new engines, the fuel economy improvement effect of the developed 5W-20 oil was initially 3.5% better than for 5W-30 oil, and the effect was retained with only a slight drop for as long as 10,000 kilometers.
- (3) The low-friction effect could be retained by combining MoDTC with thiadiazole, a sulfur compound. This is thought to be because thiadiazole acts as a source of the sulfur required to form a low-friction MoS₂ film.
- (4) The optimum viscosity to improve fuel economy without increasing wear or oil consumption is an HTHS viscosity of 2.6 mPa·s, or SAE grade 5W-20. It was also confirmed that oil volatility is a more important factor than viscosity in reducing oil consumption.
- (5) The friction coefficient of the oil was lowered from 0.16 to 0.05 – 0.06 by the addition of the friction modifier MoDTC.

6. Acknowledgments

The authors wish to express their deep appreciation to the staffs of Taiho Kogyo Co., Ltd., NOK Corporation, Toray Industries, Inc., Three Bond Co., Ltd., and Shin-Etsu Chemical Co., Ltd., Japan Energy Corporation, Tonen Corporation, Esso Sekiyu K.K., Nippon Oil Company, Ltd., Asahi Denka Kogyo K.K., and Lubrizol Japan Limited, as well as to the staff of Toyota Central R&D Labs., Inc. for their cooperation in this

development program.

References

- (1) Kenyu Akiyama, F. Ueda, J. Miyake, K. Tasaka, S. Sugiyama: Fuel economy performance of the highly efficient fuel economy oils using chassis dynamometer test. SAE Paper 932690 (1993)
- (2) Mamoru Tohyama, Ohmori, Yamamoto, Akiyama, Kawai, et al.: Effects of engine oil viscosity and friction modifier on engine wear. Japanese Society of Tribologists, Proceedings of JAST Tribology Conference Kitakyushu, P. 120, October (1996)
- (3) Kiyoshi Inoue, E. Tominaga, K. Akiyama, T. Ashida: Effects of lubricant composition on fuel efficiency in modern engines. SAE Paper 951037 (1995)
- (4) Kenyu Akiyama, Kikuchi, Sugiyama, Ashida, Tanaka: Gasoline engine oil durability on fuel economy improvement performance. Japan Society of Automotive Engineers, 1995 JSAE Spring Convention Proceedings, p. 207, JSAE 9535279 (1995)
- (5) Katsuya Arai, M. Yamada, S. Asano, S. Yoshizawa, H. Ohira, et al.: Lubricant technology to enhance the durability of low friction performance of gasoline engine oil. SAE Paper 952533 (1995)
- (6) Koichi Kurono, Owaki, Suzuki, Akiyama, Shionoya: Study of effects of engine oil additives on the properties of fluoroelastomers. Japan Society of Automotive Engineers, 1997 JSAE Autumn Convention Proceedings, P. 245, JSAE 9740127 (1997)

Authors



K. AKIYAMA



H. KAWAI



S. SUGIYAMA

Contributions of Automatic Transmission to Fuel Economy

Sinya Nakamura*
Masahiro Kojima*
Katsumi Kohno*

Abstract

In recent years, technologies for reducing fuel consumption are becoming more important than ever, due to the heightened global interest in protecting the environment. In line with this trend, various improvements are also being made to enhance the transmission efficiency of automatic transmissions.

As a result of research into power loss in the automatic transmission, it has been found that the torque converter incurs the largest loss. This paper mainly shows new technologies for the torque converter. The first is torque converter lock-up clutch slip control. This system engages the lock-up clutch by applying a steady slip speed to prevent the torque fluctuation of the engine from being transmitted to the drive train while enhancing the transmission efficiency of the torque converter. The second technology is a new design procedure for the flow passage using computational fluid dynamics. Three-dimensional incompressible turbulent flow within a flow passage is numerically analyzed.

These new technologies are now contributing to large-scale fuel economy.

Keywords: automatic transmission, slip control, torque converter performance, fuel economy improvement

1. Introduction

In recent years, against a backdrop of problems such as the depletion of fossil fuels and public pressure to preserve the global environment, the development of clean and efficient products and, in the automobile industry in particular, the improvement of vehicle fuel economy have become the most pressing issues.

The installation rate of automatic transmissions (ATs) in passenger cars now exceeds 80%. Improving the fuel economy of AT vehicles (**Fig. 1**) has thus far been accomplished by means of multi-speed transmissions, electronic control, lock-up systems, and so on. But the fuel economy of AT vehicles generally remains 10% to 15% worse than that of manual transmission vehicles, so fuel economy improvement is rapidly becoming more important. The authors used loss analysis to discover the causes of the AT's inferior fuel economy. **Fig. 2** shows an example analysis of the causes of loss when a conventional AT vehicle accelerates gradually to 60 km/h. The results indicate that reducing loss in the torque converter (**Fig. 3**) is the most important issue.

This paper describes efforts to improve the fuel economy of AT vehicles, focusing on lock-up clutch slip control and the designing of the flow path by means of numerical analysis on a supercomputer as technologies for reducing loss in the torque converter.

2. Lock-up Clutch Slip Control

A feeling of smooth acceleration and smooth shifting are often cited as features of AT vehicles. These advantages are gained by transmitting power via the torque converter, but their realization is premised on a proportionate loss of power. The lock-up clutch slip control system⁽¹⁾ was developed for the purpose of greatly enhancing power transmission efficiency while maintaining the characteristic advantages of the torque converter.

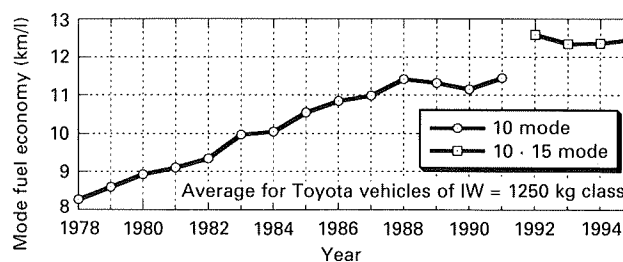


Fig. 1 Mode Fuel Economy for AT Vehicle

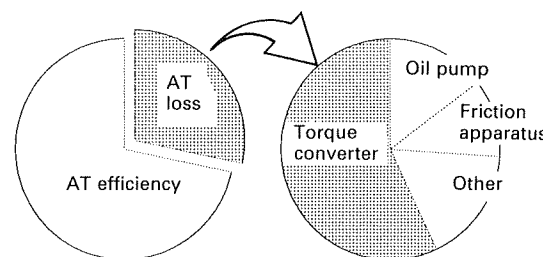


Fig. 2 Causes of AT Loss

* Drive Train Engineering Div.

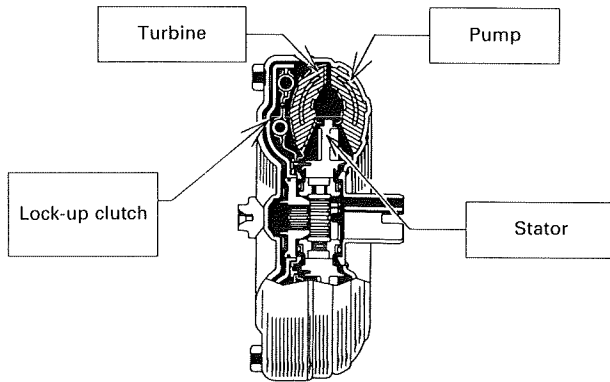


Fig. 3 Torque Converter Structure

The following major issues were confronted in the development of slip control as a product:

- (1) Development of a control system with superior response and robust stability, capable of controlling slip speed precisely
- (2) Development of automatic transmission fluid (ATF) and friction materials that provide stable friction characteristics and can be used with slippage conditions different from those in which friction elements are generally used

This section describes the slip control system and the manner in which these problems were addressed.

2.1 Operating Concept

Lock-up systems have been used to improve fuel economy in AT vehicles for some time. When the lock-up clutch engages, the torque converter's input and output shafts become locked and maximum transmission efficiency is obtained.

However, in the low-speed range, engine combustion is accompanied by a large torque fluctuation component that is greater than the internal damping system can absorb, so in terms of vehicle vibration, drivers can not get much benefit from the lock-up system in the vehicle speed ranges typical of city driving.

Slip control is a technology that engages the lock-up clutch while constantly applying a predetermined amount of slip speed. **Fig. 4** shows the power flow through the torque converter when slip control is implemented. As the drawing shows, power is transmitted by way of both the torque converter (hydraulic transmission) and the clutch (mechanical transmission), with the ratio of mechanical transmission dropping and the ratio of hydraulic transmission rising as the slip speed increases. That is to say, the distribution ratio of power transmission can be selected at will by setting the slip speed. As **Fig. 5** shows, the level of torque fluctuation transmitted to the drive train drops as the ratio of hydraulic transmission rises, but power transmission efficiency drops at the same time, because

of the power loss incurred due to slippage. But if slip control is implemented so as to maintain the lowest hydraulic distribution ratio at which the torque fluctuation does not become a problem in terms of vehicle vibration, power transmission efficiency can be improved without undue vibration.

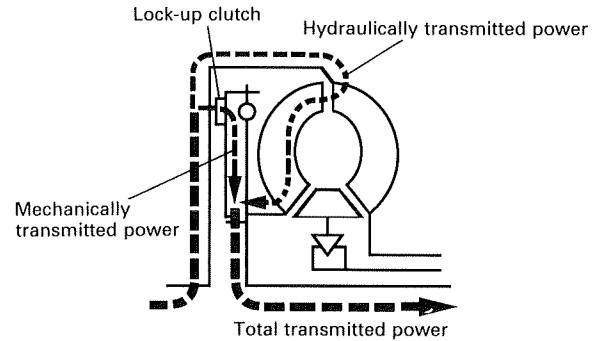


Fig. 4 Power Flow with Slip Control

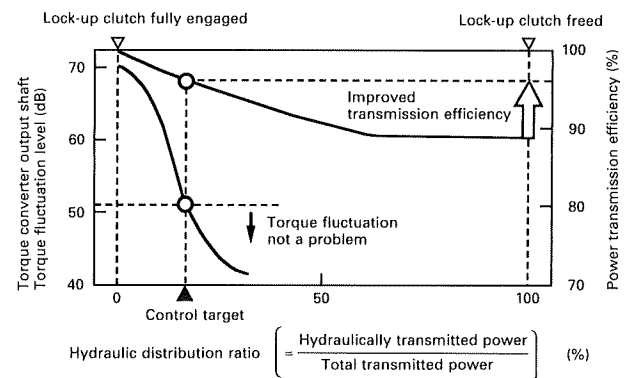


Fig. 5 Vibration Damping and Transmission Efficiency with Slip Control

2.2 Slip Control System

The system shown in **Fig. 6** has been adopted in order to control the slip speed at a predetermined value. The system compares the actual slip speed, as detected by speed sensors, to the target slip speed, then inputs a command value to the hydraulic control circuit to bring the actual speed into line with the target speed. The command value is used as the control input to the feedback control function, which continuously adjusts the pressure difference between the clutch engage and disengage pressures.

Fig. 7 shows the hydraulic control circuit. The transmission torque capacity of the lock-up clutch is controlled by using a linear solenoid valve to adjust the pressure difference between the engage pressure and the disengage pressure. The linear solenoid valve is an actuator that regulates the hydraulic pressure

in proportion to the electrical current, and for purposes of this system, the design of the magnetic path in the electromagnetic portion was optimized to provide a high level of response.

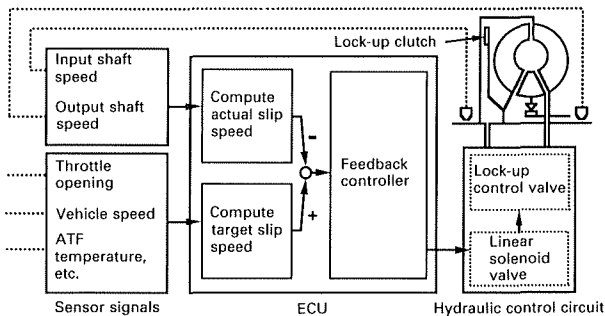


Fig. 6 Slip Control System

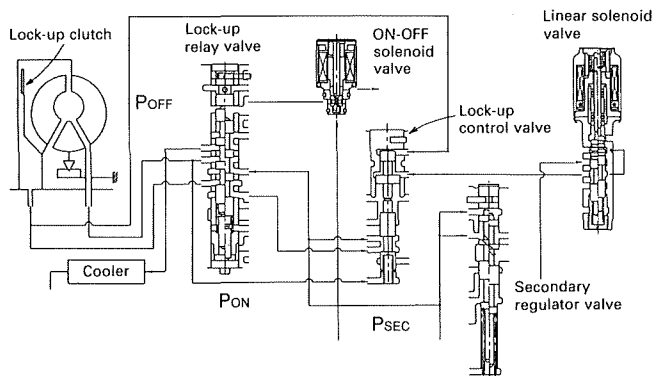


Fig. 7 Hydraulic Control Circuit

Fig. 8 shows the implementation region of the slip control function. Control has been extended to the vehicle speed range in which the conventional lock-up system could not be utilized (such as the normal range for city driving). Slip control is im-

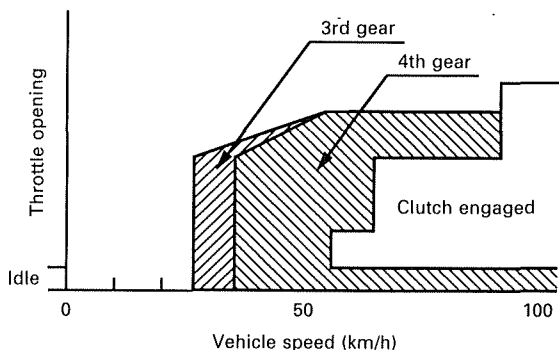


Fig. 8 Implementation Region of Slip Control

plemented even while the idle switch is on. Because slip control raises the engine speed in this case, the fuel cutoff time during vehicle deceleration is extended and the amount of fuel consumed can be reduced.

2.3 Slip Control Support Technology

2.3.1 Feedback Control System

The feedback control system is the heart of the slip control system. It must ensure the kind of responsiveness that can cope with sudden changes in the driving conditions, and at the same time, guarantee robust stability to handle factors whose values are dispersed over a wide range and to cope with the aging that the system incurs over time.

The feedback controller we designed to meet these requirements is the first mass-produced component in the world to make use of the H^∞ (H-Infinity) control theory⁽²⁾. The H^∞ control theory introduces the concept of loop shaping in the frequency domain into a part of the design theory of the control system, thereby making possible a detailed design that employs the H^∞ norm (the maximum value of the frequency response gain) as a measure of system performance.

To clarify the performance, the H^∞ controller should be compared to a PID controller (the conventional technology) with the same response. The method is to examine the step response of the two controllers when the condition of the control object varies.

Fig. 9 shows the results of a step response simulation (based on the time series model) when the DC gain is intentionally doubled on the assumption that the stationary friction coefficient changes.

Fig. 10 shows the results after a durability test, when the ATF and friction materials are deteriorated. It can be said that a high level of reliability is obtained with the H^∞ controller.

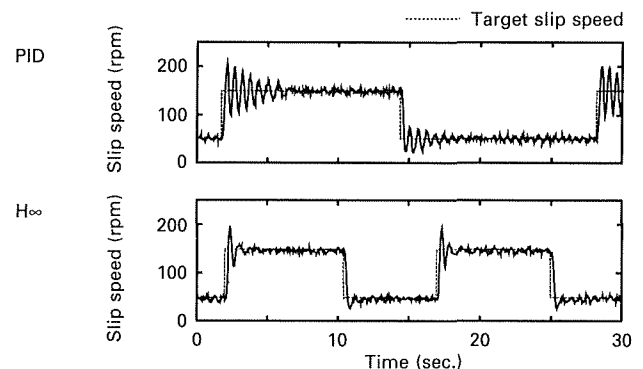


Fig. 9 Step Response Simulations (DC Gain Variation)

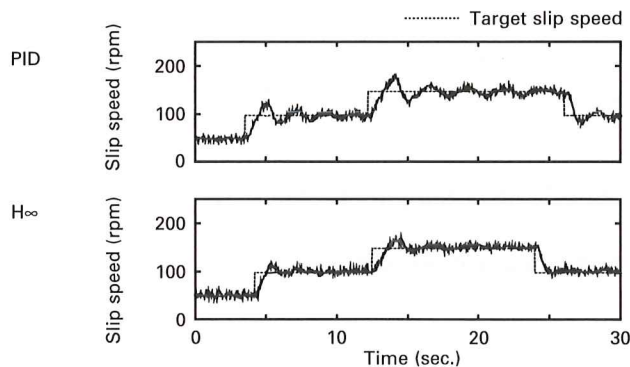


Fig. 10 Step Response Simulations (ATF, Friction Element Deterioration)

2.3.2 ATF and Friction Materials

In the slip control system, which uses the clutch in a constantly slipping state, the ATF and friction materials must be of especially high durability. And in order for the system to perform high-precision slip control, the friction characteristics must also remain stable over the long term. One standard for judging whether the friction characteristics are appropriate for slip control is whether or not the friction coefficient/slip speed characteristics (μ -V characteristics) have a positive gradient ($d\mu/dV > 0$). It is known that if the gradient is negative, it may cause clutch shudder, which is a type of stick/slip phenomenon. Moreover, good μ -V characteristics tend to run counter to static clutch torque capacity, so satisfying both of these requirements at the same time has been a problem.

By means of ATF additive mixture optimization⁽³⁾ and microscopic analysis of the clutch surface⁽⁴⁾, in parallel with the development of new materials that completely change the clutch lining formulation, materials were successfully developed that ensure the stability of excellent friction characteristics over time, while maintaining static torque capacity.

Fig. 11 shows a comparison of the durability of the friction characteristics of the conventional ATF and the new ATF developed for use with slip control.

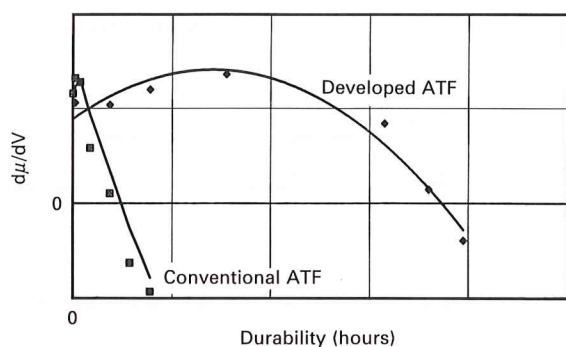


Fig. 11 ATF Durability

2.4 Effects of Slip Control

Fig. 12 shows the frequency of lock-up clutch operation in the 10 · 15 mode and the power transmission efficiency of the torque converter at different points. Power transmission efficiency is greatly improved by slip control.

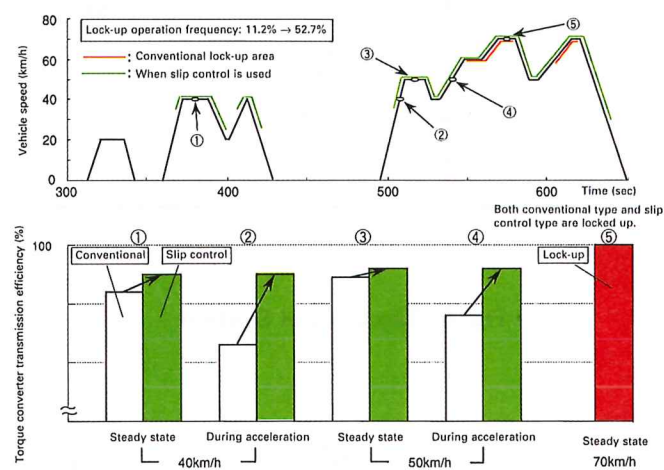


Fig. 12 Performance in 10 · 15 Mode

3. High-performance Torque Converter

Although the torque converter improves the driveability of the AT vehicle, it carries with it the disadvantage that power loss can not be avoided, because power is transmitted hydraulically. This section describes a new torque converter designed to reduce power loss when hydraulic transmission is used. Analysis of the torque converter's internal flow was put to practical use in the design.

3.1 Torque Converter Structure

As stated previously, the torque converter is a device that transmits power hydraulically. As shown in **Fig. 3**, it is constructed of three blade cascades: a pump and a turbine arranged opposite each other, and a stator positioned between them.

The rotation speeds of the three blade cascades are independent of one another, and the rotating conditions differ according to the driving conditions.

It is extremely difficult to gain an understanding of the torque converter's flow path profile in order to improve its performance, because the internal flow exhibits a complex, three-dimensional shape, each of the individual blade cascades has a different number of blades, and the converter itself is a pressure vessel forming a closed-loop flow around and about the three cascades.

3.2 Torque Converter Design Support System

Traditionally, each of the blade cascades that make up the torque converter has been designed by a method that conceives of the internal flow as quasi-one-dimensional and focuses on the angular momentum of the blade cascade, taking into account certain empirical factors. Analysis of internal flow in actual torque converters⁽⁵⁾ has also been actively pursued, but it has only been since the computational power represented by supercomputers has been developed that full-fledged analysis has become possible.

The flow path profile design method⁽⁶⁾ focuses on the pressure balance when an ideal flow pattern is posited within the torque converter flow path. The method for designing the stator, which strongly affects the torque converter characteristics, uses the inverse problem method⁽⁷⁾ to design a stator blade profile that effectively suppresses the separating flow that is directly connected to energy loss. A torque converter design support system was constructed that uses these methods as a base and combines them with computational tools incorporating a turbulence model, which is useful for simulating the separating and reattaching turbulent flow in the three-dimensional viscous flow calculation⁽⁸⁾ that is used to gain a quantitative understanding of the closed-loop flow around and about the three blade cascades. The system is capable of predicting performance with no greater than a 5% degree of error within a range of computing time (10-20 hours of CPU time) that makes the system suitable for practical use.

An example of a torque converter designed by this system is shown in **Fig. 13**. This shows velocity vectors in the turbine's meridional plane with a speed ratio of 0.8, showing that fluctuation in the flow path is effectively suppressed.

The torque converter flow was evaluated by the dissipation function, a measure that expresses the distribution of localized energy losses, making it easy to judge the flow.

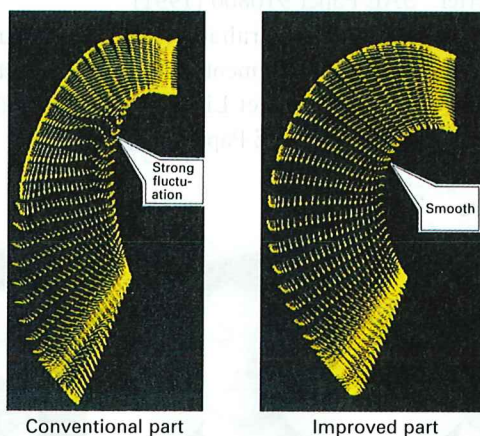


Fig. 13 Velocity Vectors Through Turbine Cascade (Speed Ratio 0.8)

A graphics screen was also devised to facilitate understanding of the various aspects of the complicated internal flow. (See **Fig. 14**.)

Fig. 15 shows an example of a flow path that was designed using the design support system.

In parallel with this technical development, experiments were conducted to check the computational results and their hypothetical validity against the empirical standards that ultimately determine their usefulness.

For the stator portion, the flow velocity was measured using a hot film anemometer with an X-type probe, and the pressure distribution on the blade surfaces was measured using a small pressure sensor. Through the arrangement of the torque converter input and output shafts (one-sided coaxial-shaft construction), the stator cascade flow, including the stator inlet and outlet flow, was measured by means of a laser Doppler velocimeter⁽⁹⁾. Flow within the turbine and the pump was also quantitatively evaluat-

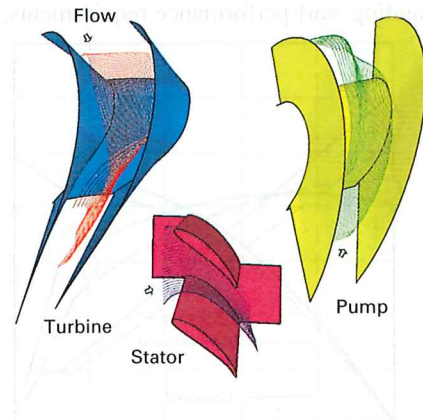


Fig. 14 Torque Converter Flow (Stream Line)

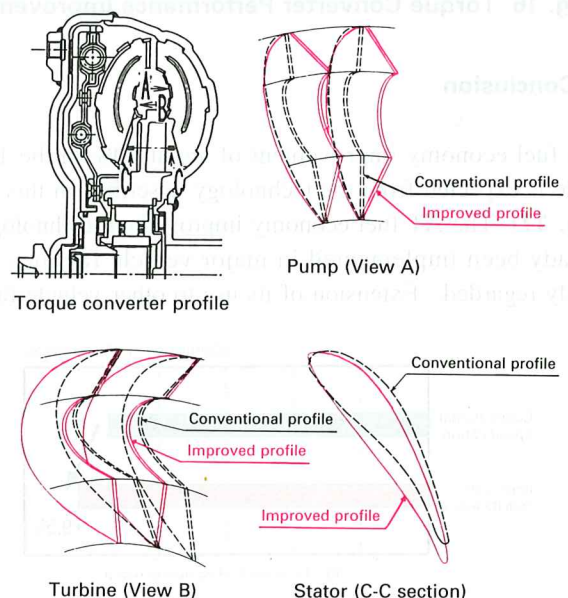


Fig. 15 Torque Converter Flow Path Improvement

ed by an experimental approach. All of these measurements contributed to making the design support system more practical.

3.3 Torque Converter Performance Improvement

As shown in **Fig. 16**, the performance of the torque converter has been improved with respect to the following points:

- (1) Torque converter transmission efficiency (η) was improved by smoothing the internal flow to suppress the power loss incurred due to slippage.
- (2) The torque capacity coefficient (c) is suppressed when the speed ratio is zero, in order to reduce the drag torque when the vehicle is stopped.
- (3) Torque converter slippage is reduced when the vehicle is cruising to increase the use of the high-efficiency range. Suppression of slippage is achieved by raising the torque capacity coefficient at high speed ratios.
- (4) A torque ratio (t) is ensured that is appropriate for the vehicle's standing start performance requirements.

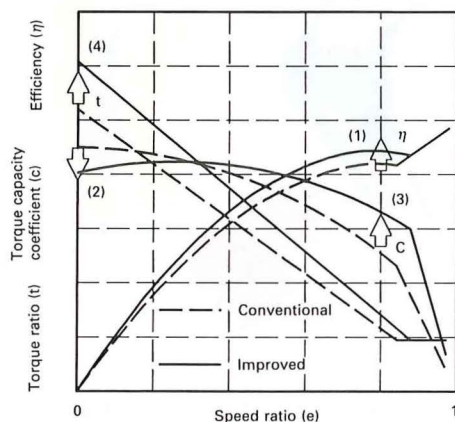


Fig. 16 Torque Converter Performance Improvement

4. Conclusion

A fuel economy improvement of about 10% in the 10 · 15 mode is expected from the technology described in this paper. (**Fig. 17**) The AT fuel economy improvement technology has already been implemented in major vehicle families and is highly regarded. Extension of its use to other vehicle families

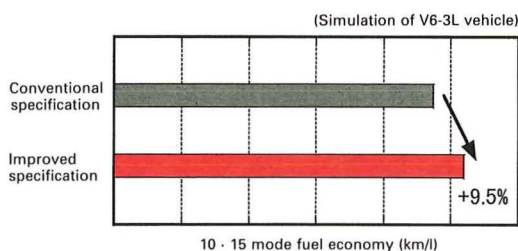


Fig. 17 10 · 15 Mode Fuel Economy Improvement

is planned for the future, because it is a key technology making a major contribution to fuel economy improvement.

References

- (1) K. Kono, H. Itoh, S. Nakamura, K. Yoshizawa, M. Osawa: Torque Converter Clutch Slip Control System. SAE Paper 950672 (1995)
- (2) M. Osawa, R. Hibino, M. Yamada, K. Kono, Y. Kobiki: Application of H_{∞} Control Design to Slip Control System for Torque Converter Clutch. IFAC Advances in Automotive Control (1995)
- (3) T. Kugimiya, J. Mitsui, N. Yoshimura, H. Kaneko, H. Akamatsu, et al.: Development of Automatic Transmission Fluid for Slip-Controlled Lock-up Clutch Systems. SAE Paper 952348 (1995)
- (4) A. Suzuki, K. Hayashi, Y. Kotani, Y. Nagasawa, S. Sanda: Mechanism of Friction of Wet Clutch with Paper Based Facing 2, The Effect of Surface Behavior for μ -v Characteristics. International Tribology Conference, Yokohama 1995 (1995)
- (5) A. Numazawa, F. Ushijima, K. Fukumura, T. Ishihara: An Experimental Analysis of Fluid Flow in a Torque Converter. SAE Paper 830571 (1983)
- (6) A. Hoshino, T. Goto, T. Akashi, T. Ishihara, I. Fujita: A Consideration on Performance Improvement of Hydraulic Torque Converter. ASME Fluid Eng. Div., Vol. 100 (1990)
- (7) Y. Kondo, M. Yamada, K. Imai, H. Itoh, M. Kojima: Method of determining torque converter stator blade profile using the inverse problem method. The Japan Society of Mechanical Engineers, Fluids Engineering Conference '95, Printed Material for Presentations No. 95-19 (1995)
- (8) K. Abe, T. Kondoh, K. Fukumura, M. Kojima: Three Dimensional Simulation of the Flow in a Torque Converter. SAE Paper 910800 (1991)
- (9) H. Watanabe, T. Kurahashi, M. Kojima: Flow Visualization and Measurement of Torque Converter Stator Blades Using a Laser Sheet Lighting Method and a Laser Doppler Velocimeter. SAE Paper 970680 (1997)

Authors



S. NAKAMURA



M. KOJIMA



K. KOHNO

Development of D-4 Engine

Zenichiro Mashiki*
Souichi Matsushita**
Takeshi Gouno*

Abstract

A new direct-injection gasoline engine (the Toyota D-4) has been developed which makes ultra-lean burn (stratified-charge combustion) possible by direct fuel injection into the cylinder with much lower throttle and cooling losses. It features new technologies such as a piston with a concave cavity, a high-pressure fuel injection system, and a swirl intake port to produce an optimum swirl in the cylinder by means of a variable swirl-control valve. A seamless output torque transition between the stratified-charge and homogeneous-charge ranges is achieved by using a semi-stratified-charge range. NO_x emissions are reduced by using an electrically controlled EGR system and a NO_x storage-reduction catalyst. Several controls are achieved by using an electronic throttle control system.

It has been confirmed that a vehicle with this system successfully improves fuel economy while satisfying emission requirements.

Keywords: *direct fuel injection into the cylinder, stratified-charge combustion, swirl, fuel pressure, high-pressure fuel injection valve, electronically controlled throttle valve*

1. Introduction

In recent years, public attention has been focused on global environmental problems. For automobiles, great importance has been attached to the reduction of CO₂ emissions, which is to say, the reduction of fuel consumption, due to global warming and the depletion of natural resources.

Lean burn technology is an effective measure for reducing fuel consumption in gasoline engines, and it has been commercialized by virtually all automobile makers. Research has also been reported on stratified-charge combustion by means of direct fuel injection into the cylinder as a measure for further fuel economy improvement.

The direct-injection, stratified-charge engine has been studied for many years and offers the following advantages:

- (1) Pumping losses and cooling losses are low.
- (2) Anti-knock characteristics are good and charging efficiency is high, due to the lower temperature of the charge air.
- (3) Response is good.

However, the technology presents the following problems that make its commercialization difficult:

- (1) It is difficult to perform stratified-charge combustion across the entire range of operating conditions.
- (2) Smoke tends to be generated in the high-load range.
- (3) NO_x emissions are high.
- (4) Deposits tend to accumulate on the injection nozzle, making it difficult to ensure a stable spray.

To solve these problems, the D-4 engine uses stratified, semi-stratified, or homogeneous combustion, depending on the

operating range. This paper describes the combustion characteristics and combustion control.

Table 1 D-4 Main Specifications

Displacement	1998 (cc)
Bore x stroke	86×86 (mm)
Number of cylinders	In-line, 4 cylinders
Number of intake/exhaust valves	4
Compression ratio	10.0
Combustion chamber	Pent roof (concave piston)
Intake ports	Helical & straight
Fuel supply	Direct injection into cylinder
Fuel pressure	8.0~13.0 (MPa)
Fuel	Regular gasoline

2. System Overview

Table 1 shows the main specifications for the D-4 engine, and **Fig. 1** shows the main structure. The structure consists of three primary components, as described below.

(1) Piston with large cavity

In stratified-charge combustion, fuel is injected under high pressure during the compression stroke and enters the piston cavity. The swirl and the spray penetration cause the fuel to flow along the side walls of the cavity toward the spark plug. In the process, the fuel absorbs heat from the piston and the surrounding air, causing it to evaporate and form a combustible air-fuel mixture. When most of the mixture has passed the spark plug, ignition occurs. The shape of the cavity is intended to allow rapid expansion of the fuel that has passed the spark plug, thereby suppressing the formation of smoke.

* Engine Engineering Div. I
** Engine Engineering Div. II

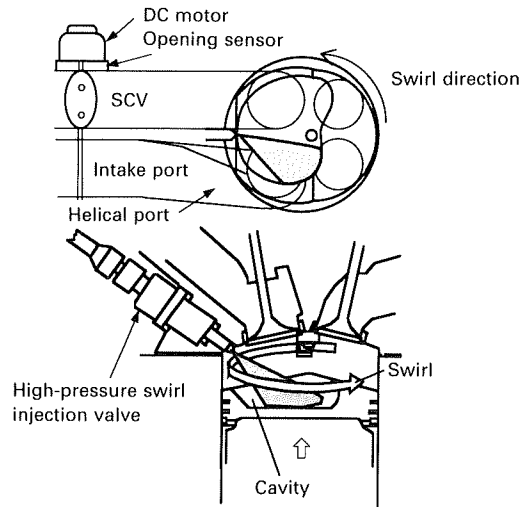


Fig. 1 Main Structure for Stratified-charge Combustion

After 3 msec (12 MPa)

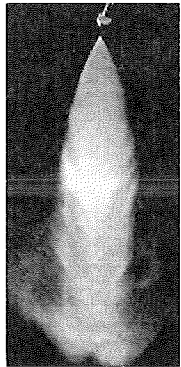


Fig. 2 Spray (shape)

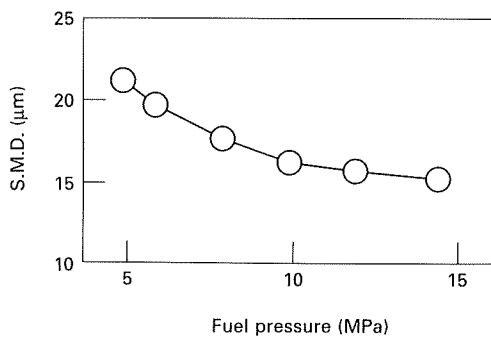


Fig. 3 Effect of Fuel Pressure on Spray Droplet Size

(2) High-pressure swirl fuel injection valve

The high-pressure injection valve is constructed to produce a rotating flow (swirl) at the nozzle tip. The swirl, at a fuel injection pressure 30 to 40 times normal (8 to 13 MPa), causes the fuel to form ultra-fine droplets without causing dispersion. This hastens evaporation of the fuel and shortens the time required to form the air-fuel mixture.

Fig. 2 is a photograph of the spray (shape) when fuel is injected at 12 MPa into a chamber that is at atmospheric pressure. **Fig. 3** shows the average droplet size in the spray relative to fuel pressure. As fuel pressure rises, the droplet size becomes smaller, until near-total saturation is achieved at around 12 MPa.

Fig. 4 shows the improvement in fuel economy in relation to fuel pressure, compared to the conventional engine. At low engine speed, the greatest improvement is achieved by reducing the fuel pressure and lengthening the injection time to prevent the concentration of fuel, while at high engine speed, the best

results are obtained by raising the fuel pressure and shortening the injection time to inhibit fuel dispersion.

(3) Intake port with swirl control valve (SCV)

A moderate degree air flow in the cylinder is necessary for the fuel to form a combustible air-fuel mixture as it absorbs heat from the piston and the air and evaporates. If the air flow is too weak, the post-ignition flame propagation speed is too slow, and combustion tends to be incomplete. If the air flow is too strong, the fuel will disperse, making it difficult to form a stratified mixture. **Fig. 5** shows an example of the relationship between the SCV opening and torque fluctuation during stratified combustion. If the SCV opens too little or too much, torque fluctuation becomes worse.

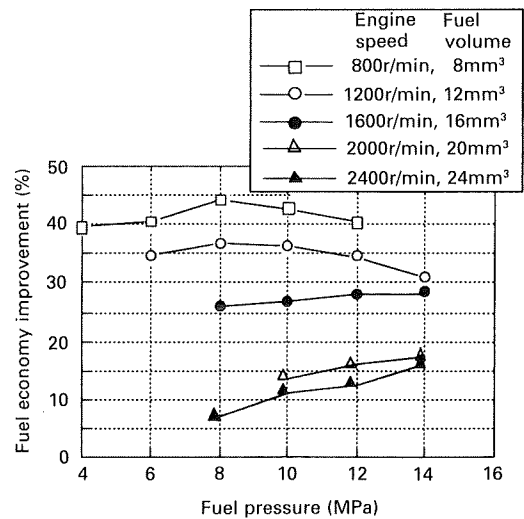


Fig. 4 Fuel Economy Improvement Effect

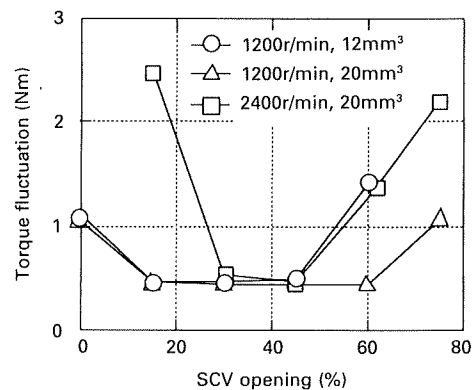


Fig. 5 Effect of SCV Opening on Torque Fluctuation

The strength of the air flow required to form a stratified air-fuel mixture changes with the engine load and speed. For that reason, the intake port is divided into a straight port and a helical port, and the straight port is fitted with an electronic swirl

control valve (E-SCV), which maintains the optimum swirl strength for the combustion conditions. The swirl strength when the SCV is completely closed is approximately 2.1, and lean combustion is achieved by closing the SCV during homogeneous combustion.

3. D-4 Engine Combustion Concept

Fig. 6 shows the different combustion modes in relation to the range of engine operation. Stratified combustion is used up to the medium-speed, medium-load range. Homogeneous combustion is implemented in the high-speed, high-load range by injecting fuel on the suction stroke. The homogeneous combustion range is further divided into two ranges, one for lean combustion and another for combustion using the same stoichiometric air-fuel ratio as the conventional engine, as well as an even richer mixture. In the boundary area between the stratified and homogeneous ranges, fuel is injected twice, once on the suction stroke and again on the compression stroke. Fig. 7 shows the pattern of fuel injection control. By optimizing the combustion mode according to the load and engine speed, the system maximizes fuel economy and ensures continuity of engine torque.

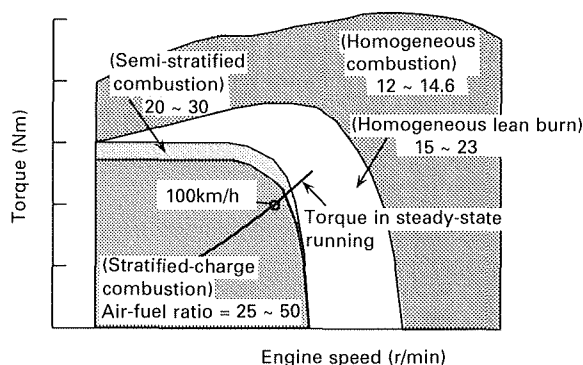


Fig. 6 Combustion Modes and Operating Ranges

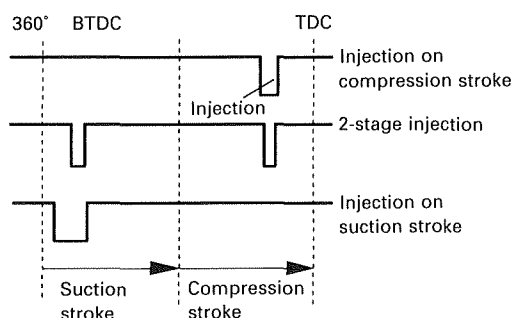


Fig. 7 Fuel Injection Control

4. Combustion Characteristics

4.1 Light Load (Stratified Combustion)

Fig. 8 shows the relationship between the lean combustion limit and NOx. Engine operation is stable even when the throttle is wide open. In stratified combustion, even if the total air-fuel ratio is lean, the ratio in the vicinity of the spark plug is rich, so NOx reaches its peak at a leaner air-fuel ratio than it does in normal homogeneous combustion. NOx is reduced by gradually increasing EGR, until with EGR at 35%, NOx is reduced by 90%.

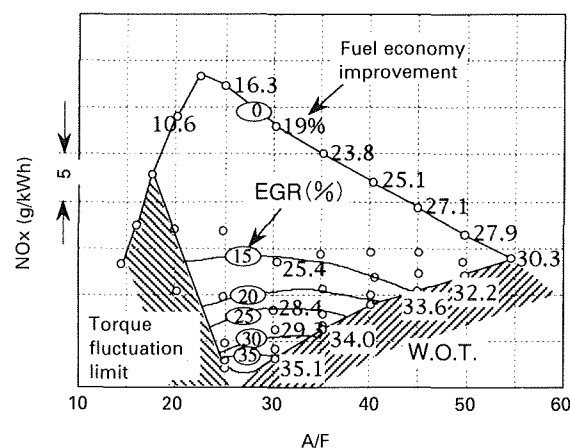


Fig. 8 Relationship of EGR and NOx (1200 r/m, 12 mm³/st)

4.2 Medium Load (Semi-stratified Combustion)

Fig. 9 shows the combustion characteristics when fuel is injected on the compression stroke, on the suction stroke, and on both the compression and suction strokes. If too much fuel is used in stratified combustion, an excessively rich air-fuel mixture will exist in the vicinity of the spark plug, even if the throttle is wide open, and smoke will be generated. On the other hand, if fuel is injected on the suction stroke for homogeneous combustion, but at the throttle angle required by stratified combustion, the resulting excess air will cause misfiring. This difference in the throttle angle is the cause of torque discontinuity between compression stroke injection and suction stroke injection. But if a semi-stratified mixture is created by dividing fuel injection between the compression and suction strokes, the transition to homogeneous combustion can be made without generating smoke.

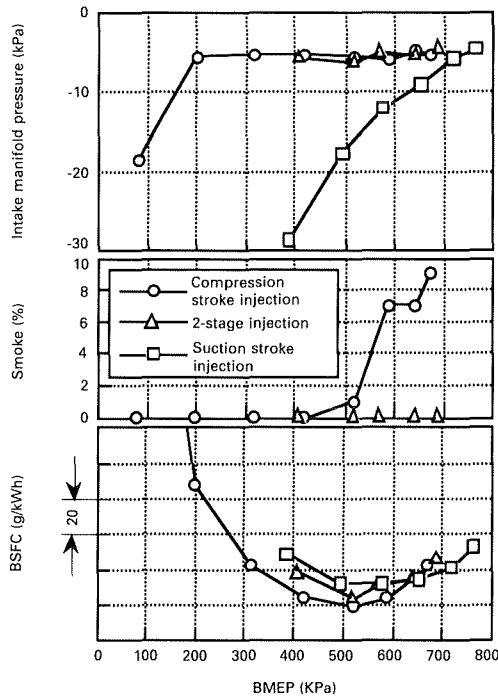


Fig. 9 Combustion Characteristics under Medium Load

4.3 High Load (Homogeneous Combustion)

Homogeneous combustion is achieved in the high load range by injecting fuel on the suction stroke. As explained previously, homogeneous combustion is divided into three ranges: lean combustion, combustion with a stoichiometric air-fuel ratio, and combustion with a rich air-fuel ratio.

5. D-4 Engine Control

Fig. 10 is a structural diagram of the control system. A number of special controls have been implemented in order to maximize the advantages of the D-4 engine. The sections below describe some representative examples.

5.1 Control of Basic Injected Fuel Quantity

A stratified combustion engine uses a large amount of air even in the light load range, and the specific volume of charge air does not change much when the load changes. It is therefore difficult to judge changes in load from the specific volume of charge air. For that reason, in the light and medium load ranges, the D-4 engine determines the amount of injected fuel based on the accelerator angle and engine speed. In the high load range and for cold starting, the engine computes the volume of charge air from the intake manifold vacuum, and determines the amount of fuel on that basis, in the same manner as a conventional engine.

5.2 Single-valve Electronic Throttle Control

In theory, an engine with stratified combustion can operate without a throttle valve, but in fact, a throttle valve is required, primarily for the following reasons:

- (1) Because a large volume of EGR gas is introduced in order to reduce NOx, a vacuum must be generated to some extent.

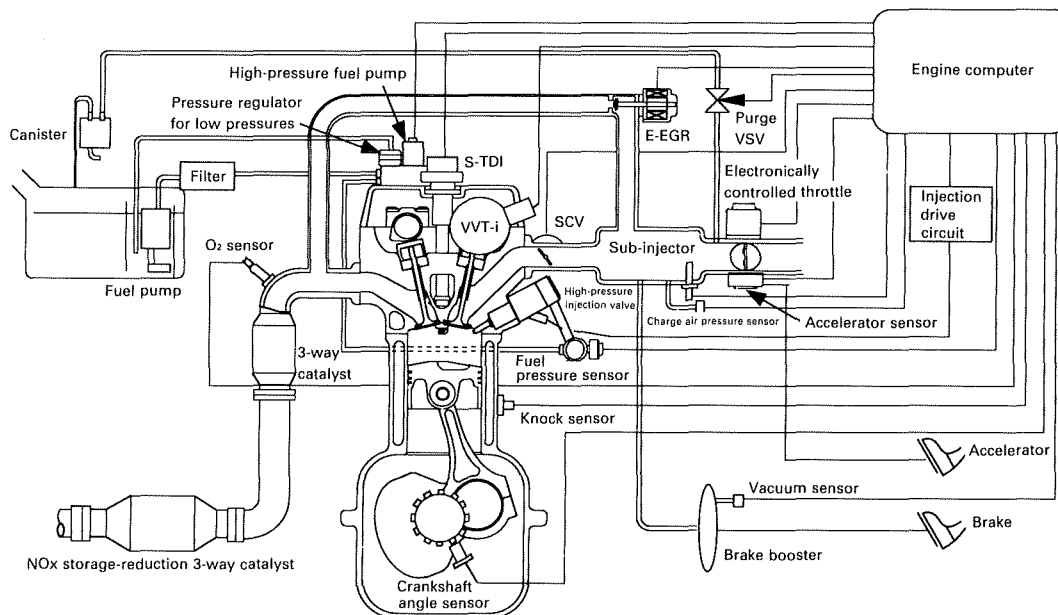


Fig. 10 System Diagram

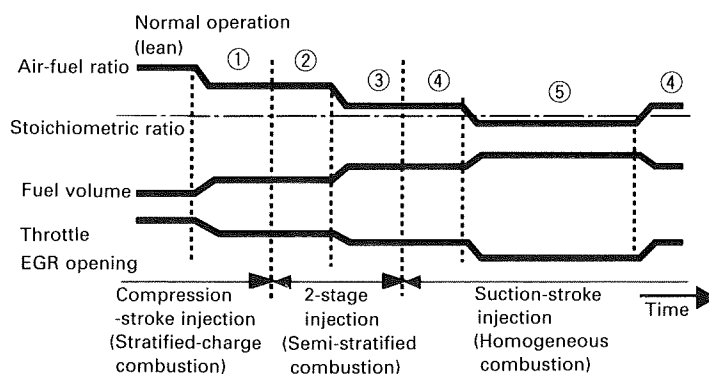


Fig. 11 Rich Spike Control

(2) Throttling is required to form a stoichiometric air-fuel ratio for cold starting.

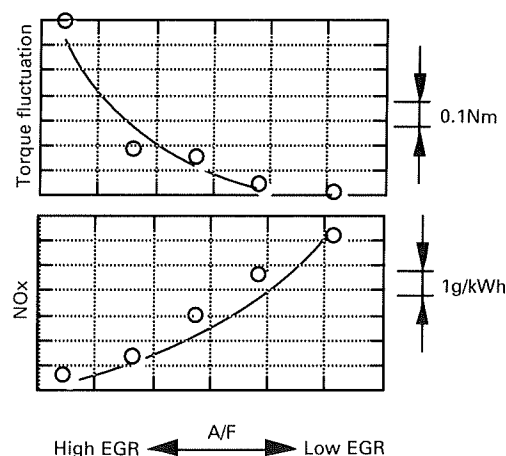
It is difficult to satisfy these requirements, and to achieve comfortable driveability, using a throttle valve with a mechanical linkage, so an electronically controlled throttle valve is used instead.

The use of an electronically controlled throttle valve makes possible the forms of control described below.

(1) Rich spike control

The engine uses a NO_x storage-reduction 3-way catalyst to remove NO_x from the emissions during lean combustion. The catalyst functions by storing NO_x during lean combustion and then chemically reducing the stored NO_x during an extremely short interval of rich combustion using an air-fuel ratio richer than the stoichiometric ratio.

If the air-fuel mixture is enriched by increasing the volume of fuel while maintaining the same throttle opening, torque increases, making driveability worse. In a lean-burn engine with conventional fuel injection in the intake port, the air-fuel mixture can be enriched without changing the torque by retarding ignition. However, if the amount of injected fuel is increased during stratified combustion, an excessively rich mixture forms around the spark plug and combustion becomes unstable. For this reason, it is necessary to change to homogeneous combustion to enrich the air-fuel mixture. However, the throttle, SCV, and EGR settings required to maintain the same torque differ greatly between stratified combustion and homogeneous combustion. If a sudden change were made to homogeneous combustion, excessively unstable combustion would occur, making driveability worse. To avoid this problem, the engine changes the form of combustion gradually from stratified to semi-stratified to homogeneous, finally making the transition to rich combustion. At this time, the same torque is achieved by an increase in pumping loss, because the throttle and EGR are closed, but the decrease in fuel economy is minimized. Fig. 11 is a schematic diagram of this sequence.

Fig. 12 Relationship of Torque and NO_x in Stratified Combustion

(2) Brake booster vacuum maintenance control

With the typical automobile braking system, braking is assisted by the intake manifold vacuum, but with stratified combustion, there is less throttling than in a conventional engine, and correspondingly less vacuum. As a result, the brakes may be less effective. This is countered by closing the throttle to ensure a vacuum in cases where brake booster vacuum must be maintained.

5.3 Lean Combustion and EGR Limit Control

Fig. 12 shows the relationship of the air-fuel ratio to torque fluctuation and NO_x in stratified combustion. NO_x decreases as EGR is increased, but torque fluctuation becomes worse. This shows that with stratified combustion, the variation in the amount of EGR strongly affects both NO_x and driveability. In order to correct for the variation in the amounts of air and EGR, the system uses the signal from the crankshaft angle sensor to compute a value that substitutes for the torque fluctuation. It then uses this value as feedback to correct the volume

of EGR and air in the stratified and semi-stratified combustion ranges, so that torque is maintained at the target level.

In the homogeneous lean combustion range, variations in the amount of injected fuel and the volume of air strongly affect exhaust emissions and driveability. Therefore, the system uses the substitute torque fluctuation value as feedback to control the fuel injection time, so as to gradually approach the limit of lean combustion and reduce the amount of NOx.

5.4 High-pressure Fuel Pump Control

Fig. 13 is an overview of the high-pressure pump. Fuel is sent to the high-pressure pump by the low-pressure pump (feed pump). The plunger inside the high-pressure pump is driven by the pump drive cam on the camshaft and pumps fuel to the high-pressure delivery pipe. The fuel pressure is read from the fuel pressure sensor attached to the delivery pipe, and the volume of pumped fuel is corrected accordingly. As explained previously, variable fuel pressure control is used to optimize the fuel pressure to fit the operating conditions. By pumping only the required volume of fuel, the system minimizes the pump's friction loss.

6. Performance

Due to the cooling effect on the charge air that results from injecting fuel directly into the cylinder, the engine achieves a high compression ratio of 10.0:1 with regular gasoline. Moreover, the use of intelligent variable valve timing (VVT-i), together with the high volumetric efficiency obtained by the cooling effect, allows the engine to achieve a 10% improvement in torque over a conventional engine. (**Fig. 14**)

As for fuel economy performance, a vehicle with a 4-speed automatic transmission and an equivalent inertia weight of 1250 kg achieves a 35% improvement in fuel economy when driven in the 10-15 mode. (**Fig. 15**)

7. Conclusion

- (1) By dividing the forms of combustion into three patterns, the D-4 engine suppresses smoke generation over its entire operating range while ensuring torque continuity.
- (2) Compared to a conventional engine, torque has been improved by 10%, and fuel economy has been improved by 35%.
- (3) Various control technologies were developed and implemented in order to maximize the direct-injection gasoline engine's characteristics of high output and low fuel consumption.

In closing, we would like to express our deepest appreciation to those companies that have cooperated with us in the development of the D-4 engine.

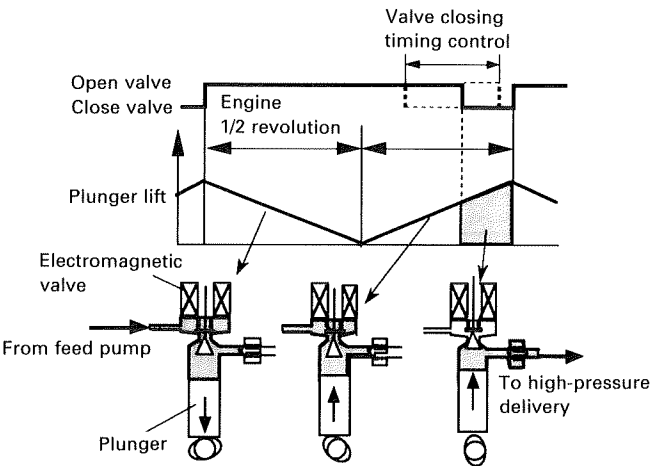


Fig. 13 High-pressure Pump Control

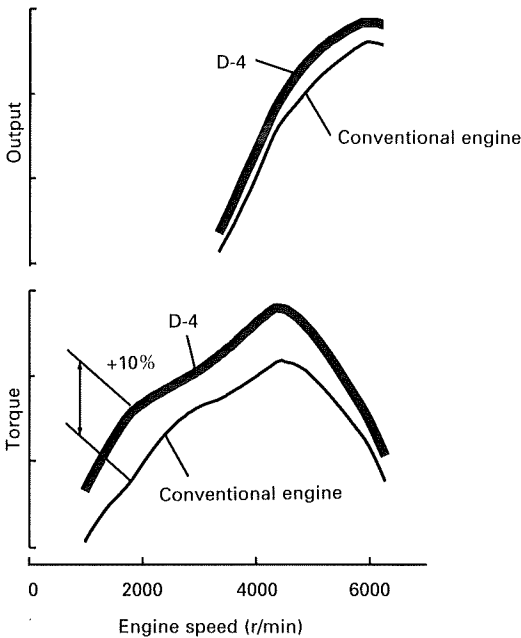


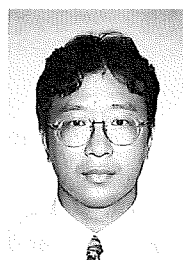
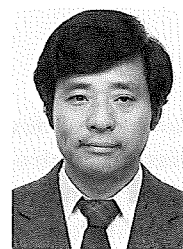
Fig. 14 Output Performance

		Automatic transmission vehicles	
		Fuel economy (km/ℓ) in 10・15 mode	
		10	20
With D-4 engine			17.4
With conventional engine		13.0	

Fig. 15 Fuel Economy Performance

■ References

- (1) Soichi Matsushita, Kiyoshi Nakanishi, Takeshi Gouno, Daisaku Sawada: Mixture Formation Process and Combustion Process of Direct Injection S.I. Engine, Journal of the Society of Automotive Engineers of Japan, Printed Material for Presentations 965.1996-10
- (2) J. Harada, T. Tomita, H. Mizuno, Z. Mashiki, Y. Ito: Development of Direct Injection Gasoline Engine. SAE Paper 970540 (1997)

■ Authors**Z. MASHIKI****S. MATSUSHITA****T. GOUNO**

Electric Vehicle "RAV4 EV"

Masao Kinoshita*
Sadahiro Kimura*

Abstract

The types and numbers of devices in use have been increasing greatly in recent years. Though energy saving, exhaust emission control, and noise reduction have been promoted by making use of the most advanced technologies in individual devices, global warming by CO₂, acid rain, and noise pollution have become the topics of dispute. Departure from dependence on fossil fuels is also an important task to cope with increasing energy consumption and the limitations on fossil fuel resources. With regard to vehicles requiring countermeasures as mobile sources of air pollutants, aside from other fixed sources, an electric vehicle without exhaust emissions or noise, and capable of using various resources other than fossil fuels, is one promising solution to the said problems.

This paper introduces the electric vehicle "RAV4 EV", sales of which started in Japan and the United States in October, 1997.

Keywords: *electric vehicle, nickel-metal hydride battery, permanent magnet synchronous motor, regenerative braking*

1. Introduction

The history of the electric vehicle (EV) is longer than that of the internal-combustion engine (ICE) vehicle. However, it is widely known that in contrast to the ICE vehicle, the market for which was expanded by means of rapid progress in technology and the establishment of the necessary infrastructure, the EV has never secured a sizable market, due primarily to the lack of progress in battery development. However, in recent years the massive expansion of the ICE vehicle market has come under scrutiny as a factor in everything from world-wide problems such as global warming to local problems such as emissions and noise in urban areas. In order to deal with these problems, as well as with the depletion of fossil fuel resources in the future, every automobile maker has been developing its own original EV. Toyota began full-scale EV research and development in 1982, putting the Town Ace EV on sale in the domestic market in 1993. However, because the vehicle was based on existing technologies, it left room for improvement in such areas as the range per charge and battery control and recharging. At around the same time in the American state of California and elsewhere, regulations were proposed to require zero-emission vehicles by 1998 (although this was later changed to a demonstration program using advanced batteries), which further strengthened EV development among automobile makers.

Technological progress in batteries and electronic control has been remarkable in recent years. Using the gasoline-powered RAV4 as the base vehicle, Toyota developed the world's first mass-produced EV to use nickel-metal hydride batteries and a permanent magnet motor, a three-door model boasting significantly improved performance. It went on sale in Japan in September of 1996. In October, 1997, Toyota

began marketing a higher-performance five-door model in both Japan and the United States.

2. Objectives and Features

The RAV4 EV is the EV version of the gasoline-powered RAV4, a sport utility vehicle mainly for city driving that has been well-received by younger drivers throughout the world. It features significantly better performance than previous EVs, but because it uses a performance-boosting unit and its production volume is small, the sale price in both Japan and the US had to be set rather high. For that reason, the target users in both countries are presumed to be government agencies and businesses that wish to show leadership in environmental improvement, with the vehicle being used mainly for work-related transportation and light-duty hauling over short-to-medium distances.

<RAV4 EV development objectives and vehicle features>

1) Extending the range per charge

The range per charge has been extended to at least 200 kilometers by using nickel-metal hydride batteries and a permanent magnet motor, as well as high-efficiency regenerative braking.

2) Total balance of vehicle performance

The type and number of batteries used is well-balanced with respect to the vehicle weight, and performance is maintained at a constantly high level regardless of the state of the batteries. The heavy batteries are mounted under the floor to lower the center of gravity and provide superior driveability.

3) Vehicle packaging

Because the floor of the base vehicle is high, it is easy to mount the batteries under the floor, converting it into an EV without sacrificing interior space. This preserves certain advantages of the base vehicle. The cargo compartment's flat floor maximizes storage capacity, and

* Vehicle Development Center III

Table 1 Main Specifications and Performance

		TOYOTA RAV4 EV	HONDA EV PLUS	NISSAN PRAIRIE Joy EV	GM EV1	Peugeot 106 EV
Vehicle type		5-door	3-door	4-door van	2-door coupe	3-door
Overall length	(mm)	3980	4045	4545	4309	3680
Overall width	(mm)	1695	1750	1690	1766	1600
Overall height	(mm)	1675	1630	1695	1281	1380
Complete vehicle curb weight	(kg)	1560	1620	1700	1350	1087
Passenger capacity	(persons)	5	4	4	2	4
Range per charge in urban areas	(km)	230	220	>200	*113	80
Maximum speed	(km / h)	125	>130	120	129	90
Batteries	Type	Nickel-metal hydride	Nickel-metal hydride	Lithium ion	Lead-acid	Nickel-cadmium
	Number of modules	24	24	12	26	20
	Total voltage (V)	288	288	354	312	120
Motor	Type	Permanent magnet synchronous	Permanent magnet synchronous	Permanent magnet synchronous	AC induction	DC shunt
	Maximum output (kw)	50	49	62	102	20
	Maximum torque (N-m)	190	275	159	—	127
Charger		On-board type Stationary type	On-board type	Stationary type	Stationary type	On-board type Stationary type

the rear seats can be folded up to enlarge the cargo space. The wide-opening rear door and lip-free doorsill make loading and unloading easy. Also, because the vehicle is taller than a passenger car, but lower than a recreational vehicle, it is easy for the driver to get in and maintenance and repair out, even at frequent intervals. The overall package is attractive to the target users.

4) Usability and comfort

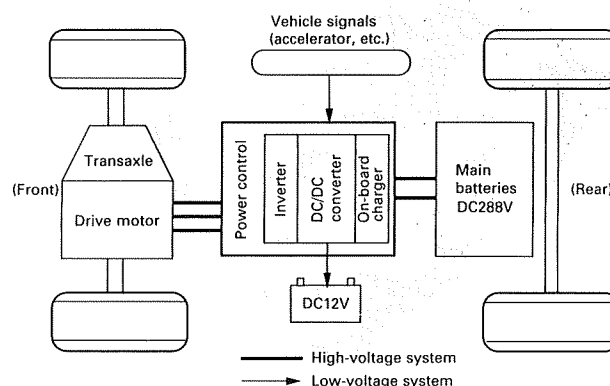
The RAV4 EV is designed for usability and features amenities such as power steering and air conditioning. The switches, instruments, and other controls are designed to feel as much as possible like those of a gasoline-powered vehicle. The on-board battery charger is provided with a one-touch connector, making it easy to recharge the battery from any ordinary power supply.

5) Safety

The vehicle's electrical system has been adapted to ensure safety in all operating conditions and during maintenance and repair.

3. EV System

The EV system of the RAV4 EV is shown in **Fig. 1**. The arrangement of EV units is shown in **Fig. 2**, and the details of each unit are described in the sections below. The basic operation of the EV system is that the charger converts alternating-current electricity into direct-current to charge the batteries. The control unit controls the inverter according to signals from the accelerator and other devices, and outputs alternating-current electricity. That power operates the transverse-mounted motor to drive the vehicle's front wheels.

**Fig. 1 EV System**

3.1 Batteries

In terms of the total balance of performance, product life, and safety, nickel-metal hydride batteries have been judged to be the most appropriate for use as the main EV batteries at the present time, and the RAV4 EV is the first mass-produced vehicle in the world to employ them. (**Photo. 1, Table 2**) Lithium batteries show promise in terms of performance, but they present cost and other problems that remain to be solved.

Nickel-metal hydride batteries provide approximately twice the performance and three times the product life of the lead batteries used heretofore in EVs. Their output is stable, consistently providing 90%

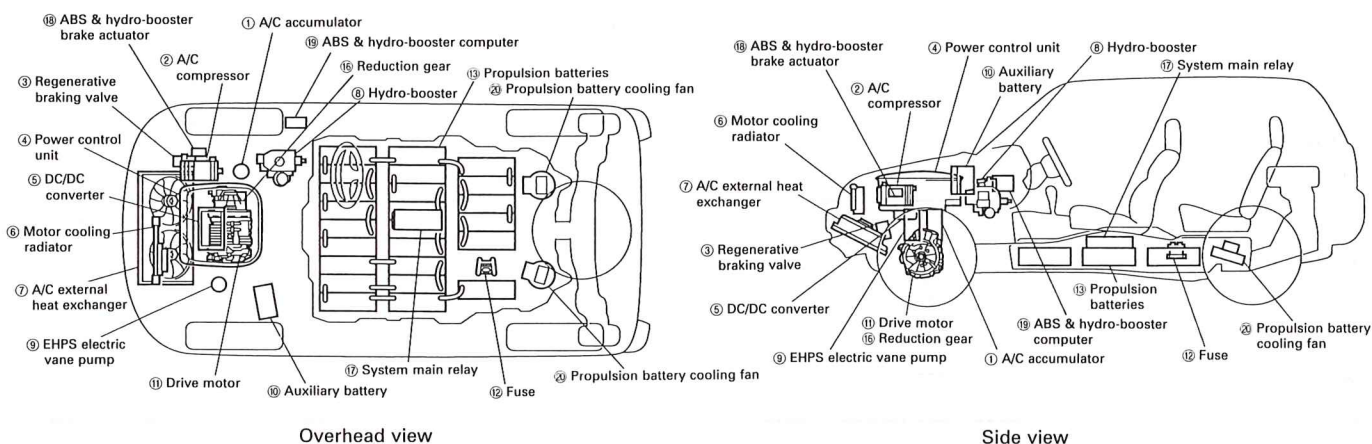


Fig. 2 Arrangement of EV Components

or more of the vehicle's required output. (Fig. 3) Because they have a sealed structure, water refilling and other maintenance are unnecessary. The RAV4 EV is equipped with 24 batteries, installed in a battery carrier under the floor and weighing a total of 450 kilograms. The battery carrier is made of lightweight, corrosion-resistant plastic.

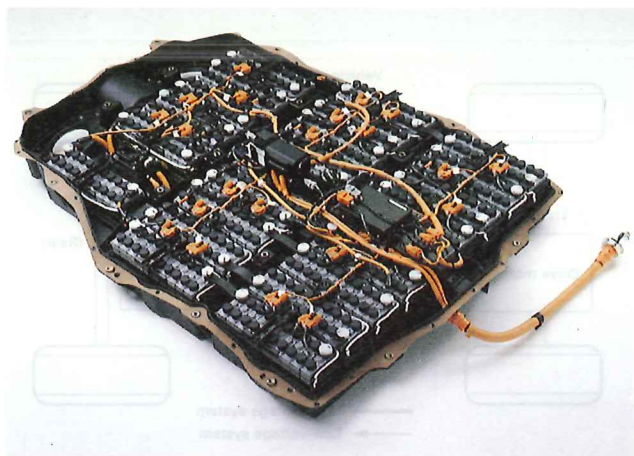


Photo. 1 Nickel-Metal Hydride Batteries

Table 2 Comparison of Battery Types

	Sealed lead	Nickel-cadmium	Nickel-metal hydride	Lithium
Energy density	△	○	○	◎
Power density	◎	◎	◎	◎
Life	△	○	◎	○
Safety	○	○	◎	△
Cost	○	△	△	△

(By Toyota Motor Corporation)

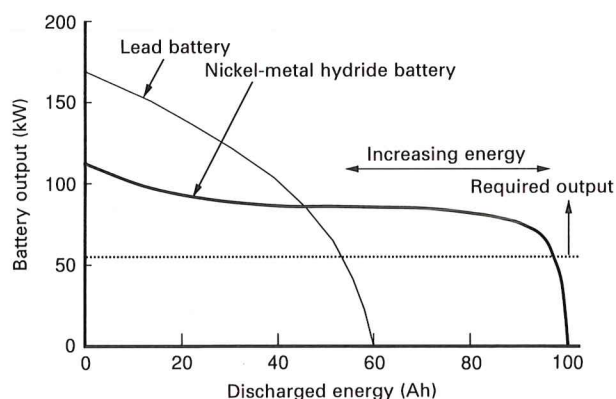


Fig. 3 Battery Output Characteristics

3.2 Power Train

The RAV4 EV is the world's first mass-produced vehicle to use a permanent magnet synchronous motor, which is more efficient, lighter, and smaller than the DC and AC motors heretofore used in EVs. (Photo. 2)

A rare-earth metal magnet (neodymium-iron-boron type) with high magnetic density is used for the rotor. The magnetic circuit is designed to enhance heat resistance and durability, and combines small size with high output. With conventional motors of this type, the voltage generated by the rotor magnet (back electromotive force) increases in proportion to the motor speed, making it difficult to extend the speed range. However, advances in control technology in recent years have made it possible to use field weakening control to reduce the back electromotive force by advancing the current phase, thus achieving higher motor speeds.

With the EV motor, torque arises at a lower motor speed than with the ICE. For that reason, the EV transaxle functions well with only single-speed reduction. Also, the RAV4 EV's transaxle uses a plane-

tary gear with a stepped pinion gear that rotates on the same shaft as the motor, making it smaller, lighter, and more efficient than the conventional multi-shaft transaxle. In **Fig. 4**, the drive force generated by the rotor is transmitted by the stepped pinion gear via the rotor's central shaft, then transmitted via the differential to the left and right wheels.

Fig. 5 shows the motor's performance curve. The range of motor operation varies according to the type of driving, but the motor shows ample performance in all operating ranges.

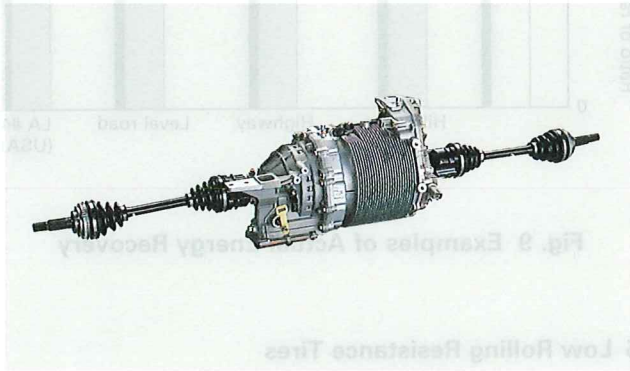


Photo. 2 Power Train

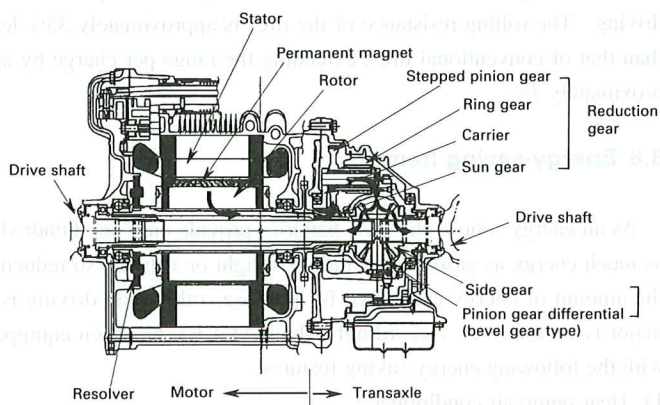


Fig. 4 Power Train Section

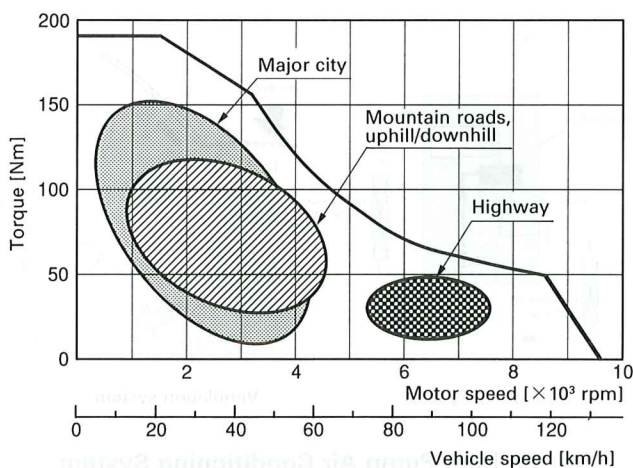


Fig. 5 Motor Performance Curve

3.3 Power Control Unit

The parts listed below have been incorporated into a single case in order to effectively reduce electrically radiated noise and to ensure safety with respect to high voltages. (**Photo. 3, Fig. 6**)

- 1) EV computer: Controls the motor and regenerative braking.
- 2) Battery computer: Controls charging and discharging of the batteries.
- 3) Inverter: Converts DC power from the batteries to 3-phase AC and supplies it to the motor.
- 4) On-board charger: See section 3.7.
- 5) DC-DC converter: Converts voltage (288V) from the main batteries to voltage (12V) for auxiliary system operation.
- 6) Control devices for each component



Photo. 3 Power Control Unit

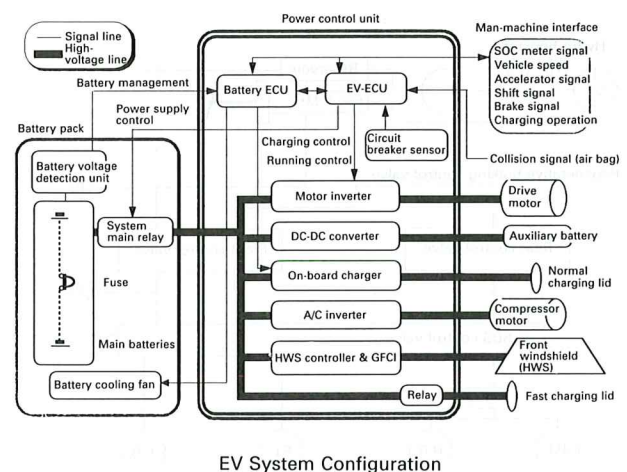


Fig. 6 Power Control System

3.4 Regenerative Braking System

Regenerative braking is a system for using energy effectively that is unique to electric and hybrid vehicles. It is not found in ICE vehicles. When the vehicle decelerates, the system operates the motor as a generator to convert the kinetic energy of the vehicle's motion into electrical energy, which it then stores in the batteries at the same time that it generates braking force. (Fig. 7)

The system is particularly useful for extending the distance the EV can travel on a single charge. The braking system of the RAV4 EV is configured as shown in Fig. 8. When the driver steps on the brake pedal, the system detects the hydraulic pressure in the master cylinder and uses the motor to generate a braking force proportionate to the pressure. When the pressure in the master cylinder rises above a fixed value, proportionate hydraulic pressure is supplied to the front and rear wheel cylinders, ensuring adequate braking force.

The energy recovery rate varies according to the driving conditions,

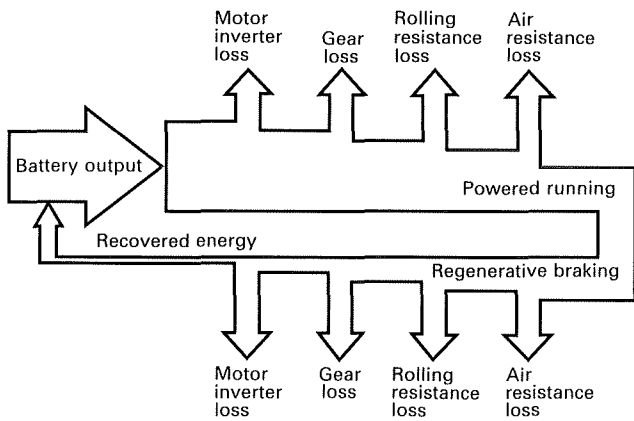


Fig. 7 EV Energy Flow

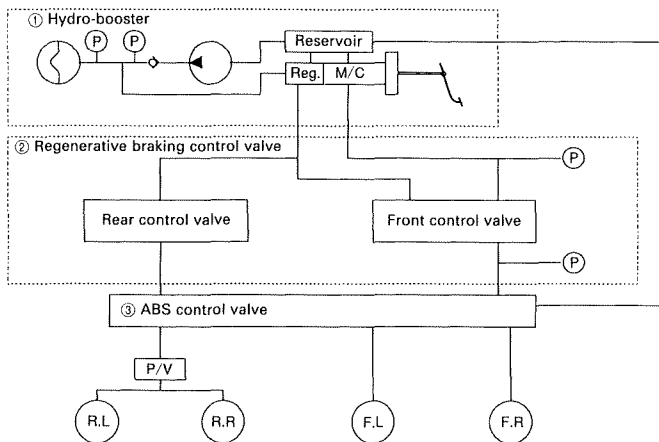


Fig. 8 Regenerative Braking System

but on level ground for example, it reaches 25% (Fig. 9), increasing the vehicle's range to the same extent.

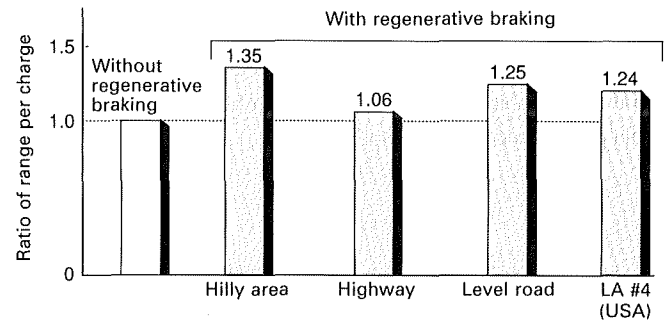


Fig. 9 Examples of Actual Energy Recovery

3.5 Low Rolling Resistance Tires

Special low rolling resistance tires were developed to lower the vehicle's running resistance and reduce its energy consumption during driving. The rolling resistance of the tires is approximately 35% less than that of conventional tires, extending the range per charge by approximately 7%.

3.6 Energy-saving Items

As an energy source, the EV's batteries provide only one-hundredth as much energy as gasoline per unit of weight or volume, so reducing the amount of energy consumed for purposes other than driving is a major issue for EVs. Accordingly, the RAV4 EV has been equipped with the following energy-saving features:

1) Heat-pump air conditioner

The vehicle uses a heat-pump air conditioner of the same type used for home air conditioning. (Fig. 10)

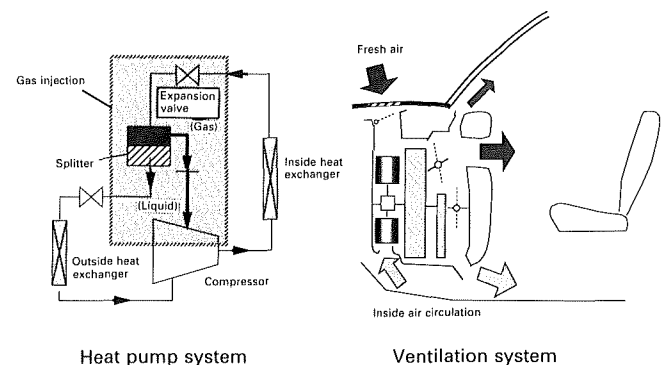


Fig. 10 Heat Pump Air Conditioning System

The electric motor drives a compressor to circulate coolant between the passenger cabin and a condenser, thus transferring thermal energy from the cabin to the atmosphere. When the heat mode on the instrument panel is switched from cooling to heating, it switches a valve in the coolant circulation system to reverse the coolant flow, thereby turning the air conditioner into a heater.

The RAV4 EV uses a gas injection system that circulates the coolant in two stages to increase efficiency. The ventilation system features a two-level flow that uses the cabin air effectively to reduce ventilation loss. These and other features provide performance comparable to that of an ICE vehicle's system, even when the outside air temperature is low. (Fig. 11) The system also uses the environmentally friendly, non-CFC coolant HFC134a.

2) Pre-heating/pre-cooling system

Setting the pre-heating/pre-cooling start time on the charging control panel causes the system to automatically operate the air conditioner in either the heating or cooling mode on household power.

3) Ultraviolet-impermeable, highly heat-absorbent glass

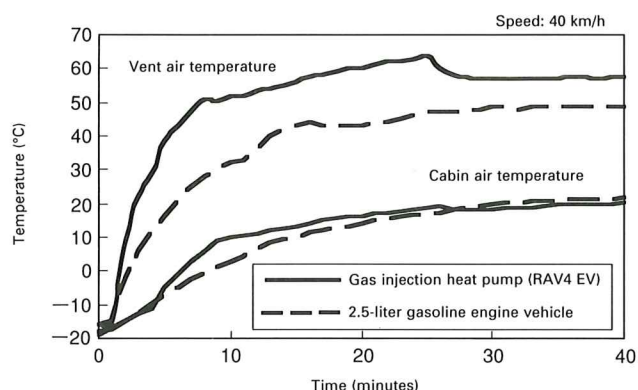


Fig. 11 Heater Performance Comparison

3.7 Charging System

The RAV4 EV's high-efficiency on-board charger and one-touch charging connector make it easy to recharge the batteries from an ordinary household power supply. (Fig. 12) The system normally uses a single-phase, 200-240V/30A power supply and requires approximately six-and-a-half hours to charge. In Japan, however, the government is also promoting the establishment of "eco-stations" for fast charging (Photo. 4), where an EV can be one-third charged in thirty minutes.

3.8 Safety System

Because the EV uses high voltage and draws a large current, electrical safety was given particular consideration.

Of course, no high-voltage parts are installed in the passenger cabin, and care has been taken to isolate the high-voltage system from

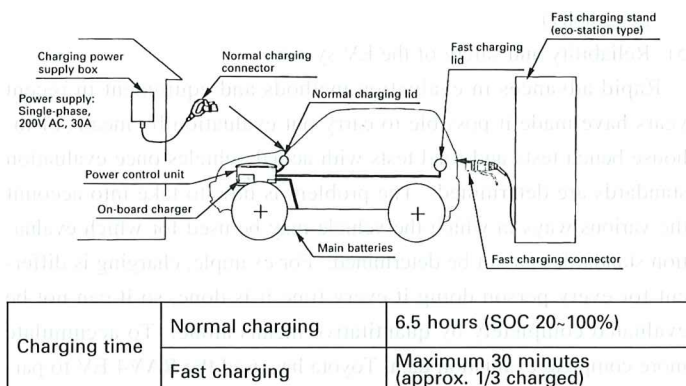


Fig. 12 Charging System



Photo. 4 Eco-station in Use

the vehicle body and to ensure that high-voltage terminals are not exposed. The system is also designed to cut off power when the key is turned off and to detect any electrical leakage. Devices have also been incorporated to cut off the power supply automatically in the event of an accident, as well as to cut off high voltage when the vehicle is being serviced. Moreover, it has been confirmed that the batteries and the electrical system are as water-resistant as those of a conventional gasoline-powered vehicle.

4. Evaluation

In order for the EV to be introduced into the market as a practical vehicle, it must be evaluated both in comparison with gasoline-powered vehicles and in terms of its unique features. The particularly important features are listed below.

- 1) The appropriateness of the cruising range and power performance to the actual market
- 2) Effect of charging method on battery performance and life
- 3) Effects of driving on the batteries and power train in the actual market

- 4) Compatibility with the use environment (climate, road conditions, geography)
- 5) Reliability and safety of the EV system

Rapid advances in evaluation methods and equipment in recent years have made it possible to carry out evaluation by means of in-house bench tests and road tests with actual vehicles once evaluation standards are determined. The problem is how to take into account the various ways in which the vehicle may be used for which evaluation standards can not be determined. For example, charging is different for every person doing it every time it is done, so it can not be evaluated completely by quantitative means alone. To accumulate more complete evaluation data, Toyota has used the RAV4 EV to participate in the first Scandinavian EV Rally and the third Monte Carlo EV Rally, and has provided ten vehicles each to Japan and the United States to be used as monitor vehicles by government agencies and electrical power companies. Market evaluation data has also been collected for one-hundred Town Ace EVs, as well as for the 3-door RAV4 EV, and the results are reflected in the new 5-door model.

5. Conclusion

The EV has reached the point where its performance is comparable to that of a gasoline-powered vehicle if it is used for limited purposes and within limited circumstances. And of course, it has the appealing features of zero emissions and low noise. The performance and convenience of the 5-door model RAV4 EV have won it very high praise from government agencies and businesses since its introduction in October.

When one ponders the direction in which the EV will develop in the future, even considering the 5-door model RAV4 EV, three major problems remain:

- 1) The price is high.
- 2) The expensive batteries must be replaced during the life of the vehicle.
- 3) A recharging infrastructure has not been established.

As the engineers who developed the vehicle, we are naturally striving to solve these problems ourselves and to further improve the vehicle's performance, but there are also strong demands for a 400-kilometer cruising range and better power performance. These goals are technologically feasible, but as they would require even larger-capacity charging equipment and raise the cost even more, they are not thought to be realistic.

In order to gain widespread public acceptance for EVs in the future, we development engineers must go back to square one to conceive of an EV that will make more people feel that its combination of performance and price makes it worth trying, a vehicle that can be used in more different places and more different ways. We also want to have users understand more deeply the environmental considerations. We particularly want to provide a wider range of experiences to the

younger generation that will become the future leaders of society, and to have them feel more familiar with the EV.

■ Authors



M. KINOSHITA



S. KIMURA

Introduction of EV Commuter "e-com"

Makoto Yamada*
Keiji Kogaki*
Toshiyuki Sekimori**
Tetsuhiro Ishikawa**

Abstract

The history of EV development is almost one century long. The performance of the EV has been improved remarkably in recent years, thanks to advancements in the battery and power electronics fields. However, with regard to its practical performance as a vehicle, many problems still remain, in the cruising range and cost, for example.

On the other hand, social problems with the environment and traffic, especially in urban areas, have been brought to the fore, requiring remedial action. This paper introduces a very small EV commuter as an urban form of personal mobility based on the most advanced EV technologies.

Keywords: electric vehicle, commuter, nickel-metal hydride battery, permanent magnet synchronous motor

1. Introduction

In the Toyota Automobile Museum, an electric vehicle (EV) named the Baker Electric, which was used in America 100 years ago, is on display. It was able to run at 40 km/h on a 1-hp motor. (**Photo. 1**) Thus, at the dawn of the automobile age, the EV was the equal of the internal-combustion vehicle, but thereafter it fell behind the dramatic advances made by the internal-combustion engine (ICE), and for almost a century it has failed to gain wide acceptance. The regulation of exhaust emissions in the 1960s and the oil crisis of the 1970s created expectations for the spread of EVs, but the development of battery technology did not keep pace, and until recently, the EV had not gained popularity.

The development of battery technology, which holds the key to success for EVs, has made great advances in recent years, spurred by growing concern over environmental problems. Marked improvement in the performance of nickel-metal hydride (Ni-MH) batteries, together with the development of practical control technology, has brought battery technology as such almost to the point where it can be put to practical use. However, when the cost/performance requirements for an automobile are considered, the disparity remains as large as ever, so that high cost is still an obstacle to using large numbers of batteries in a vehicle.

Therefore, rather than just pursuing performance that can rival that of an ICE, Toyota looked for a shorter route to EV acceptance by changing the basic concept to that of an ultra-small EV commuter designed for short-distance travel in urban areas.

This paper describes an entirely new vehicle, the "e-com", an ultra-small EV for urban driving.

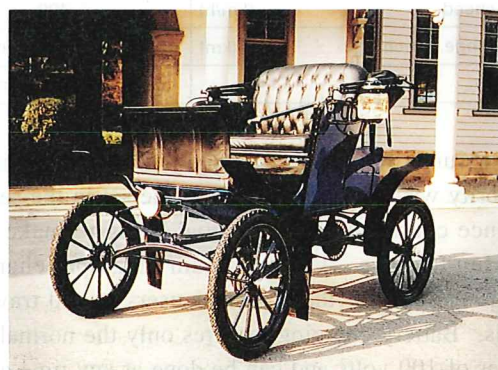


Photo. 1 Baker Electric

2. Vehicle Overview

① Basic concept

The goal of e-com development was the creation of a new kind of personal mobility for the 21st century, a practical EV designed with its actual mode of usage in mind.

The specific image of the e-com user was of someone driving short distances in large cities and surrounding areas, someone who could take real advantage of the EV's strengths.

The e-com was conceived with the following uses in mind:

- A second or third car for multi-car families living in urban areas and nearby suburbs
- A short-distance vehicle for businesses and government agencies
- A delivery vehicle for service businesses (flower shops, dry cleaners, early-morning/late-night delivery services)
- A rental car for use in tourist areas, at train stations, etc.

② Main specifications and performance

Table 1 shows the main e-com specifications. The vehicle's size was made the smallest that would still allow for conve-

* Vehicle Development Center III

** Electric & Hybrid Vehicle Engineering Div.

nient, comfortable, and safe short-distance travel in urban areas.

The cabin size ensures ample space for two adults. The motor and power control unit are in front, and the crash stroke is sufficient to ensure safety in the event of a collision. The batteries are installed under the floor to lower the center of gravity and to provide more usable interior space. A large luggage space is provided in the rear for use in shopping or business errands.

Table 1 Main e-com Specifications

Vehicle length • Vehicle width • Vehicle height (mm)	2780 • 1475 • 1605
Complete vehicle curb mass (kg)	790
Seating capacity (persons)	2
Maximum speed (km/h)	100
Maximum range per charge (km)	100 (10 • 15 mode in Japan)
Drive system	Front-wheel drive

On the assumption that the vehicle would be used in urban areas, priority was given to user convenience in the setting of performance characteristics, the goal being to make the car easy and fun to drive. The maximum range per charge was made large enough for the distances users would travel on a daily basis. Battery charging requires only the normal household power of 100 volts and can be done at any time as easily as operating a home appliance. When high-speed recharging is necessary, the batteries can handle 200-volt power for short periods of time, and if recharging is done away from the home or company, the cruising range can be extended.

3. Design

① Exterior

- The exterior has been designed so that when the e-com is seen on the street, even from a distance, it will make people want to ride in it, even if they do not know it is the e-com. It is a cute, enjoyable, friendly look. **(Photos 2, 3)**
- The body design theme is an oval shape that emphasizes compactness and consistency of form. The headlamps, rear combination lamps, side turn signal lamps, door mirrors, and door handles share a common oval shape, but with a strong appeal of individuality and enjoyment. Although the body is ultra-small, the two-tone color scheme of the cabin and underbody running around the entire vehicle gives the car as a whole an image of large-model protection and a feeling of strength and peace of mind.
- The functional aspects of the vehicle have also been subtly enhanced by design, such as the sporty front grill with its

ensured cooling performance and smart-looking recharging socket, and the back-up lamps with their graphical use of the Toyota symbol.



Photo. 2 e-com Exterior Design



Photo. 3 e-com Exterior Design

② Interior

- Although the e-com has the minimum interior space of a two-seater, its seating comfort and the ease of getting in and out are sufficient for its use in daily personal mobility. Every detail of the friendly interior creates a sense of personal space. **(Photos 4, 5)**
- The instrument panel is shaped like a table, with an open feel. The unique, disc-shaped central instrument cluster can incorporate a navigation display and features simple and easy-to-read digital meters.
- The passenger seat folds forward to expand the luggage compartment, making the largest possible utility space, suitable for a variety of uses and capable of accommodating even long items.
- The seat height (the hip point is 650 mm above the ground) is set to make it easy to get in and out. The semi-bench seat cushion is designed to produce a feeling of roominess and ease, and the stylish seat back is shaped to make it easy to reach back into the luggage compartment.



Photo. 4 e-com Interior Design



Photo. 5 e-com Interior Design

4. EV system

① Configuration

The EV system configuration is shown in **Fig. 1**. It is divided roughly into the following three parts:

- Batteries (**Photo. 6**)
- Power Control Unit (PCU) (**Photo. 7**)
- Motor and reduction gear (**Photo. 8**)

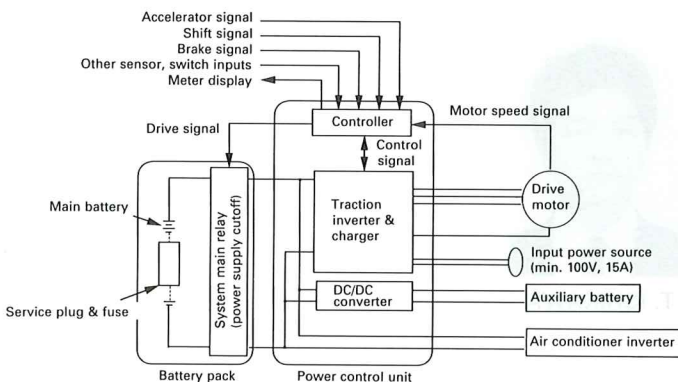


Fig. 1 Schematic Diagram of EV Electrical System

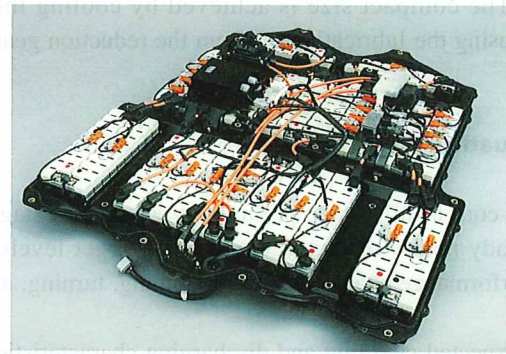


Photo. 6 Batteries

② Features

The features of the parts are described below.

- Batteries
 - 1) Ni-MH batteries with high energy density are used.
 - 2) Twenty-four individual batteries are installed under the vehicle floor, to ensure high-voltage safety, ample interior space, and driving stability, and to make them easy to install and service.
 - 3) The batteries are cooled by outside air that is introduced by the motor cooling fan.

- PCU

A single-unit PCU is used to provide common circuits for high-voltage parts and to integrate parts.

- 1) Common use of high-voltage circuits: The motor winding is used as the step-up coil, and the inverter's IGBT is used as the control element for the charger function.
- 2) Integrated case and heat sink: All heat-emitting parts have been consolidated into one part, with a cooling system consisting of a single heat sink. Putting all high-voltage parts within a single casing helps to reduce the number of parts requiring electromagnetic shielding and waterproofing, as well as the number of high-voltage waterproof connectors.
- 3) Common control system: What have conventionally been separate systems for vehicle control, charging control, and battery control have been integrated, greatly reducing the number of control boards, microprocessors, etc.

- Motor and reduction gear

- 1) A simple three-shaft-type single-speed reduction gear is used, with a counter shaft set between the input shaft from the motor and the differential gear shaft that outputs drive power to the wheels.
- 2) A compact, lightweight, high-efficiency permanent magnet synchronous motor with a high-performance magnet is used.

- 3) The compact size is achieved by cooling the motor using the lubricating oil from the reduction gear.

5. Evaluation

The e-com is still in the preliminary evaluation stage, but it has already nearly achieved the desired target levels for the basic performance characteristics of running, turning, and stopping.

The expected charging and discharging characteristics of the compact Ni-MH batteries have been confirmed in bench tests.

With respect to its driving performance as a vehicle, the e-com is expected to achieve a range per charge of 100 km in the 10 · 15 mode (the Japanese city mode). It shows good power performance for urban driving and is fun to drive, so it is achieving its performance objectives according to the vehicle plan.



Photo. 7 Power Control Unit

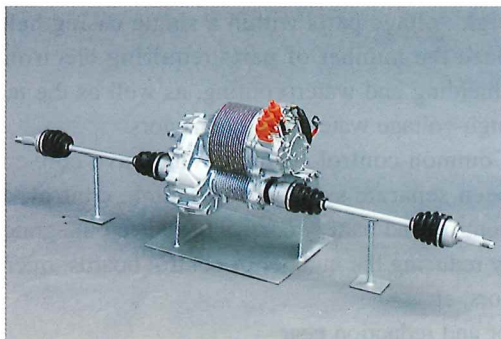


Photo. 8 Motor and Reduction Gear

6. Conclusion

When considered from the standpoint of environmental, energy, and traffic problems, the e-com holds great possibilities for playing a role in urban areas and their surrounding regions.

However, in the present circumstances, if the e-com's cost/performance ratio is compared to that of a sub-compact, for example, its widespread acceptance can not be expected. Already in America, various trials aimed at spreading EV use are under way. One of these trials, being conducted in San Francisco, Boston, New York, and other big cities, is the station car program.

Dedicated parking lots for EVs, complete with recharging devices, are established at railroad stations, and EV commuters use them in a park-and-ride system. This is said to be an extremely effective measure for solving the problems of environment, traffic congestion, and parking in center cities, and future expansion is the focus of attention. If an infrastructure is established taking the use of EVs into account, and if it is accompanied by incentives, then the time will arrive even sooner when the e-com, the new vehicle for the 21st century, can play an active role. The authors wish to devote their efforts to the rapid realization of that goal.

■ Authors



M. YAMADA



K. KOGAKI



T. SEKIMORI



T. ISHIKAWA

A Development of Toyota Hybrid System

Shinichi Abe*
Kazuo Tojima*
Takeshi Kotani*

Sumikazu Shamoto*
Ryuji Ibaraki**
Akira Sakai***

Abstract

The Toyota Hybrid System has two power sources, one or both of which engage depending on the driving conditions. A gasoline engine with improved efficiency provides the main power to drive the wheels, as in conventional automobiles.

Drive power can also be supplied by an electric motor, which derives its electricity from a battery and a generator. Fuel efficiency is further boosted by other measures, such as automatically cutting the engine when the vehicle is at a stop and regenerating the energy accumulated during deceleration. Compared with a conventional vehicle with a 1.5-liter engine running in the 10-15 mode, the CO₂ emissions are reduced by half. Moreover, by using the motor to reduce engine load during acceleration, the system cuts HC, CO, and NO_x emissions to about one-tenth of previous levels.

Keywords: hybrid, motor, generator, battery, Atkinson cycle, VVT-i, low fuel consumption, low emissions, regenerative braking, planetary gear

1. Introduction

In recent years, the reduction of CO₂ emissions has become an international issue as a way to contribute to energy conservation and the prevention of global warming. For automobile makers, reducing CO₂ means improving fuel economy, and it must be compatible with making exhaust emissions cleaner and ensuring safety.

Toyota has brought fuel economy improvement technology onto the market by introducing the lean-burn engine in 1984, and by combining the Toyota D-4 direct-injection gasoline engine with the latest transmission technology in 1996.

In a different direction, working from the standpoint of energy diversification, Toyota has developed alternative-fuel vehicles that use compressed natural gas (CNG), as well as electric vehicles, to the point where they are now practical. A fuel cell electric vehicle using hydrogen fuel was developed in 1996, and research is being promoted with an eye on the long term. These technologies have reached the stage where society needs to build systems to support their use, including the necessary infrastructure.

It is in the context of these trends that a new power train for passenger vehicles, the Toyota Hybrid System (THS), was brought to completion. This is a system that does not require external charging like an electric vehicle and that makes it possible to attain approximately twice the fuel economy of a conventional gasoline engine vehicle.

The hybrid system uses electrical energy generated by the power of a gasoline engine to drive an electric motor. It uses engine drive and/or motor drive, depending on factors such as the driving environment and vehicle speed. This makes it possible to hold down both exhaust emissions and fuel consumption, and the system has recently become the focus of attention as a way to transcend the limitations on

the cruising range of electric vehicles.

There are two main types of hybrid systems. In the series hybrid system, the engine drives a generator, and the generated electricity powers the motor to drive the wheels. In the parallel hybrid system, both the engine and the motor are used to drive the wheels, and the system selects one power source or the other according to the driving conditions. THS employs aspects of both systems.

2. Overview of THS

2.1 System Configuration

THS is configured in a way that combines the series hybrid system with the parallel hybrid system to take maximum advantage of the strengths of both.

Both the gasoline engine and the electric motor function as power sources, but the engine is the primary source. The engine's power is divided by a power split device that uses a planetary gear to send drive power to both the wheels and the generator. Some of the electricity from the generator is used directly by the motor, while the rest is con-

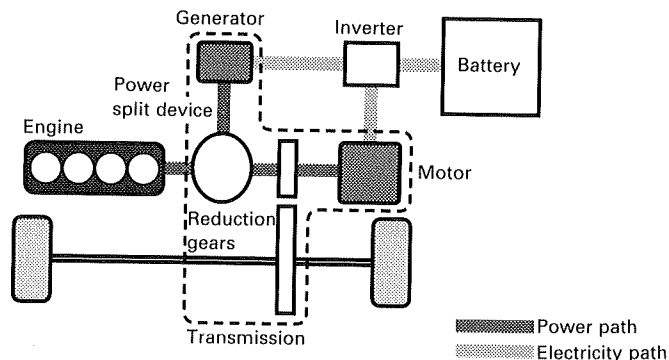


Fig. 1 THS System Configuration

* Electric & Hybrid Vehicle Engineering Div.

** Drive Train Engineering Div.

*** Chassis System Development Div.

verted to DC by the inverter and stored in the battery.

The THS transmission, consisting of the power split device, the motor, the generator, and reduction gears, is compact enough for use in a passenger car.

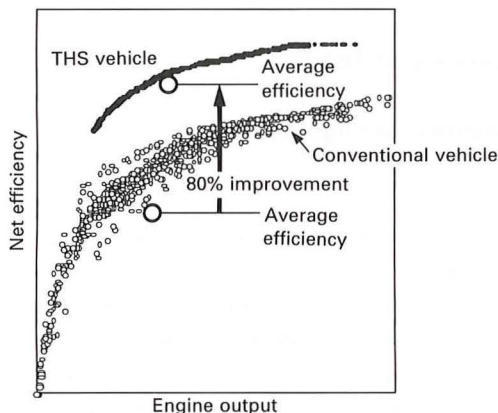
2.2 Measures to Improve Fuel Economy

2.2.1 Highly Efficient Engine

A highly efficient 1.5-liter engine was developed as the primary power source. It employs the Atkinson cycle (see the following paper) to dramatically lower the losses on both intake and exhaust, as well as to reduce the friction loss.



Photo. 1 THS Power Train

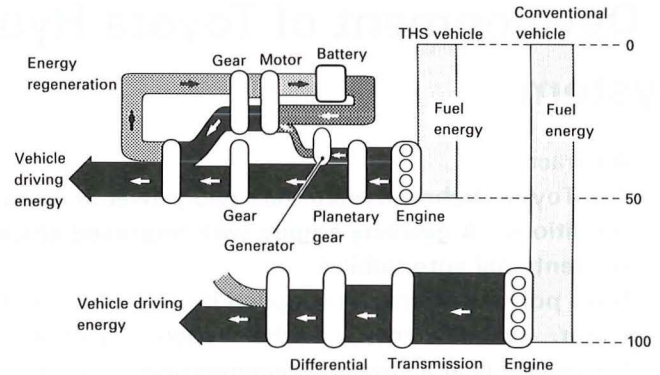


This figure compares the net efficiency of the THS vehicle with that of a conventional vehicle under city driving conditions. As the engine operates in a highly energy-efficient range, it achieves a dramatic 80% improvement over the conventional vehicle.

Fig. 2 Improved Engine Efficiency and Operating Range

2.2.2 Improved Engine Operating Range

The system controls the division of power between the engine and motor according to the driving conditions in such a way that the engine operates as much as possible in the high-torque range, where fuel economy is good. The system also reduces fuel consumption by maintaining a controlled operating range and a constant engine speed to improve fuel efficiency.



This figure uses energy flow patterns to show how THS improves efficiency. THS has twice the fuel economy of a conventional vehicle, i.e., it increases fuel economy 100%. Engine efficiency, including the motor drive flow, improves 80%, while energy regeneration raises efficiency 20%.

Fig. 3 Energy Generation and Expenditure

2.2.3 Engine Shut-off System

When the vehicle is stopped or decelerating at low speed, the engine automatically shuts off to reduce energy loss and stop the generation of exhaust emissions.

2.2.4 Recovery and Reuse of Braking Energy

By operating the motor as a generator during braking, the system converts the kinetic energy normally lost during braking into electricity and stores it in the battery. (This is known as regenerative braking.)

2.3 Achieving Smooth Acceleration and Deceleration

The system maximizes the efficiency of the engine by controlling the drive power of the engine and motor through the newly developed power split device. Because the THS transmission has a continuously variable speed function and the electric motor assists the engine, the vehicle achieves smooth acceleration and deceleration with excellent response.

During initial acceleration in particular, the system achieves smooth acceleration by taking advantage of the motor's characteristics of low speed and high torque. And in periods of maximum acceleration with the accelerator pedal fully depressed, the motor draws on electricity from the battery to add its drive power to the engine output, ensuring high acceleration performance.

The system's operating conditions are described in the following sections.

2.3.1 Initial Acceleration and Light Load

In the operating range where engine efficiency is poor, such as in accelerating from a standing start, driving at extremely low speeds, or descending a gentle slope, the system cuts off fuel to the engine and runs on the motor. (A)

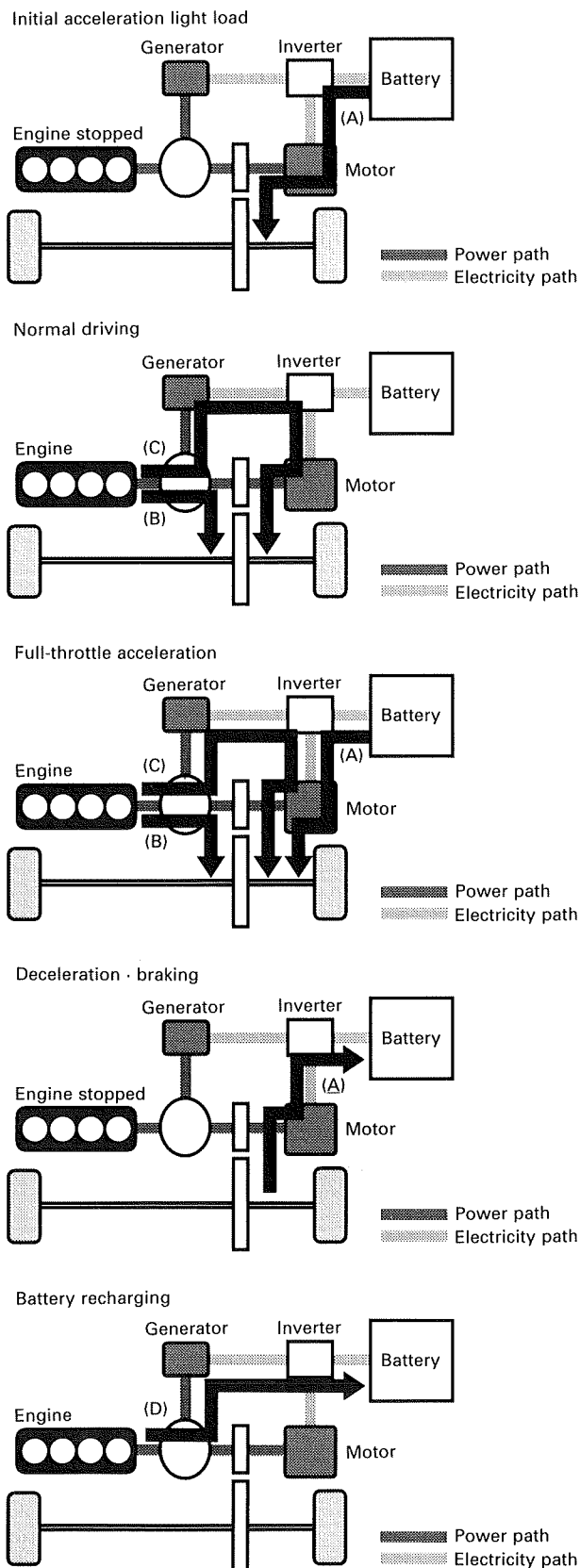


Fig. 4 System Operating Conditions

2.3.2 Normal Driving

The engine starts in response to the accelerator angle, and the engine power is separated into two paths by the power split device, with one path directly driving the wheels. (B)

The other path drives the generator to produce electricity for the motor, which assists the engine's drive power. (C)

2.3.3 Full-throttle Acceleration

During full-throttle acceleration, power is supplied from the battery as well, adding to the drive power. (A)

2.3.4 Deceleration and Braking

During deceleration and braking, the wheels drive the motor, which then acts as a generator to regenerate electricity. The recovered energy is stored in the battery. (A)

2.3.5 Battery Recharging

The battery is regulated to maintain a constant charge. When the battery gets low, the system runs the generator to start recharging. (D)

2.3.6 Stopped

The engine automatically shuts off when the vehicle is stopped.

2.4 THS Transmission

The THS transmission consists of the power split device, the generator, the motor, and the reduction gears. The power from the engine is divided into two parts by the power split device, with one part going directly to the motor and the wheels, while the other is connected to the generator. In other words, engine power is transmitted by two paths, one mechanical and the other electrical.

The transmission functions like an electronically controlled continuously variable transmission, accelerating and decelerating the vehicle by continuously shifting the speeds of the engine, the generator, and the motor.

2.4.1 Power Split Device

The power split device uses a planetary gear. The rotating shaft of the carrier is connected to the engine, and power is transmitted via pinion gears to the outer ring gear and the inner sun gear. The shaft of the ring gear is connected directly to the motor and transmits drive power to the wheels. The shaft of the sun gear is connected to the generator.

2.4.2 Engine, Generator, and Motor Operations

The operations of the engine, generator, and motor under different driving conditions are shown in the power interaction diagram (Fig. 6) and Table 1.

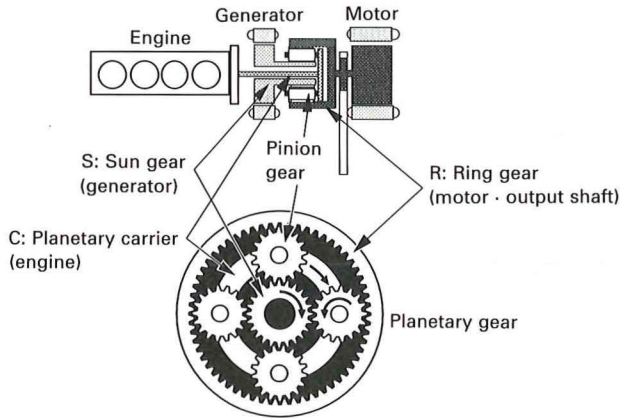
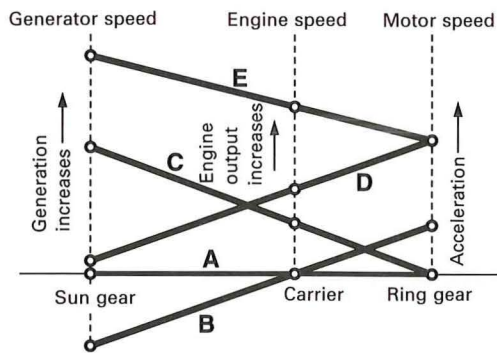


Fig. 5 Power Split Device



A power interaction diagram is used to illustrate the revolutions of the planetary gear shafts. The diagram shows that the revolution speeds of the various gears, shown on the vertical axes, are connected in an absolutely linear relationship.

Fig. 6 Power Interaction Diagram

2.5 Regenerative Braking System

When the vehicle decelerates, either by engine braking or by application of the brakes, the system uses the motor as a generator to convert the kinetic energy of the moving vehicle into electrical energy, which it then stores in the battery.

This regenerative braking system is particularly advantageous in city driving, with its pattern of repeated acceleration and deceleration, because the energy-recovery effect is especially high.

When the driver applies the brakes, the hydraulic and regenerative braking systems are coordinated, with priority given to regenerative braking in order to recover more energy.

2.6 System Components

2.6.1 Battery

The sealed nickel-metal hydride battery technology developed for electric vehicles is renowned for its superior power density, light weight, and long life. The high-performance THS battery, newly developed to match the hybrid system's characteristics, represents a further advance in this technology, greatly increasing the output per unit

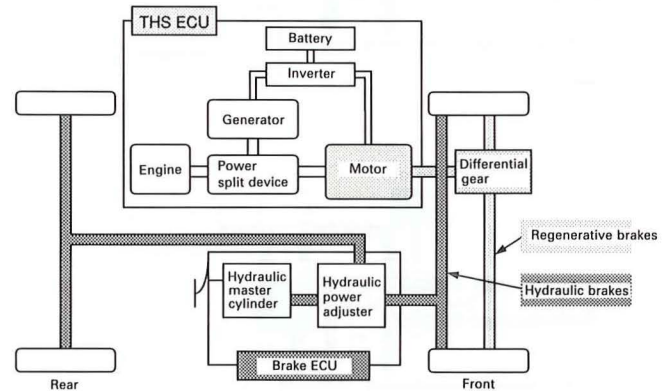


Fig. 7 Regenerative Braking System



Photo. 2 Battery

Table 1 Operating Conditions

Point on diagram	Driving condition	Generator	Engine	Motor
A	Stopped	Stopped	Stopped	Stopped
B	Initial EV acceleration	• Rotates as engine remains stopped	Stopped	• Starts moving on motor drive power only
C	Acceleration when engine starts	• Acts as engine starter • Generates electricity	• Starts • Output	• Accelerates on electricity supplied by generator
D	Normal driving	• Low generation	• Output as required	• Drive power assist
E	Acceleration	• High generation	• Output as required (high)	• Drive power assist (high)

of capacity.

The system uses the generator and the motor to maintain a constant battery charge, so unlike an electric vehicle, recharging from an external source is not required.

2.6.2 Motor

THS uses a compact and lightweight, but highly efficient, AC permanent magnet synchronous motor. As a supplementary power source, it assists the engine's output to achieve superior power performance for smooth starting and acceleration. During regenerative braking, it converts the vehicle's kinetic energy into electricity and stores it in the battery.

2.6.3 Generator

THS uses a high-efficiency AC permanent magnet synchronous motor for the generator. It generates electricity to recharge the battery and drive the motor. In addition, the system controls the amount of electricity generated to regulate the generator's revolution speed, which functions to control the continuously variable speed of the power split device.

The generator also serves as the starter for the engine.

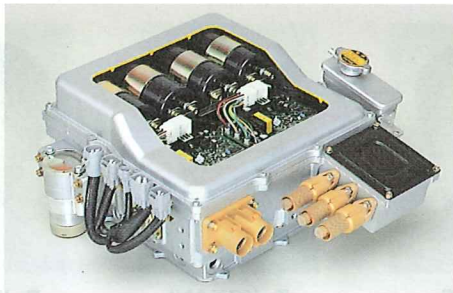


Photo. 3 Inverter

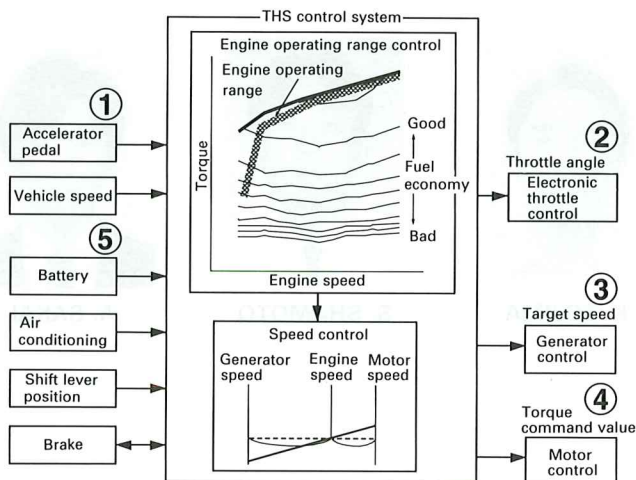


Fig. 8 Control System Configuration

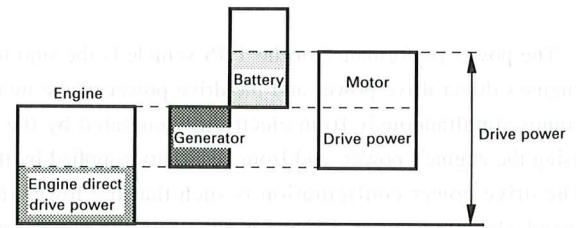


Fig. 9 Power Performance

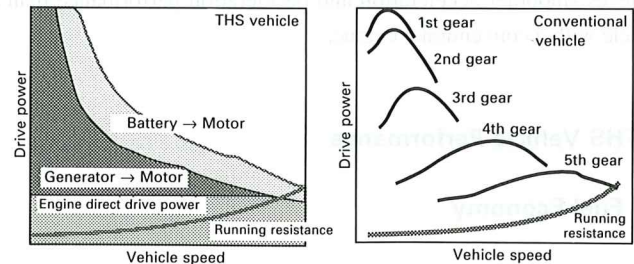


Fig. 10 Power Performance Comparison

2.6.4 Inverter

The inverter is a unit that converts the battery's DC power into AC to drive the motor and converts the AC power from the generator into the DC required by the battery. The circuit uses an intelligent power module to increase reliability.

2.7 System Control

THS computes the required operating conditions and the actual operating conditions of the engine, motor, generator, battery, and other components, and controls them in real time.

2.7.1 Engine Operating Range Control

The system automatically controls the engine speed and electronic throttle opening to match the driving conditions, so that the engine is operated in the preset high-torque range with good fuel economy.

2.7.2 Driving Control

When the driver presses down on the accelerator pedal ①, the electronic throttle opens to a corresponding degree ② in response to the engine operating range control, while the engine speed is also controlled ③. The system simultaneously controls the ratio of engine power that is allocated to direct drive, and to motor drive via the generator ④, combining engine power and motor power to provide drive power to the vehicle. When the battery requires recharging, the system increases the engine output in the direction of the generator to boost its electrical output ⑤.

2.7.3 Engine and Motor Drive Power Control

The power performance of the THS vehicle is the sum total of the engine's direct drive power and the drive power of the motor, which comes simultaneously from electricity generated by the generator using the engine's power, and from electricity supplied by the battery. The drive power configuration is such that the lower the vehicle speed, the more motor drive is used. With the power split device functioning like a continuously variable transmission, the vehicle achieves smoother acceleration and deceleration performance than a vehicle with a conventional engine.

3. THS Vehicle Performance

3.1 Fuel Economy

In in-house driving tests in the 10 · 15 mode, the THS vehicle achieved approximately twice the fuel economy of a vehicle with a conventional engine and automatic transmission, or 28 km/liter.

3.2 Exhaust Emissions

The THS vehicle emits only half as much CO₂ as a gasoline engine vehicle, and its emissions of carbon monoxide, hydrocarbons, and nitrogen oxides have been reduced to approximately one-tenth of their regulation standard levels.

3.3 Acceleration

The passing acceleration of the THS vehicle matches or exceeds that of a vehicle with a conventional engine and automatic transmission, and its acceleration is smoother, without any kick-down.

Fuel economy (10 · 15 mode)

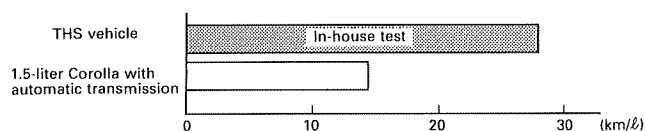


Fig. 11 10 · 15 Mode Fuel Economy

Emissions (10 · 15 mode/In-house test)

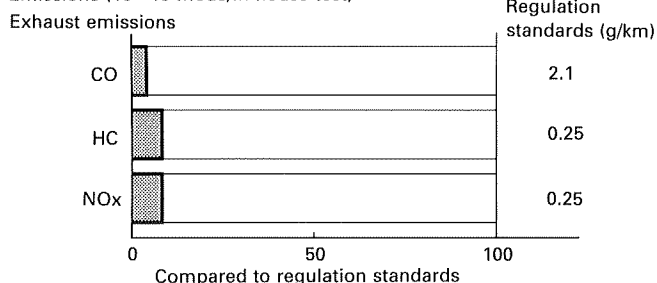


Fig. 12 10 · 15 Mode Emissions

Power performance

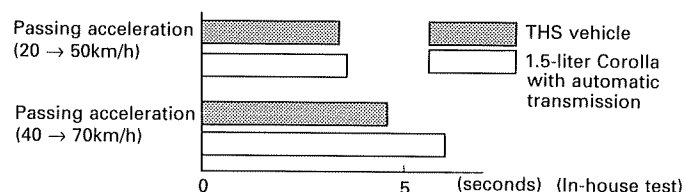


Fig. 13 Passing Acceleration Performance

4. Conclusion

In January of 1997, Toyota announced the promotion of the "Toyota Eco-Project". Among the goals of the project, particularly with respect to reducing CO₂ emissions to prevent global warming, is the development of a hybrid vehicle with twice the fuel economy of conventional vehicles. The authors firmly believe that the completion of the Toyota Hybrid System is a major contribution toward the achievement of this objective.

This paper has been based upon information released to the press in the spring of 1997.

■ Authors



S. ABE



T. KOTANI



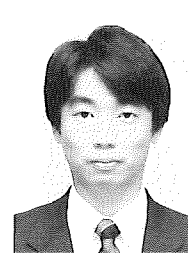
R. IBARAKI



K. TOJIMA



S. SHAMOTO



A. SAKAI

A High-Expansion-Ratio Gasoline Engine for the TOYOTA Hybrid System

Toshifumi Takaoka**

Katsuhiko Hirose*

Tatehito Ueda*

Yasushi Nouno**

Hiroshi Tada**

Hiroshi Kanai*

Abstract

A 50% reduction in CO₂ and fuel consumption in comparison with a vehicle with the same engine displacement has been achieved by the newly developed gasoline engine for the Toyota Hybrid System. This is achieved by a combination of an electric motor and an internal-combustion engine that is optimized in terms of its displacement and heat cycle. Delaying the closing of the intake valve effectively separates the compression ratio and expansion ratio, so that the expansion ratio, which is normally set to 9:1 to 10:1 to suppress knocking, can be set to 13.5:1. Motor-assisted quick start, improved catalyst warm-up, and the elimination of light-load firing allow the system to achieve emissions levels that are only one-tenth of the current Japanese standard values.

Keywords: hybrid, low fuel consumption, low emissions, low friction, variable valve timing

1. Introduction

The earth's remaining reserves of fossil fuels are said to total approximately two-trillion barrels, or about a 50-year supply. The electric vehicle, because of its zero emissions level and the diversity of sources to supply electrical energy, is regarded as a promising automobile for the future. On the other hand, the energy limitations of on-board batteries, which is to say, their inferior energy density in comparison with fossil fuels, has meant that the electric vehicle has remained no more than just one future technology. The internal-combustion/electric hybrid system is promoted as a technology that compensates for this shortcoming of the electric vehicle, but it is also the object of attention as a system that eliminates the problems of the internal-combustion engine.

Because the drive energy of the hybrid system comes either from electrical generation by the internal-combustion engine or from the engine's direct drive of the axle, the efficiency of the engine, the primary power source, strongly influences the efficiency of the entire system. In the development of the Toyota Hybrid System, a new gasoline engine was developed with more emphasis on thermal efficiency than on specific output. Because priority was given to the total efficiency of the entire system, it was decided that a high-expansion-ratio cycle would be used, and the engine displacement and maximum output were chosen to reduce friction loss. This paper describes the investigative process and the results that were obtained.

engine output and the motor output by means of a planetary gear system to control the power split. One notable feature is that because the drive power is the combined power of the engine and the motor, the engine output can be set to a relatively low value without reducing vehicle performance.

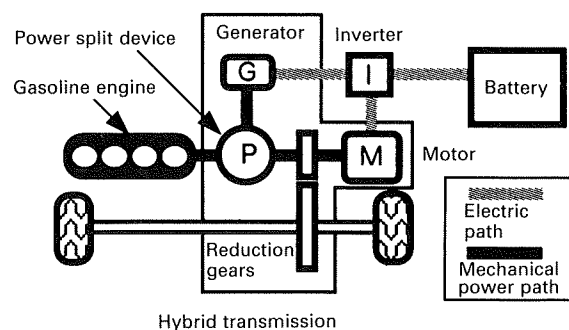


Fig. 1 Toyota Hybrid System Configuration

Fig. 2 shows the relationship between output and efficiency. One issue for the engine was how to raise the net thermal efficiency from point A to point B.

2.2 Engine Specifications

In order to achieve the thermal efficiency objective, the engine for the hybrid vehicle was planned with the following three points in mind:

- (1) The only restriction to be placed on the choice of engine displacement would be that it be within a range that satisfies the engine output and installability requirements. This makes it possible to use a high-expansion-ratio cycle with delayed intake valve clos-

2. Hybrid System and Engine Specifications

2.1 Hybrid System

The configuration of THS is shown in Fig. 1. The system links the

* Engine Engineering Div. II

** Power Train Engineering Div. II

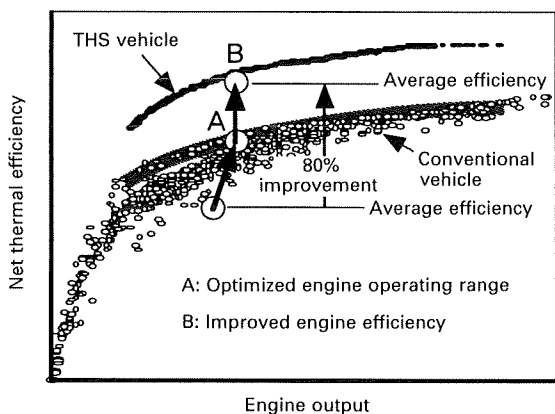


Fig. 2 Relationship of Engine Output and Efficiency

ing, as well as to reduce friction loss by lowering the engine speed.

- (2) In order to achieve a major reduction in emissions, the engine would operate with $\lambda = 1$ over its entire range, and the exhaust system would use a 3-way catalyst.
- (3) Active measures would be taken to reduce weight and increase efficiency.

Fig. 3 shows the relationship between the S/V ratio (the ratio of combustion chamber surface area to combustion chamber volume) and the indicated mean effective pressure. The smaller the S/V ratio, the less heat is dissipated into the coolant, raising the indicated mean effective pressure. Since the S/V ratio tends to decrease as the displacement per cylinder increases, this also raises the indicated mean effective pressure.

Fig. 4 shows the relationship between displacement and friction loss in two engines designed to have identical output. Because the maximum engine speed can be set lower as the displacement increases-

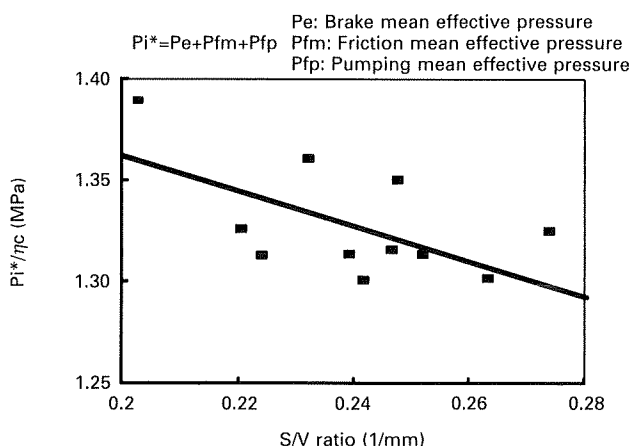


Fig. 3 Relationship of S/V Ratio and Indicated Mean Effective Pressure

es, it is possible to reduce friction loss by reducing both the load on the valve system springs and the tensile strength of the piston rings while maintaining the same output.

Based on these considerations, the relationship between displacement and fuel consumption was calculated. The results are shown in **Fig. 5** and **Fig. 6**. From **Fig. 5** it can be seen that in the high-output range, thermal efficiency rises as the displacement becomes larger, but in the low-output range, thermal efficiency is higher with a small-displacement engine. Both the indicated thermal efficiency and the mechanical efficiency (friction loss) improve as displacement becomes larger, but in the low-output range, because of the effect of the pumping loss that results from the shift to a partial load, thermal efficiency is better with a small-displacement engine.

Fig. 6 shows the relationship between displacement and fuel consumption. For the reasons cited above, 1500 cc was deemed the optimum engine displacement, given the curb weight of the THS vehicle.

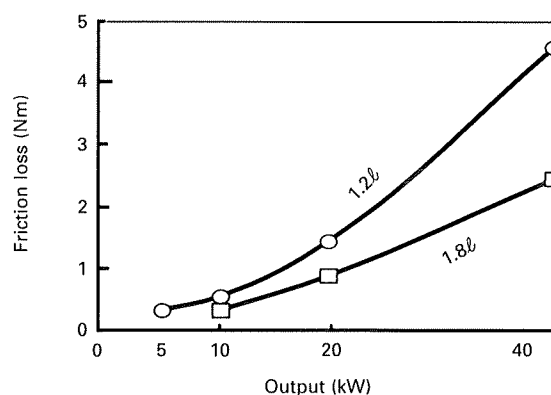


Fig. 4 Relationship of Displacement and Friction

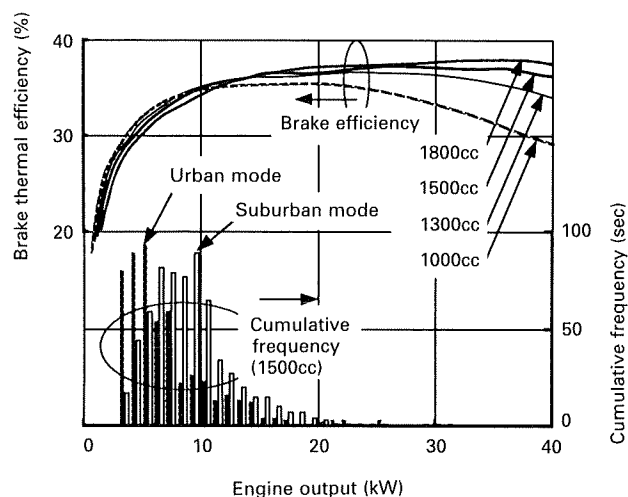


Fig. 5 Displacement and Engine Efficiency

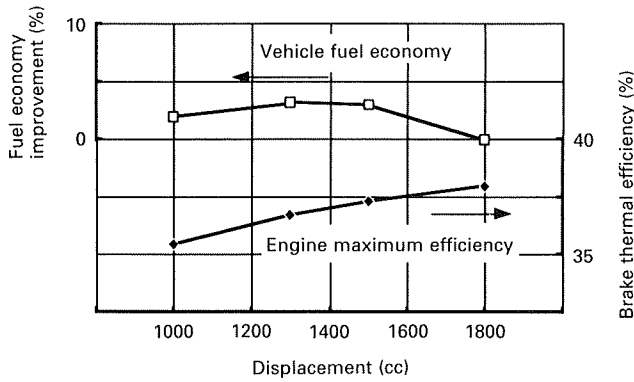


Fig. 6 Displacement and Fuel Economy

3. Improving Efficiency by Means of High Expansion Ratio

3.1 Principle

The theoretical thermal efficiency of an equivalent charge cycle is improved by raising the compression ratio. But if the compression ratio is raised in a gasoline engine, the compression end temperature rises, and knocking occurs. To prevent knocking in the high-expansion-ratio engine, the timing of intake valve closing was delayed considerably, thus lowering the effective compression ratio and raising the expansion ratio, which essentially controls the thermal efficiency. Fig. 7 is a pressure-volume (p-V) diagram comparing the high-expansion-ratio cycle with the conventional cycle when the charging efficiencies of the two are equal. Fig. 8 shows the same sort of comparison when the compression end pressures are equal. When the charging efficiency is identical, delaying the closing of the intake valve raises the maximum pressure and increases the positive work, and also reduces pumping loss. With identical compression end pressure, increasing the expansion ratio raises the theoretical efficiency.

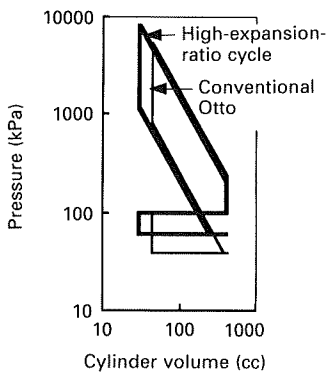


Fig. 7 p-V Diagrams with Equivalent Charging Efficiency

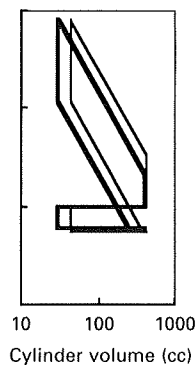


Fig. 8 p-V Diagrams with Equivalent Compression End Pressure

3.2 Relationship of Mechanical Compression Ratio, Valve Timing, and Brake Thermal Efficiency

Before a prototype of the high-expansion-ratio engine was built, the effects of the mechanical compression ratio and valve timing on brake thermal efficiency were studied. An in-line four-cylinder, 2164-cc Toyota 5S-FE engine was used in the experiments.

Fig. 9 shows the changes in thermal efficiency with different combinations of expansion ratio and valve timing. If the expansion ratio is increased and intake valve closing is delayed, brake thermal efficiency rises, but it reaches a limit at an expansion ratio of 14.7:1. Also, the maximum value of the brake mean effective pressure drops as the delay in intake valve closing increases.

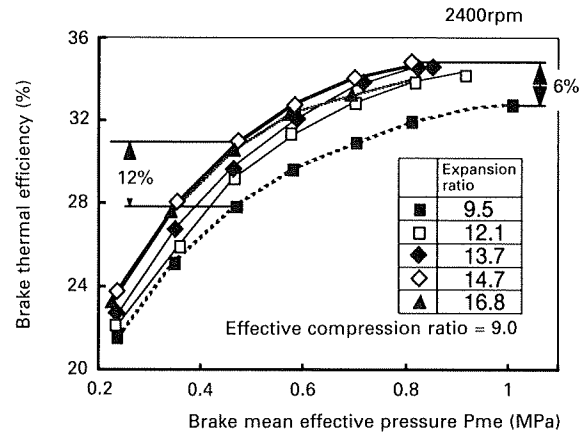


Fig. 9 Expansion Ratio and Thermal Efficiency

Fig. 10 shows the relationship between brake thermal efficiency and brake mean effective pressure under full load. As the expansion ratio increases, the timing advance becomes slower due to knocking, and the brake thermal efficiency drops, but if the intake valve closing

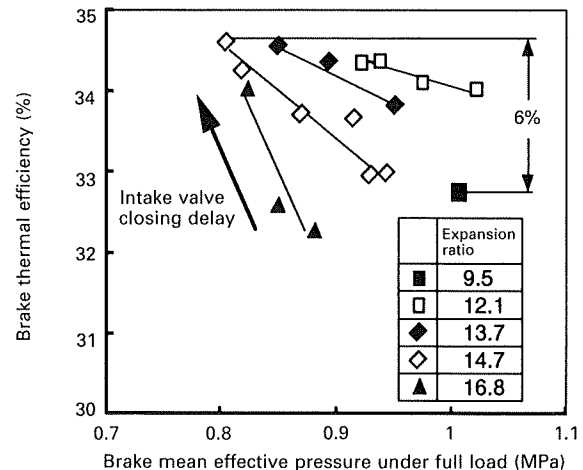


Fig. 10 Relationship of Brake Mean Effective Pressure and Thermal Efficiency as Expansion Ratio and Compression Ratio Change

is delayed at the same time, knocking gradually diminishes and efficiency improves. Therefore, if the brake mean effective pressure is allowed to fall, the combination of high expansion ratio and delayed intake valve closing achieves high efficiency. Fig. 11 is an indicator diagram of actual measured results showing that the heat cycle illustrated in Fig. 7 and Fig. 8 was achieved.

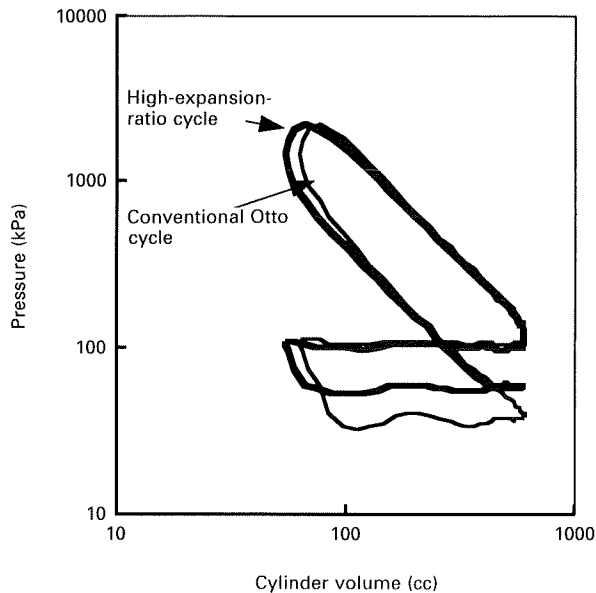


Fig. 11 Indicator Diagram of Actual Measurements

4. High-expansion-ratio THS Engine

4.1 Basic Specifications

Table 1 shows the main specifications for the high-expansion-ratio engine. The mechanical compression ratio is set to 13.5:1, but the effective compression ratio is suppressed to the range of 4.8:1 to 9.3:1 by using intelligent variable valve timing (VVT-i) to time the intake valve closing between 80° and 120° after bottom dead center (ABDC). The ratio of 4.8:1 is obtained by the maximum delay of VVT-i and is used to counter vibration during engine restart, as explained below.

Table 1 Design Specifications

Engine model	1NZ-FXE
Displacement (cc)	1497
Bore×stroke	φ75×84.7
Maximum output	43kW/4,000rpm
Combustion chamber volume	30cc
Mechanical compression ratio	13.5
Effective compression ratio	4.8~9.3
Intake valve closing timing	80~120° ABDC
Exhaust valve opening timing	32° BBDC

4.2 Engine Structure

Fig. 12 is a transverse sectional view of the high-expansion-ratio engine. An aluminum-alloy cylinder block, offset crankshaft,⁽¹⁰⁾ and ladder-frame structure are used. The crankshaft has been made thinner and lighter, and the load on the valve system springs has been reduced, as has the tensile strength of the piston rings. The connecting rod/stroke ratio has been increased, and the intake inertia effect has been reduced by using a small intake manifold. The engine also uses a slant squish combustion chamber. All of these features combine to achieve lighter weight, lower friction, and improved combustion.

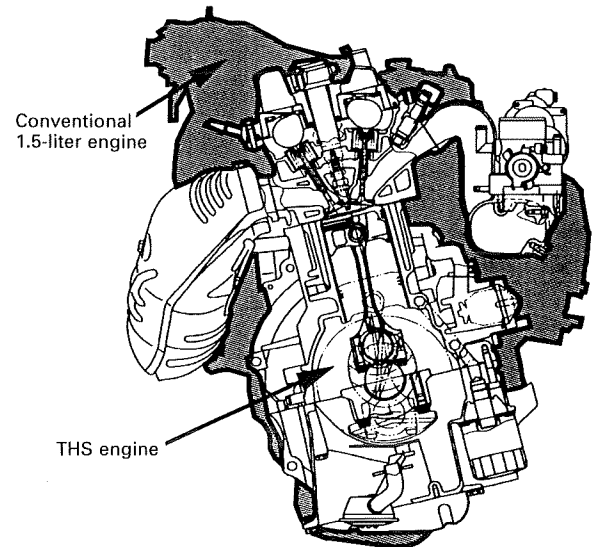


Fig. 12 Transverse Section of High-expansion-ratio Engine

5. Experimental Results and Considerations

This section summarizes the results of experiments conducted on the 1.5-liter high-expansion-ratio engine and some considerations concerning them.

5.1 Relationship of Expansion Ratio and Brake Thermal Efficiency

Fig. 13 shows the relationship of ignition timing to torque and to brake specific fuel consumption (BSFC). Expansion ratios of 13:1, 14:1, and 15:1 were compared, and it can be seen that as the expansion ratio increases, the trace knock ignition timing is delayed. With a 15:1 expansion ratio, the efficiency improves at the point of minimum spark advance for best torque (MBT), but the expansion ratio is restricted by the knocking that occurs due to the high effective compression ratio. The best results in terms of torque and BSFC were obtained with an expansion ratio of 14:1.

Fig. 14 shows the results of a study of thermal efficiency versus engine output. A 14:1 expansion ratio showed the best results over the entire output range. Ultimately, an expansion ratio of 13.5:1 was chosen, taking into account such factors as the allowable variation in

combustion chamber volume and the adhesion of deposits in the combustion chamber, in order to leave a margin for pre-ignition.

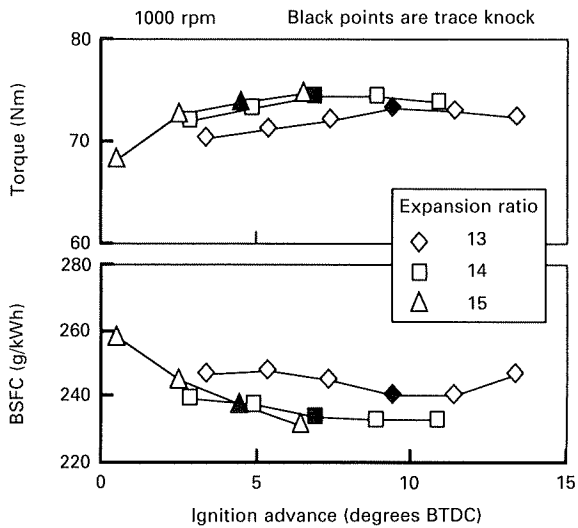


Fig. 13 Relationship of Ignition Timing and BSFC

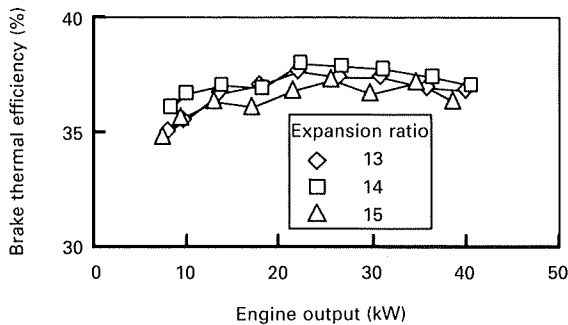


Fig. 14 Expansion Ratio and Brake Thermal Efficiency

5.2 Torque Improvement by VVT-i

Full-load torque was adjusted using VVT-i. The results are shown in Fig. 15. An improvement in torque of 10% or more was made possible by advancing the intake valve closing by 10°. In THS, the engine is controlled so that intake valve closing is advanced when the load requirements are high.

5.3 Friction Loss

As stated previously, the engine speed was lowered in an attempt to reduce friction loss. The measured results are shown in Fig. 16. It can be seen that the friction loss for the high-expansion-ratio engine is at a consistently lower level than the cluster of points plotted for con-

ventional engines and that the objective of reducing friction loss was achieved.

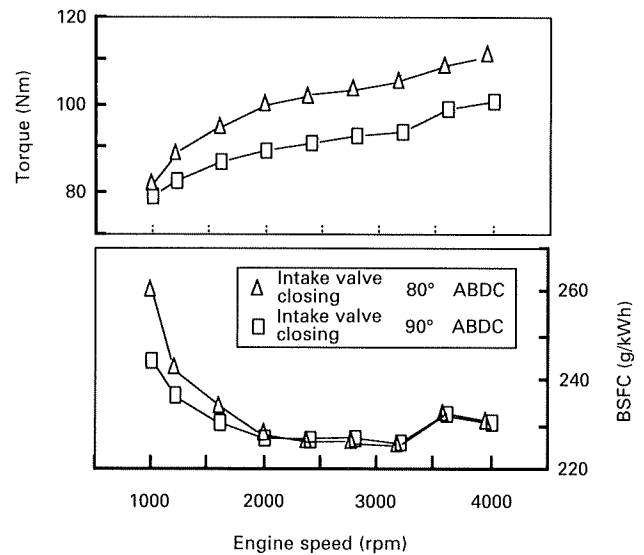


Fig. 15 Torque Improvement Effect of VVT-i

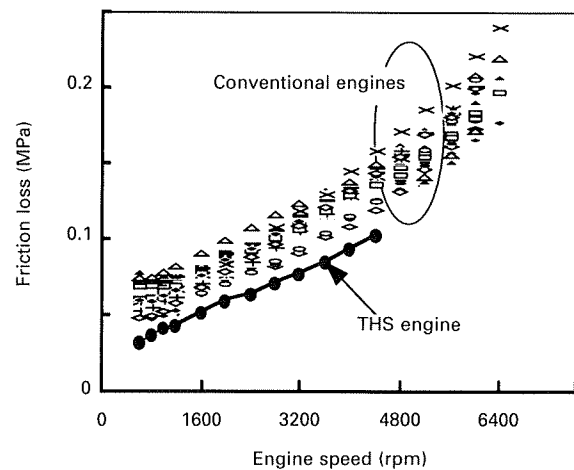


Fig. 16 Comparison of Friction Loss

5.4 Reduction of Exhaust Emissions

The advantages and disadvantages of the hybrid vehicle with respect to cleaner exhaust emissions are summarized below.

Advantages

- (1) By using the supplementary drive power of the electric motor, the system eliminates the light-load range, where concentrations of hydrocarbons in the emissions are high and the exhaust temperature is low.

- (2) By allocating a portion of the load to the electric motor, the system is able to reduce engine load fluctuation under conditions such as rapid acceleration. This makes it possible to reduce quick transients in engine load so that the air-fuel ratio can be stabilized easily.

Disadvantages

- (1) Because the engine is used in the high-efficiency range, the exhaust temperatures are lower than for a conventional vehicle.
- (2) There is concern that the more the engine is stopped and restarted, the more unburned fuel will enter the exhaust system and the more the catalyst bed temperature will drop.

Fig. 17 shows the exhaust temperature distribution for the high-expansion-ratio engine. Although the exhaust temperatures are lower than for a conventional engine, a minimum temperature of 400°C is ensured for the engine operating range shown in the diagram. This is a temperature that can maintain the catalyst in an activated state.

Fig. 18 shows the change in the catalyst bed temperature after the vehicle stops. In a conventional vehicle, where the engine continues to idle, the catalyst bed temperature slowly drops. But in the THS vehicle, the influx of low-temperature exhaust gases can be avoided by stopping the engine, making it possible to sustain a comparatively gradual decline in temperature.

Fig. 19 shows the levels of exhaust gases at the catalyst inlet. Hydrocarbons are at the same level as a conventional vehicle, which is thought to be due to the smaller volume and higher S/V ratio of the combustion chamber. However, as explained previously, the catalyst is maintained in an activated state that is sufficient to ensure a high rate of catalytic conversion.

Exploiting the advantages cited above based on these results, Toyota optimized the system to achieve the voluntary emissions target of one-tenth of the current standard values.

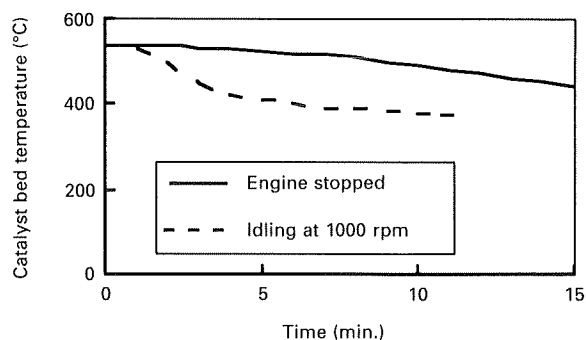


Fig. 18 Change in Catalyst Bed Temperature with Engine Stopped

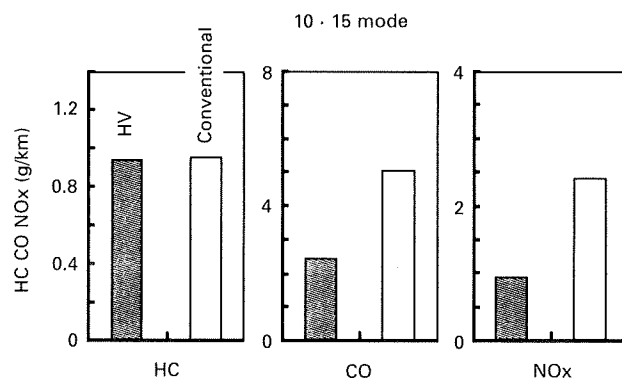


Fig. 19 Comparison of Emissions at Catalyst Inlet

5.5 Vibration Countermeasures When Starting and Stopping

Stopping the engine when the vehicle stops contributes greatly to fuel economy, realizing a 20% improvement in the 10-15 mode. On the other hand, problems have been raised with vibration as the engine speed passes through the resonance point of the drive train, as well as vibration due to the brief continuation of the compression and expansion cycle when the engine stops. The drive train resonance problem is solved by using the motor to raise the engine speed in a shorter time. It was thought that the compression and expansion cycle could be moderated by reducing the volume of air when the engine is shut off. The VVT-i function is used to reduce the volume of the intake air.

Fig. 20 shows floor vibration when the engine starts. The large amplitude of acceleration seen in area A in the diagram is due to the compression reaction force. This amplitude can be reduced considerably, as shown in area A', by using VVT-i to set the timing of intake valve closing to 120° ABDC. The vibration seen in area B arises from the rapid increase in engine torque after the engine starts firing. This is eliminated by controlling the ignition timing delay, as shown in area B'.

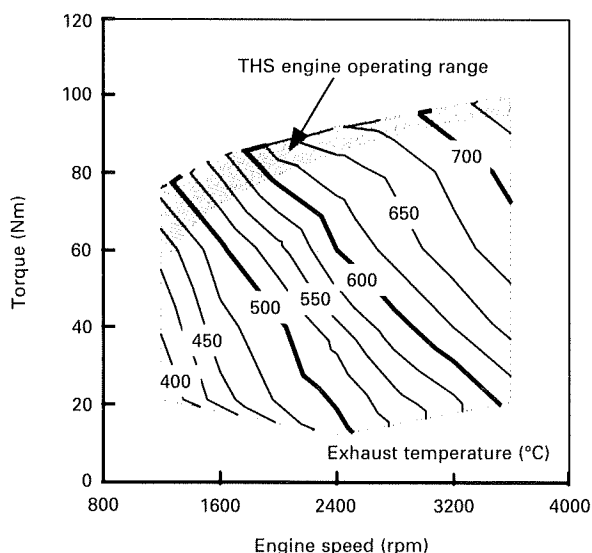


Fig. 17 Exhaust Temperature Map

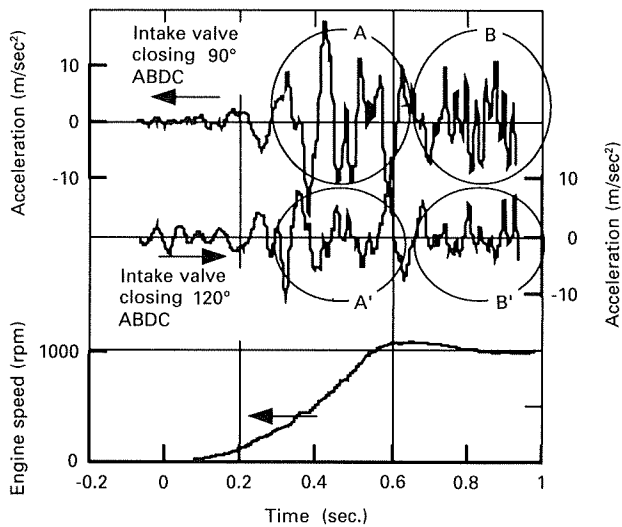


Fig. 20 Vibration When Engine Starts

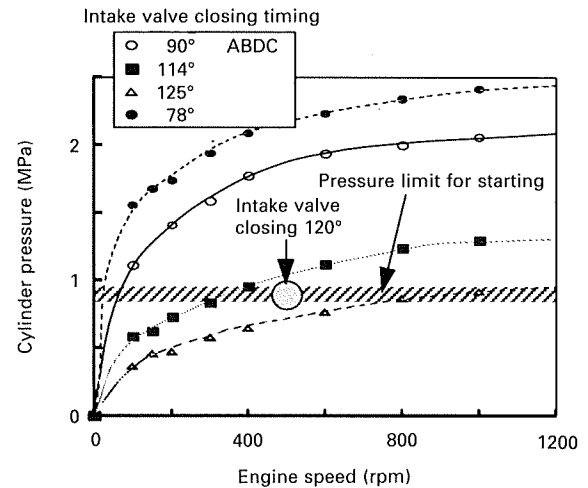


Fig. 21 Relationship of Engine Speed and Cylinder Pressure

5.6 Low-temperature Starting

In the THS system, the generator is used as a starter motor to start the engine turning. For this purpose, the generator uses the large-capacity nickel-metal hydride battery as a power supply. However, as the temperature drops, the battery power also drops, reducing the cranking speed. On the other hand, the significant delay in intake valve closing in the high-expansion-ratio engine reduces the compression end pressure (the maximum pressure within the cylinder) during cranking. The relationship between cylinder pressure and engine speed is shown in **Fig. 21**, using intake valve closing timing as a parameter. Given the combustion characteristics of the engine, the maximum pressure at which ignition is possible is approximately 0.85 MPa. In the THS system, the engine speed and intake valve closing timing are coordinated so that this pressure is maintained even under low-temperature conditions.

5.7 Vehicle Fuel Economy

Fig. 22 shows the efficiency distribution of the developed high-expansion-ratio engine when it is combined with the THS system and driven in the 10 · 15 mode. In the low-output range the engine is stopped, so that it is used only in the high-efficiency range. **Fig. 23** shows the relationship between fuel economy and the charge balance of the battery before and after mode driving. In the hybrid vehicle, the fuel economy changes as the battery charges and discharges, so the vehicle's fuel economy is defined as the value when the charge balance is zero.

Optimization of the vehicle's integrated controls, including regenerative braking, allows the THS vehicle to attain almost twice the fuel economy of a conventional vehicle of the same class.

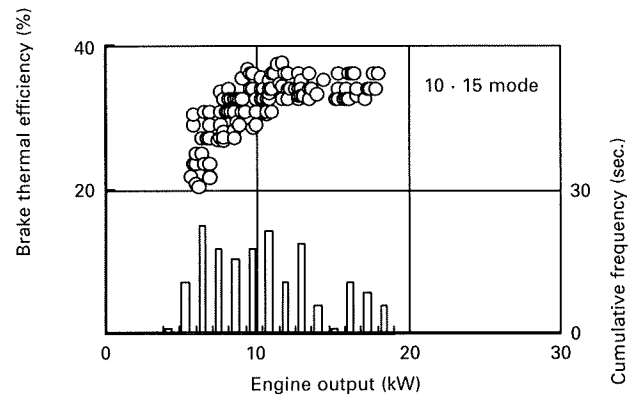


Fig. 22 Engine Operating Range and Efficiency in 10 - 15 Mode

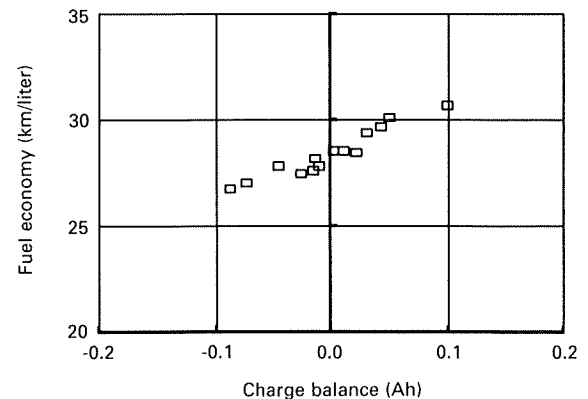


Fig. 23 Charge Balance and Fuel Economy

6. Conclusion

A lightweight, compact, high-expansion-ratio gasoline engine was developed for use in the internal-combustion/electric hybrid vehicle.

- (1) The engine output required to meet the vehicle's weight and performance requirements was determined, and the engine displacement was chosen to yield the optimum vehicle fuel economy from the high-expansion-ratio cycle.
- (2) A 1.5-liter high-expansion-ratio gasoline engine was developed as the primary power source, and it attained the target fuel consumption rate of less than 230 g/kWh.
- (3) Emissions levels much lower than the current standard values were attained by optimum control of the motor and engine.
- (4) Vibration during engine starting and stopping was greatly reduced by using VVT-i.
- (5) The hybrid system achieved twice the fuel economy of a conventional vehicle of the same class, while cutting the volume of CO₂ emissions in half.

The authors wish to express their respectful appreciation to all those who cooperated in the development of this system. We particularly wish to express our gratitude to the late Mr. Masahito Ninomiya for helping us to succeed in providing this engine to our customers.

■ References

- (1) Yoshihiro Fujiyoshi, Urata, Suzuki, Fukuo: Study of . Non-Throttling Engine Using Early Intake Valve Closing Mechanism, Report No. 1. Society of Automotive Engineers of Japan (JSAE), Printed Materials for Presentations 924006, 924 1992-10
- (2) Shinichi Nagumo, Hara: Improved Fuel Efficiency by Control of Intake Valve Closing Timing. JSAE Paper 9540921, Vol. 26 No. 4, October, 1995
- (3) Richard Stone, Eric Kwan: Variable Valve Actuation Mechanisms and the Potential for their Application. SAE Paper 890673, 1989
- (4) T. Ahmad, M. A. Theobald (GMR): A Survey of Variable-Valve-Actuation Technology. SAE Paper 891674, 1989
- (5) T. W. Asmus: Valve Events and Engine Operation. SAE Paper 820749, 1982
- (6) Hitomi Mitsuo, Sasaki, et al.: Mechanism of Improving Fuel Efficiency by Miller Cycle and its Future Prospects. SAE Paper 950974, 1995
- (7) James H. Tuttle: Controlling Engine Load by Means of Early Intake-Valve Closing. SAE Paper 820408, 1982
- (8) R. A. Stein, K. M. Galletti, T. G. Leone: Dual Equal VCT-A Variable Camshaft Timing Strategy for Improved Fuel Economy and Emissions. SAE Paper 95975, 1995
- (9) Naoharu Ueda, Ichimaru, Sakai, Kanesaka: High Expansion Ratio Gasoline Engine Using Rotary Valve for Intake Manifold Control, Report No. 3. JSAE Printed Materials for Presentations 946 1994-

10, 9437458

(10) Shinichi Sano, Kamiyama, Ueda: Improving Thermal Efficiency by Means of Cylinder Bore and Offset Crankshaft. JSAE Printed Materials for Presentations 966 1996-10

■ Authors



T. TAKAOKA



K. HIROSE



T. UEDA



Y. NOUNO



H. TADA



H. KANAI

Production Engineering Development for EV, HV Units

Ken Tanoue*

Hiroshi Miyazaki**

Yasutomo Kawabata**

Toshiaki Yamamoto*

Takao Hirose*

Hajime Nakagawa*

Abstract

The Prius introduced to the market at the end of 1997 is equipped with the innovative Toyota Hybrid System, which comprises numerous new components (motor, generator, inverter, electric power steering, regenerative brakes, etc.).

The new system presented greater challenges than ever to both the Product Development Divisions and the Production Engineering Divisions.

Through intensive simultaneous engineering by the intra-company task force, teamed up with specialists from relevant divisions, including machine-tool motor specialists, the system was made ready for its debut in a very short lead time, and the fundamental manufacturing processes were established.

Keywords: EV, HV, motor, production engineering, prototype

1. Introduction

At the end of 1997, as one part of its Eco-Project, which had already given birth to the electric RAV4L EV and the Coaster Hybrid EV, Toyota Motor Corporation introduced the Prius, which carries the innovative Toyota Hybrid System as its power train (**Photo. 1**).⁽¹⁾ The hybrid system is equipped with both a gasoline engine and an electric motor as sources of drive power. The crux of the system is the transmission, consisting of a motor, a generator, and a power split device, and this in particular raised a number of technical and managerial challenges in its development. Nonetheless, Toyota's flexible project team activity, which included suppliers, made it possible to bring the technology from development to prototyping, evaluation, and production in a very short period of time.

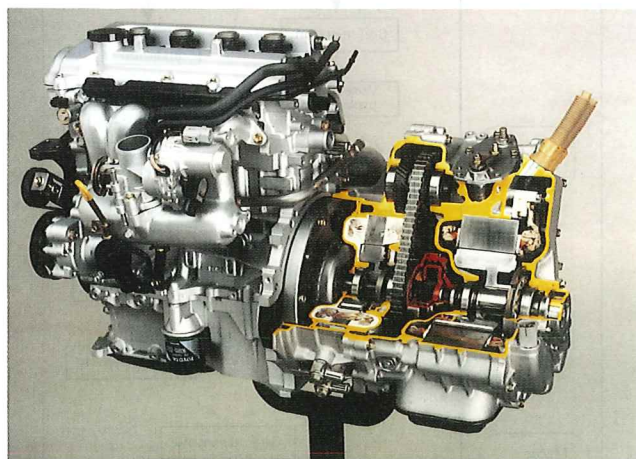


Photo. 1 Toyota Hybrid System⁽¹⁾

2. Overview of Toyota Hybrid System

Toyota has led the way to the advanced hybrid system.

Many new components and new technologies are used in the Prius that are not found in a vehicle that runs on an internal-combustion engine alone. These include a power unit consist-

Table 1 Prius HV Units

Component	Structural units
Power Unit	Engine Motor, generator Transaxle
Power control unit	Inverter Motor-ECU HV-ECU
Battery	Battery Battery-ECU
Chassis	Electric power steering Regenerative brakes ABS

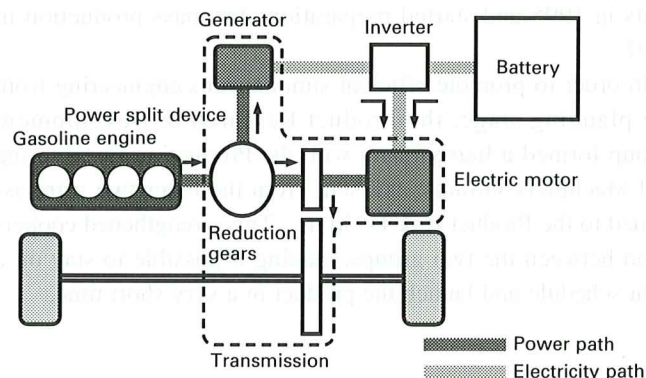


Fig. 1 Hybrid System Configuration⁽¹⁾

* Power Train & Chassis Components Production Engineering Div.

** Information Technology & Engineering Div.

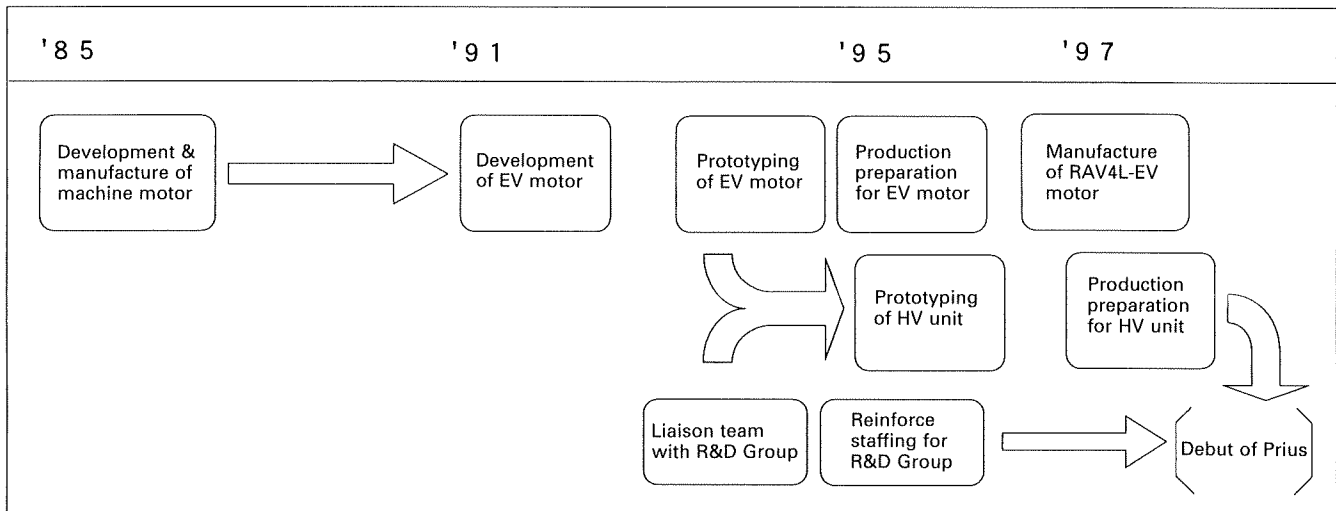


Table. 2 Involvement of Production Engineering and Machinery Groups

ing of a motor and a generator, a power split device, a power control unit containing an inverter to control the motor, a battery to serve as the power source for the motor, electric power steering, and regenerative brakes.

Fig. 1 shows the configuration of the hybrid system used for the Prius.

3. Background of Production Technology for EV, HV Units

In the Production Engineering and Machinery Groups, the EV and the hybrid system are considered key systems for the future, and both production technology and technical know-how have been built up over time, as shown in **Table 2**.

In the Machinery Group, equipment design departments have been developing and evaluating machine motors as mechatronic components since 1985. Making use of the technology thus developed, the group began development of EV motors in 1991, producing a prototype in 1994.

The Production Engineering Group began prototyping HV units in 1995 and started preparations for mass production in 1997.

In order to promote efficient simultaneous engineering from the planning stage, the Product Research & Development Group formed a liaison team with the Production Engineering and Machinery Groups, and staff from the latter two were assigned to the Product R & D Group. This strengthened cooperation between the two groups, making it possible to stay on a tight schedule and launch the product in a very short time.

4. EV, HV Motor Mass Production Technology

This section focuses on some of the production processes that presented technical challenges resulting from the specific nature of EV/HV motors

4.1 Challenges in EV, HV Motor Production Engineering

EV and HV motors are required to be more efficient and to have a higher output/weight ratio than machine motors, as well as higher reliability and durability, in light of the harsh environment in which they are used. The production volume established was a record for these kinds of electric motors.

Fig. 2 shows an overview of the assembly processes.

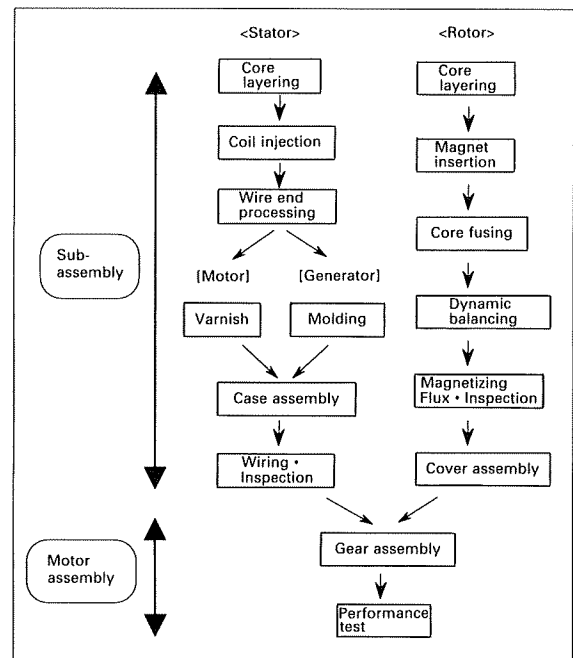


Fig. 2 Motor and Generator Assembly Processes

The motor and generator assembly processes are based on those for a permanent-magnet AC servomotor for machinery, with improvements made for required product performance, mass produceability, and manufacturing quality. Some primary examples are described below.

4.2 Stator Coil Injection

Stator coil injection (**Fig. 4**) at the rather high fill rate of 70% (**Fig. 3**) has been achieved for the first time in a mass production line. (The fill rate for industrial-use induction motors is around 50% (**Photo. 2**).)

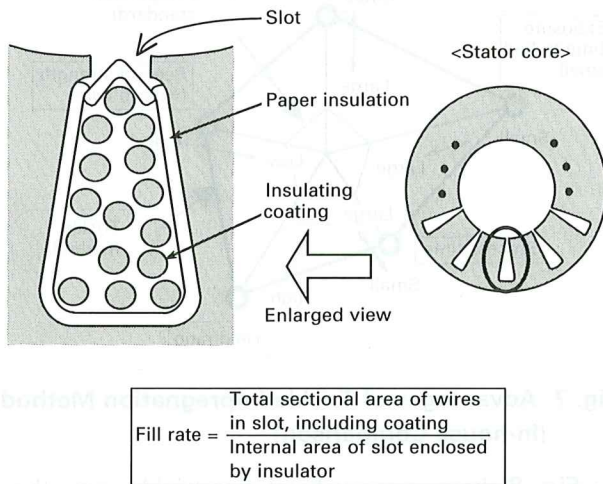


Fig. 3 Definition of Fill Rate

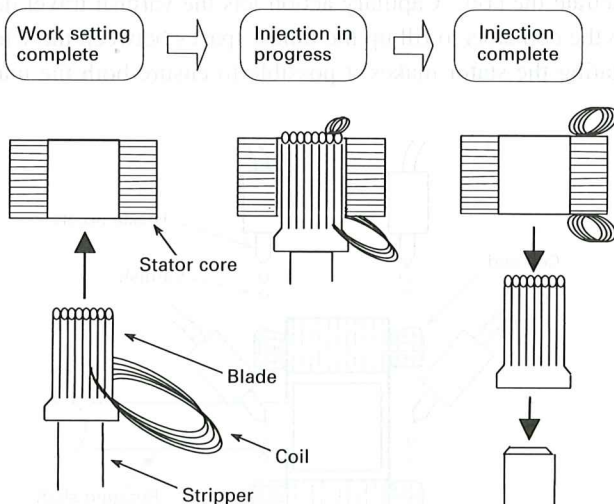


Fig. 4 Coil Injection Process

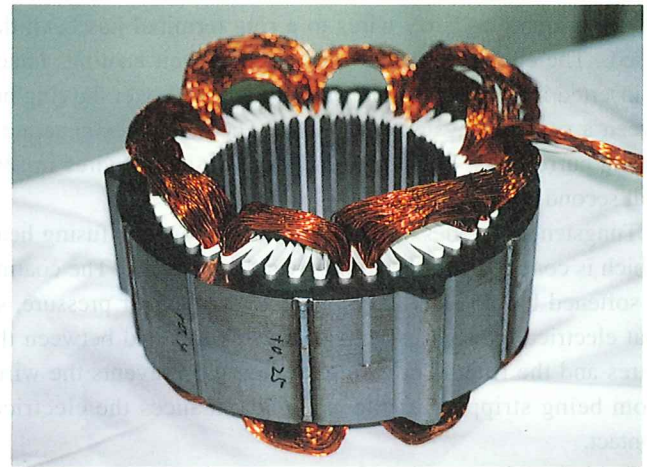


Photo. 2 After Coil Injection (Single-phase Only)

This was made possible by improving the conventional coil injection technologies that are widely used in the mass production of industrial-use induction motors, the layered winding structure of which is shared by EV and HV motors. The key to success is to optimize the size of the stator slot opening, as well as the combination of magnet wire diameter and the number of wires.

4.3 Fuse-and-crimp Method for Magnet Wire Coating Removal and Terminal Crimping

A very productive method of electrically connecting a bun-

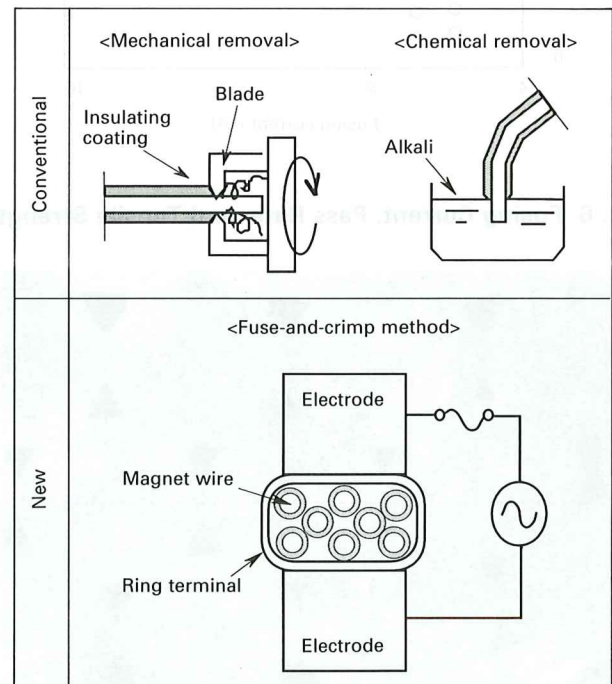


Fig. 5 Insulation Coating Removal Methods

dle of as many as forty wires to a ring terminal has been devised. The end of a bundle of wires, with their coatings intact, is inserted into the terminal's ring and crimped over the ring between a pair of tungsten electrodes. The electrodes generate a fusing current that heats the bundle and fuses the wires in several seconds.

Tungsten electrodes serve as the main source of fusing heat, which is conducted to the coating via the terminal. The coating is softened by the heat and is then expelled under pressure, so that electrical contact is made between wires and between the wires and the ring. The crimping pressure prevents the wires from being stripped off the ring and enhances the electrical contact.

Stable heat input and uniform compression are important. The pass rate (**Fig. 6**) indicates what percentage of the magnet wires are electrically connected to the terminal. When certain processing conditions are satisfied, the pass rate is stable at

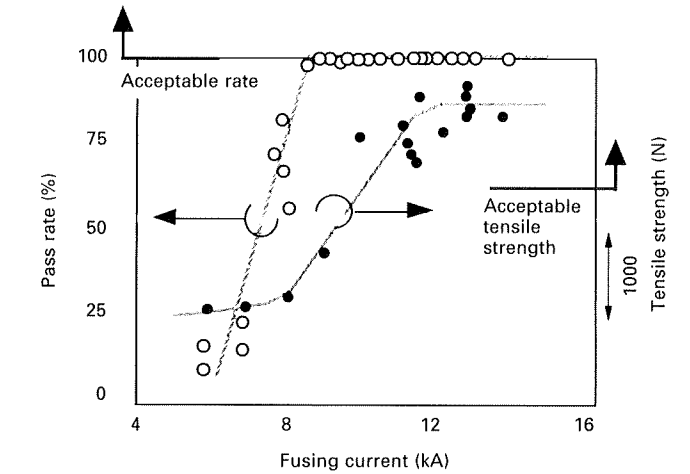


Fig. 6 Fusing Current, Pass Rate, and Tensile Strength

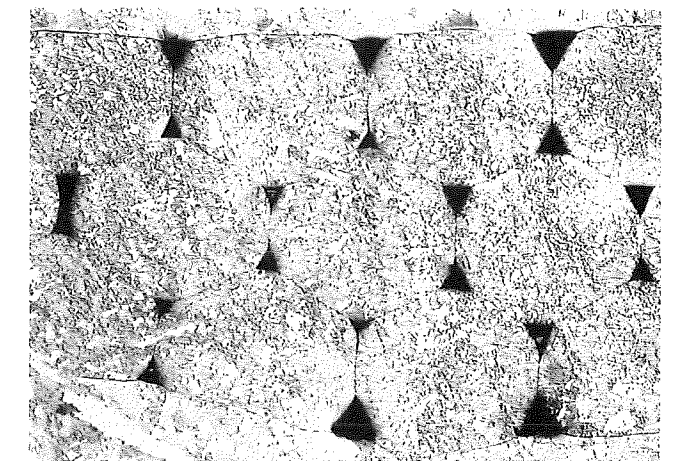


Photo. 3 Magnified View of Terminal Section

100%. The same processing conditions also maximize the resistance of the wires to being stripped off the ring.

4.4 Trickle Impregnation of Varnish into Stator Coil.

Trickle impregnation is used to impregnate the stator coil of the motor with varnish. As **Fig. 7** indicates, the method is a great improvement over conventional dip impregnation in terms of the wire-to-wire peel-off strength, the processing time, the varnish yield ratio, and the effect on the working environment.

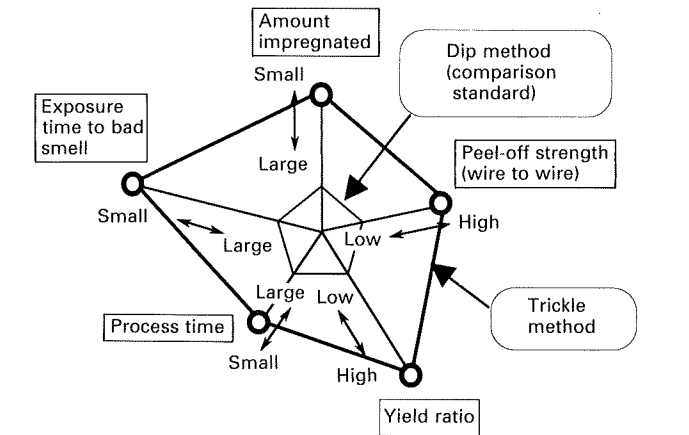


Fig. 7 Advantages of Trickle Impregnation Method (In-house Comparison)

As **Fig. 8** shows, a varnish solution trickles onto the coil ends protruding from the stator as the stator is rotated. Because the coil is preheated, the varnish that lands on the coil absorbs the heat instantly, lowering its viscosity enough to allow it to penetrate the coil. Capillary action lets the varnish travel deep into the coil slots to fill up the tiniest spaces between the wires. Rotating the stator makes it possible to ensure both the maxi-

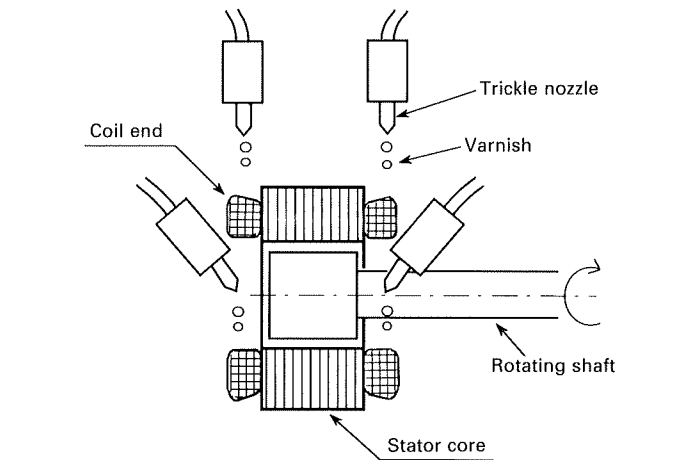


Fig. 8 Trickle Impregnation Method

mum trickling ratio, at which the trickled varnish can remain on the coil without draining from the bottom of the coil ends, and the uniformity of impregnation.

Intermittent trickling, with a pause between trickling shots, maximizes the total amount of varnish impregnated. The varnish on the coil sets up as a gel and loses its fluidity in approximately fifteen minutes. **Fig. 9** shows the varnish viscosity behavior in response to the coil temperature.

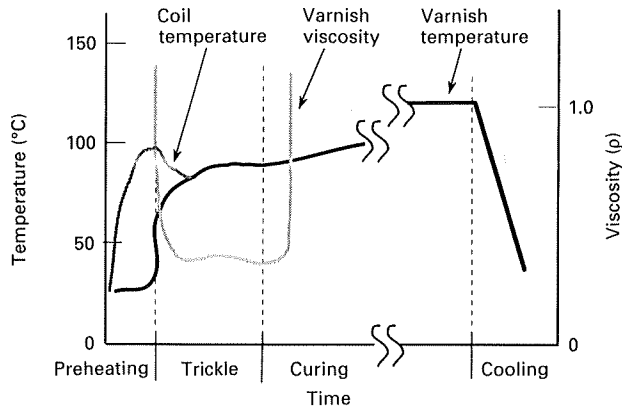


Fig. 9 Varnish Viscosity Behavior during Impregnation

4.5 Stator Coil Resin Molding

The generator's peak coil temperature under full load has been lowered to within the prescribed limit, and the time required to reach peak temperature has been increased, by resin molding the stator with the coil and casing. The resin fills up every vacant space in the coil and coil slots, and between the coil and the casing. The specially blended resin and the low-distortion molding process play key roles. The resin, a mixture of unsaturated polyester thermosetting resin and fillers such as alumina and silica, exhibits superior heat conductivity (**Fig. 11**), as well as durability under severe heat cycling and tolerable fluidity during the molding process.

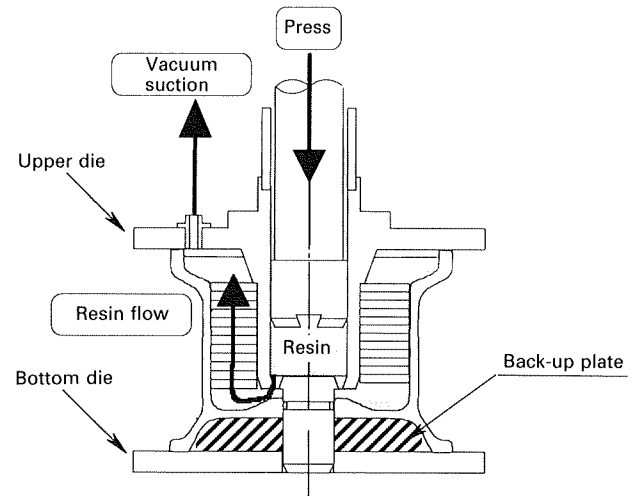


Fig. 10 Resin Molding Method

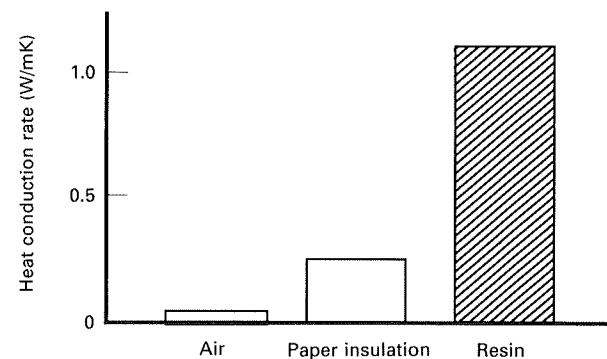


Fig. 11 Comparison of Heat

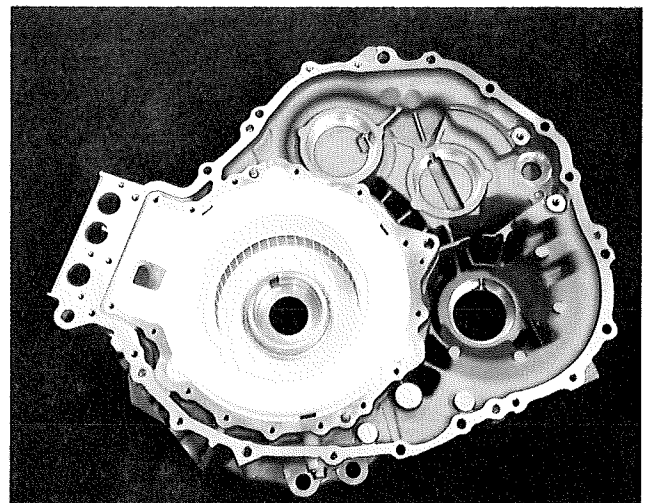


Photo. 4 Resin-molded Generator Stator

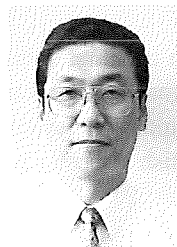
5. Conclusion

The HV unit manufacturing technologies include those originally developed for transmissions and electric motors. In addition to simultaneous engineering among the divisions involved, which required hard work from suppliers as well, taking maximum advantage of proven technologies in these two fields made it possible for the Prius to make its debut in a very short lead time. Our experience shows that many proven technologies in the motor industry are transferable to the new sector of EV/HV motor mass production.

■ References

- (1) Toyota Motor Corporation, Public Affairs Div.: Toyota Press Information '97, Toyota Hybrid System (1997)

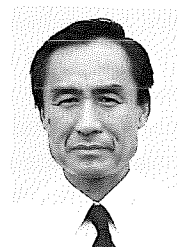
■ Authors



K. TANOUE



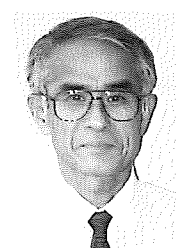
H. MIYAZAKI



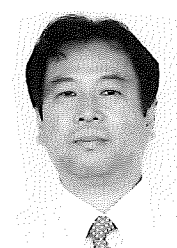
Y. KAWABATA



T. YAMAMOTO



T. HIROSE



H. NAKAGAWA

Development of Electric Vehicle Powered by Fuel Cell

Yasuhiro Nonobe*
Yoshio Kimura*

Abstract

Recently, manufacturers have been developing low-emission vehicles to solve environmental problems. The electric vehicle is expected to be one of the alternative low-emission vehicles and has made great progress in driving performance and ride comfort. However, the long time required to recharge the batteries, the limited driving range due to the low energy density of the batteries, and the high product cost are barriers to the acceptance of electric vehicles by the general public.

An experimental vehicle using a fuel cell as a power source has been developed. The fuel cell is expected to give the electric vehicle high energy efficiency and ease of use. It has been verified that the fuel cell has ample potential as a power source for the electric vehicle, as well as the advantages of low emissions and high efficiency.

Keywords: polymer electrolyte membrane fuel cell, hydrogen-absorbing alloy

1. Introduction

In recent years, in response to environmental problems, almost all automobile makers have energetically pursued the development of low-emission vehicles. Particularly in response to the zero-emission vehicle (ZEV) regulations in the U.S. state of California, the development of electric vehicles, which until now has been at the research and development stage, is being accelerated with an eye to gaining more widespread user acceptance. However, at the present time, primarily due to problems with battery technology, the electric vehicle's utility is inferior to that of the gasoline-powered car, and this has been a major barrier to its increased use.

One measure that is expected to provide a radical solution to these problems is the Fuel Cell Electric Vehicle (FCEV), an electric vehicle that uses a fuel cell as its power source. The FCEV carries fuel in the form of hydrogen or a source of hydrogen, and converts the fuel to electrical energy by means of the fuel cell in order to generate the power to drive the vehicle. This system gives the FCEV a degree of utility that rivals that of the gasoline-engine car in terms of cruising range, refueling, and other factors. And because its superior energy efficiency gives it the advantages of much better fuel economy and lower emissions, the expectations are great for the FCEV to become the next-generation electric vehicle.

Toyota has built a prototype FCEV based on the RAV4L EV in order to verify the feasibility of using the fuel cell as the power source for an electric vehicle, as well as to confirm its advantages. This paper describes the technologies employed in the prototype FCEV.

2. Fuel Cell⁽¹⁾

2.1 Principle of the Fuel Cell

The fuel cell is a battery that, in principle, can output electrical energy forever, irrespective of the battery capacity, by continuously supplying active material from outside in either gaseous or liquid form.

In the typical fuel cell, oxygen (air) is used as the cathode active material and hydrogen is used as the anode active material. **Fig. 1** illustrates the principle by which the fuel cell generates electricity, with the formulas at the bottom indicating the chemical reactions. The hydrogen supplied to the anode is dissociated into individual protons by a catalyst, and the protons move through the electrolyte and react with the oxygen of the

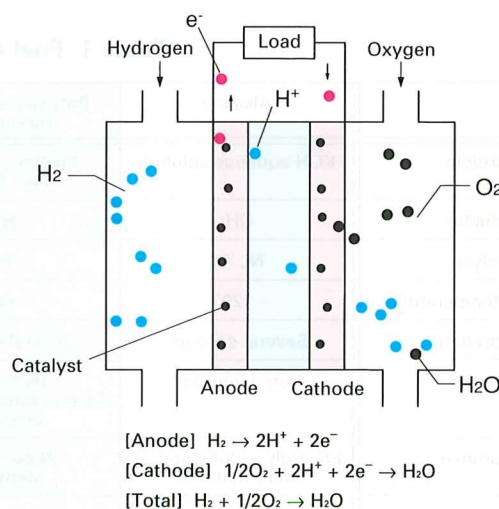


Fig. 1 Principle of Fuel Cell Electricity Generation

* Electric & Hybrid Vehicle Engineering Div.

cathode to create water. At this time, the electrons emitted by the anode generate electricity by arriving at the cathode via an external circuit. The standard electromotive force is 1.23 volts.

2.2 Advantages of the Fuel Cell

Two advantages are expected from the principle of electrical generation used in the fuel cell. The first results from the fact that the chemical energy change that occurs the reaction is converted directly into electrical energy, without passing through any intermediate form of energy. This means that much higher generating efficiency can be expected from the fuel cell than from other forms of electrical generation. (Fig. 2)

The other advantage is that because the reaction that creates water from hydrogen and oxygen does not require high temperatures, it generates almost no emissions, such as nitrous oxide. If hydrogen is used as the fuel, the only exhaust gas is water vapor, and even if the system operates by reforming methanol fuel, the amounts of hydrocarbons and nitrous oxide emitted are extremely small. (Fig. 3)

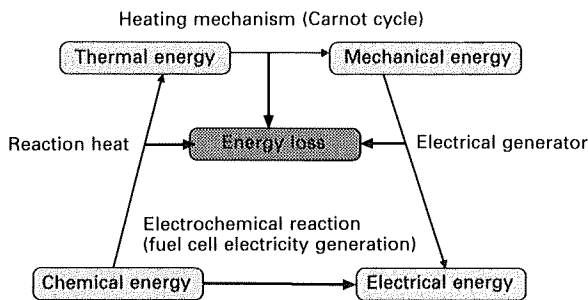


Fig. 2 Energy Exchange Paths

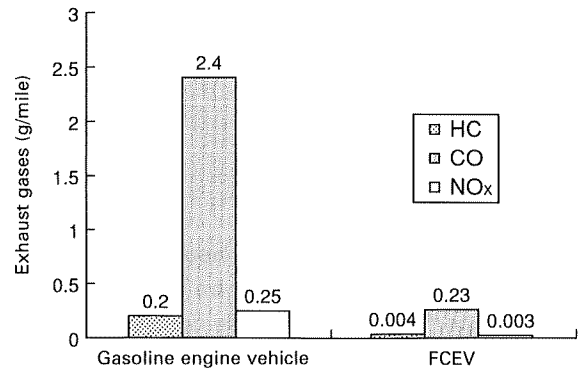


Fig. 3 Comparison of Automobile Emissions

3. FCEV Fuel Cell

The FCEV fuel cell must satisfy the following requirements:

- It must be able to operate at low temperature, and its start-up time must be short.
- It must have high output density and be small and light-weight.
- It must be able to use crude hydrogen reformed from hydrocarbon-based fuels such as alcohol.

Table 1 shows the characteristics of various types of fuel cells classified according to the type of electrolyte they use.⁽¹⁾ Among them, the polymer electrolyte membrane type is the one that best satisfies the requirements of the FCEV. With this type of cell, the electrolyte consists of a polymer called a proton exchange membrane that shows good proton conductivity when wet. Development of this type of cell has advanced rapidly, thanks to the development in recent years of proton exchange membranes with superior proton conductivity.

In light of these considerations, the polymer electrolyte membrane fuel cell was chosen for use in the Toyota FCEV,

Table 1 Fuel Cell Types and Characteristics

	Alkaline	Polymer electrolyte membrane	Phosphoric acid	Molten carbonate	Solid oxide
Electrolyte	KOH aqueous solution	Proton exchange membrane	Phosphoric acid	K ₂ CO ₃ Li ₂ CO ₃	ZrO ₂ +Y ₂ O ₃
Conductor	OH ⁻	H ⁺	H ⁺	CO ₃ ²⁻	O ²⁻
Catalyst	Ni, Ag	Pt	Pt	—	—
Operating temperature	~ 120°C	~ 80°C	180 ~ 250°C	500 ~ 750°C	800 ~ 1000°C
Start-up time	Several seconds	Several seconds	10-20 minutes	Several hours	10 or more hours
Fuel	Pure hydrogen	Hydrogen (Carbon dioxide gas also possible)	Hydrogen (Carbon dioxide gas also possible)	Hydrogen Carbon monoxide	Hydrogen Carbon monoxide
Fuel source	Electrolysis (of water or other material)	Natural gas Methanol	Natural gas Methanol	Natural gas Methanol Coal Petroleum	Natural gas Methanol Coal Petroleum
Developed uses	Spacecraft Submarine EV	Spacecraft EV	Distributed power plants On-site generator EV	Centralized power plant	Centralized power plant

and its development was promoted. **Fig. 4** shows the basic structure of the polymer electrolyte membrane fuel cell.

Normally, the cell is constructed of an electrode membrane assembly sandwiched between a pair of gas-impermeable connectors (collectors) that form the flow path for the gaseous fuel. In the electrode membrane assembly, the proton exchange membrane is pressed between two sheets of conductive porous material (e.g., carbon paper) that forms a catalytic layer of platinum or other noble metal.

The fuel cell in the Toyota FCEV uses a DuPont Nafion membrane for the proton exchange membrane, with a platinum catalyst on the cathode and a platinum-ruthenium alloy catalyst on the anode.

Cells of this type are stacked serially in units capable of the necessary voltage (approximately 300 volts in the case of the electric vehicle), with one cooling plate inserted per every two or three cells. The consolidated whole is referred to as a fuel cell stack. **Photo. 1** shows a 5 kW fuel cell stack. The FCEV carries a stack with four times that power (20 kW), packaged as a unit with the necessary piping. (**Photo. 2**)

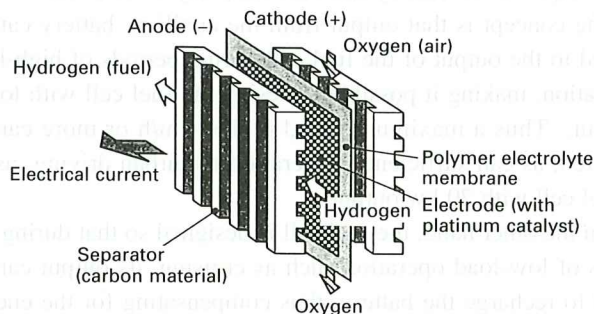


Fig. 4 Structure of Polymer Electrolyte Membrane Fuel Cell

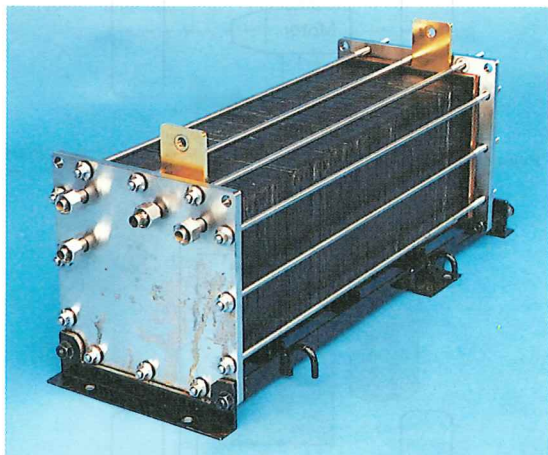


Photo. 1 5 kW Fuel Cell Stack

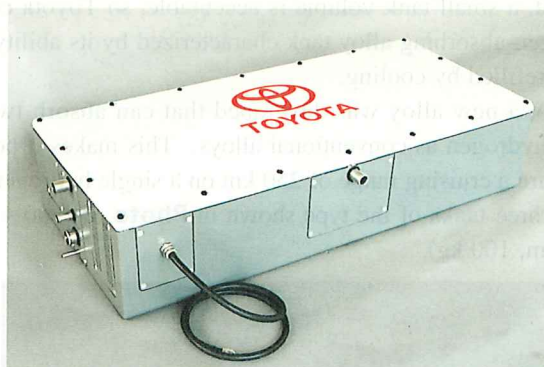


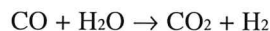
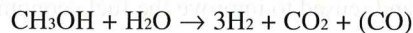
Photo. 2 20 kW Fuel Cell Unit

4. Hydrogen Fuel

4.1 Hydrogen Fuel Supply Method

There are two basic types of sources for the hydrogen that is supplied as the active material for the fuel cell. One method uses hydrogen that is stored in some form, while the other method manufactures hydrogen using a hydrocarbon-based fuel as the source.

The first method uses a high-pressure gas cylinder, a liquid hydrogen cylinder, or a tank containing a hydrogen-absorbing alloy. The hydrogen-absorbing alloy⁽³⁾ has the property of trapping molecules of hydrogen in a metal lattice, generally absorbing hydrogen when cooled and releasing it when heated. It can be used repeatedly. The second method uses a hydrocarbon-based fuel such as methanol or natural gas as the source of hydrogen, generally making hydrogen by water vapor reforming in a reformer⁽⁴⁾. Shown below is an example of the reactions when methanol is used.



The problem with this method is that, along with carbon dioxide, a tiny amount of carbon monoxide is generated, and this poisons the fuel cell's platinum catalyst, causing output to drop. The platinum-ruthenium catalyst on the fuel cell anode, mentioned above, is used specifically because it is far more resistant to carbon monoxide poisoning than is platinum alone.

Toyota has chosen the hydrogen-absorbing alloy method for the FCEV, both from the standpoint of zero emissions and for the purpose of ensuring the performance of the fuel cell system.

4.2 Hydrogen-absorbing alloy tank

The issues to address with regard to the hydrogen storage method are how large a container to use and how to refill it

with fuel. With the alloy method, unlike the other storage method, a small tank volume is acceptable, so Toyota chose a hydrogen-absorbing alloy tank characterized by its ability to be easily refilled by cooling.

Also, a new alloy was developed that can absorb twice as much hydrogen as conventional alloys. This makes it possible to ensure a cruising range of 250 km on a single hydrogen refill using three tanks of the type shown in **Photo. 3** (700 * 450 * 170 mm, 100 kg).

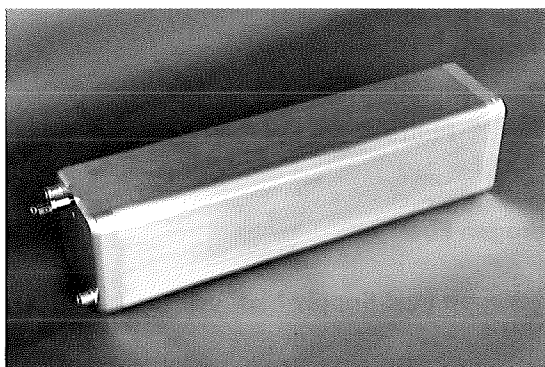


Photo. 3 Hydrogen-absorbing Alloy Tank

5. Fuel Cell System

The fuel cell system shown in **Fig. 5** uses the fuel cell and hydrogen-absorbing alloy tank described above. The system configuration is divided roughly into a fuel supply system, an air supply system, and a cooling system.

The fuel supply system humidifies the hydrogen from the tank (in order to maintain the wetness of the proton exchange membrane) and supplies it to the fuel cell. The pressure is adjusted so that new hydrogen is supplied to replace that consumed by the fuel cell. Any hydrogen not consumed by the fuel cell is recirculated and reused to improve the fuel economy even further.

The air supply system humidifies the air and supplies it to

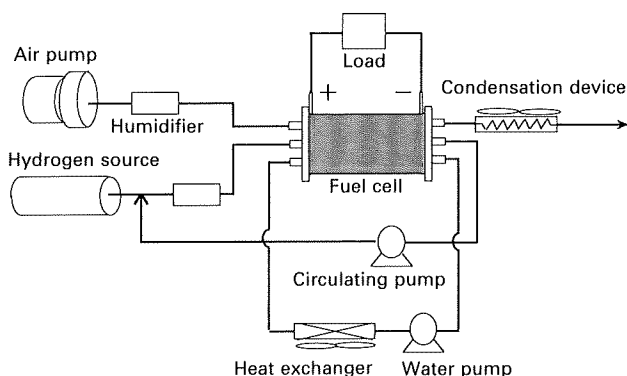


Fig. 5 Polymer Electrolyte Membrane Fuel Cell System

the fuel cell by means of a compressed air cylinder or a compressor.

In the cooling system, the cooling plates in the fuel cell stack collect the heat that is produced by the fuel cells as they generate electricity, and an external heat exchanger is used to release the collected heat. The system improves its efficiency by drawing from the collected heat the amount of heat required to release hydrogen from the hydrogen-absorbing alloy tank and to humidify both the hydrogen and the air.

6. FCEV system

The FCEV system combines the polymer electrolyte membrane fuel cell system described above with an electric vehicle system using both fuel cells and an auxiliary battery as power sources in a parallel configuration. (**Fig. 6**)

The auxiliary battery is included to take advantage of regenerative braking, by which 10 ~ 30% of the energy expended in normal running is recovered and stored in the battery for reuse. This improves efficiency and fuel economy even more.

The concept is that output from the auxiliary battery can be added to the output of the fuel cell during periods of high-load operation, making it possible to design the fuel cell with lower output. Thus a maximum speed of 100 km/h or more can be ensured, as can sufficient acceleration for urban driving, using a fuel cell with 20 kw output.

On the other hand, the fuel cell is designed so that during periods of low-load operation such as cruising, its output can be used to recharge the battery, thus compensating for the energy

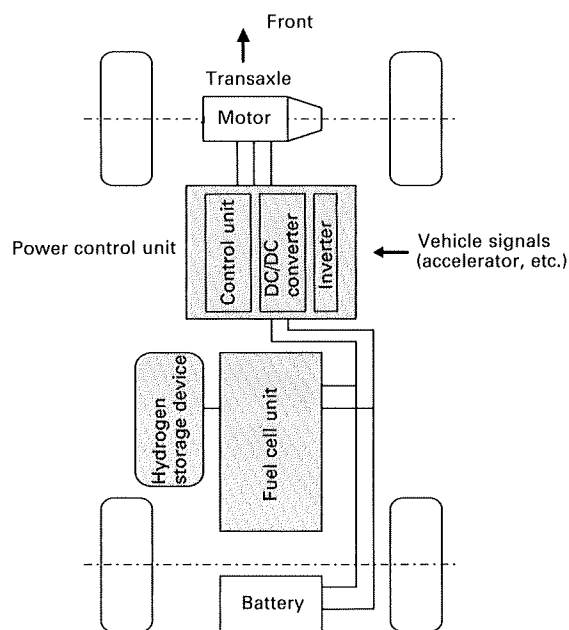


Fig. 6 FCEV System Diagram

consumed during high-load operation.

In addition, Toyota has pushed to make the individual components much smaller, so that the fuel cell, the hydrogen-absorbing alloy tank, and other major parts can all be mounted under the floor of the vehicle. The passenger space and luggage space is no more restricted than in a conventional vehicle. (Fig. 7)

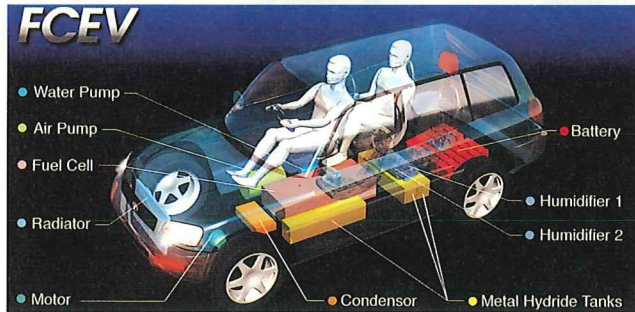


Fig. 7 FCEV Installation Diagram

7. FCEV Specifications

Table 2 shows the main specifications for the FCEV, and Photo. 4 shows its exterior appearance. Power performance is confirmed by a maximum speed in excess of 100 km/h, and although acceleration performance is less than for the current RAV4EV, it has been confirmed that acceleration is sufficient for urban driving.

By using hydrogen from the hydrogen-absorbing alloy tanks

as the fuel, the FCEV achieves zero emissions, and it has been confirmed that the tanks can be refilled quickly, in around 10 to 20 minutes.

It has also been confirmed that by reducing the size of the fuel cell, the hydrogen-absorbing alloy tanks, and other parts, and increasing their performance, it has become possible to install the entire system in a small passenger car.



Photo. 4 FCEV Exterior

8. Conclusion

Through the development of the FCEV, it was verified in terms of power performance, zero emissions, and installability that the fuel cell system has ample potential as a power source for electric vehicles. However, at the present time, it can not be said that the technology has reached the point of transition

Table 2 FCEV Specifications

Vehicle specifications	Base vehicle		RAV4L V	
	Overall length * width * height	(mm)	3,975 * 1,695 * 1,635	
Power performance	Maximum speed	(km/h)	100 minimum	
	Cruising range per hydrogen refill	(km)	250 (target value)	
Drive system			FF	
Drive motor	Type		Permanent magnet synchronous	
	Maximum output	(kw)	45	
	Maximum torque	(Nm)	165	
Fuel cell	Type		Polymer electrolyte membrane	
	Overall length * width * height	(mm)	1,050 * 500 * 230	
	Weight	(kg)	120	
	Rated output	(kw)	20	
Hydrogen storage device	Type		Hydrogen-absorbing alloy	
	Overall length * width * height	(mm)	700 * 450 * 170	
	Hydrogen-absorbing alloy weight	(kg)	Approx. 100	
	Hydrogen storage capacity	(kg)	Approx. 2	

from the research and development stage to the product development stage, and numerous issues must be addressed before it can be commercialized.

Among the issues for the fuel cell itself are to improve its output density (make it smaller and lighter), reduce its cost, confirm its reliability in the on-board environment, and control the moisture levels of the hydrogen gas and air.

The next set of issues concerns the source of fuel. The FCEV described in this paper uses hydrogen from hydrogen-absorbing alloy tanks, but while that has the advantages of zero emissions and high efficiency, the outlook for the establishment of a hydrogen refueling infrastructure is not bright. Therefore, the reforming of hydrogen from hydrocarbon-based fuels is considered the mainstream technology for the time being. The important issues in that case become the choice of fuel and the development of a reformer.

With respect to control, the critical issue is the response of the fuel supply system. Here the key is just how quickly the system can supply gaseous fuel to the fuel cell in response to sudden changes in load. Particularly where reformed gas is used, the control system is more complex, so the building of a compact and responsive control system becomes necessary.

■ Authors



Y. NONOBE



Y. KIMURA

■ References

- (1) The Institute of Electrical Engineers of Japan, Special Survey Committee on Fuel Cell Operability: Fuel Cell Electricity Generation, P. 6, 11. Corona (1994)
- (2) Editorial Committee on Fuel Cell Electricity Generation Systems: Fuel Cell Electricity Generation Systems, P. 11. Ohm (1993)
- (3) Osumi: Hydrogen-Absorbing Alloys, P. 61. Agne Technology Center (1990)
- (4) Editorial Committee on Fuel Cell Electricity Generation Systems: Fuel Cell Electricity Generation Systems, P. 14. Ohm (1993)

CO₂ Reduction Activities in TMC Production Process

Hidehiro Ono*
Wataru Sato*
Tomoki Nakagaki**
Takeo Sakai***

Abstract

Activities to reduce energy consumption have been energetically promoted in Toyota's production processes for more than 25 years for purposes of saving energy and reducing cost. In recent years, the need to preserve the environment by alleviating global warming has increased the importance of CO₂ reduction (energy saving), resulting in further acceleration of activities with self-imposed targets. This paper introduces some examples of recent CO₂ reduction activities and describes the common, company-wide improvement theme of reducing compressed air consumption as an excellent example of steady improvement activities in Toyota plants.

Keywords: energy, CO₂ reduction activities, global warming

1. Introduction

In order to reduce CO₂ emissions, considered a major factor in global warming, as a way to preserve the Earth's environment, Toyota Motor Corporation is actively promoting activities to reduce energy consumption, the main source of CO₂ emissions. This paper describes some of those activities.

2. Background

Concerning the global warming that is said to accompany the emission of CO₂ and other gases, it has been forecast in the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) that one hundred years from now, the average air temperature may have risen by about 2°C and sea levels may have risen approximately fifty centimeters. Because it is feared that these changes would adversely affect terrestrial ecosystems, a rapid worldwide response to the issue is expected.

In December of last year, the Third Conference of Parties of the United Nations Framework Convention on Climate Change (COP3) was held in Kyoto. In response to the global warming problem, the developed nations established CO₂ reduction targets for the year 2000 and beyond. It is thought that these targets will henceforth further accelerate CO₂ reduction activities in these countries and contribute to the expansion of critical activities worldwide.

In Japan, energy consumption has been on a consistently upward trend in recent years due to the recovering economy, the progress of computerization, and changes in lifestyle. These

circumstances make it difficult to attain the CO₂ reduction targets for the year 2000 to which the Japanese government has committed itself in the international arena. In order to exert the maximum effort to make progress in saving energy, the government revised the Law concerning the Rational Use of Energy and announced a stronger policy in February of 1997. It is in the context of these changes that Toyota is seeking to stimulate increased energy conservation efforts in its plants. (Table 1)

Table 1 Main Policies

Industrial divisions	• Implement targets for each plant (Improve energy efficiency at least 1% every year.) • Provide stronger leadership to plants consuming much energy, based on Rational Use of Energy Law.
----------------------	--

3. Toyota's Efforts

3.1 Toyota's Response

Toyota regards its response to environmental problems as a critical issue. In 1992, the company established the Toyota Earth Charter, and in 1993, announced the Toyota Environmental Action Plan, which was updated in 1996. Autonomous efforts are now being expanded to the entire corporation in an effort to achieve more demanding targets.

One activity currently being promoted in the production process in an effort to deal with global warming has set itself the extremely ambitious goal of stabilizing both the total emissions of CO₂ and the emissions per hundred-million yen in sales at their 1990 levels by the end of the year 2000.

* Plant Engineering Div.
** Tahara Plant Administration Div.
*** Motomachi Plant Administration Div.

3.2 Recent Activities

In-house activities have also become more energetic over the years, improving the environmental awareness of individual employees. Countermeasures have been implemented in a planned manner in both technical development and equipment design, and their effects have been steadily accumulating.

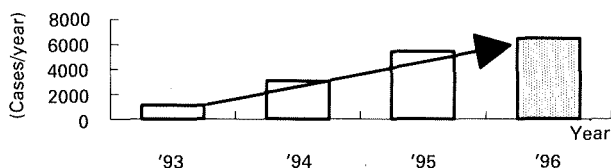


Fig. 1 Results of Energy Conservation Activities

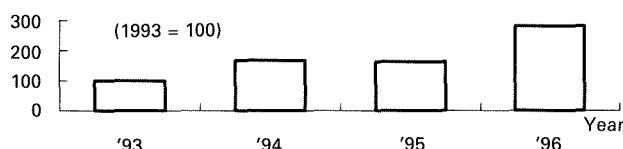


Fig. 2 Investment in Energy Conservation

3.3 Energy Conservation Results

As of 1996, as **Fig. 3** shows, the amount of energy used was below its peak, and the energy use per hundred-million yen in sales was also steadily improving.

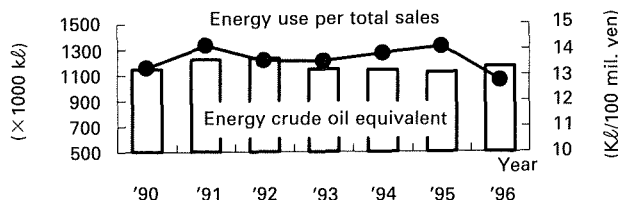


Fig. 3 Energy Use

Table 2 Comparison

	1990	Peak	1996
Energy use	100	108	102
Basic units	100	107	96

4. Examples of Reduced Energy Consumption

At the 1996 National Energy Conservation Conference sponsored by the Energy Conservation Center, Toyota employees made five presentations on energy conservation activities. Two presentations that were particularly well-received concerned efforts to reduce the consumption of compressed air at Toyota

plants.

The plants' main uses for compressed air are for air blowers to remove dust and moisture and for air cylinders and air motors to operate equipment and tools. In almost all cases, the compressed air is generated by compressors, and the electricity consumed in running them accounts for roughly 10% of the company's total electricity consumption. (**Fig. 4**)

This paper describes two examples of energy conservation activities: ① the Tahara Plant's improvements in the generation and delivery of compressed air, and ② the Motomachi Plant's improvements in the equipment that consumes the compressed air.

The activities described below are now being implemented comprehensively at both plants.

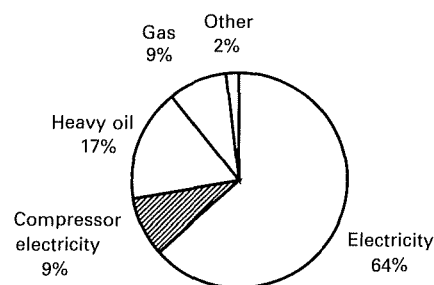


Fig. 4 Energy Use in 1995

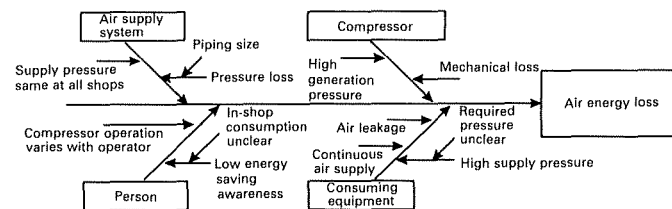


Fig. 5 Factors in Air Energy Loss

4.1 Tahara Plant

Theme: Compressed air energy-saving measures

4.1.1 Content and Effects of Measures

Table 3 Effects of Measures (MWH/year)

	Measure	Action	Effect
1	Reduce consumption during operation	Reduce air leakage	2,830
		Correct supply pressure	1,410
2	Reduce consumption when not in operation	Change Monday morning start time	280
3	Improve compressor efficiency	Lower compressor generation pressure	140
		Control number of compressors	140
4	Other	Reduce consumption in transport	40

4.1.2 Specific Examples

(1) Reduction of air leakage

At the Tahara Plant, the Administration Division measures air leakage and provides the measurement data to the Manufacturing Divisions to support countermeasures, as shown in **Fig. 6**. However, measurements were initially made with the main valve open on the air line to the shop. This meant that the pressure had to be increased every time measurements were made, and the measurement process required considerable time. The system was improved by installing a flow meter to measure air leakage, so that measurements could be conducted simply by switching from the main valve to the measurement valve. This shortened the time required for measurement and yielded more accurate results. The system allows measurements to be made once a month, creating a smooth flow of data to each division, and making it possible to actually see the effects of countermeasures.

Fig. 7 shows the effect of these activities on the amount of air leakage in recent years. In 1996, air leakage on weekdays was down 16%, resulting in an energy savings of 2,830 MWH per year over the 1994 figure.

However, 1996 saw an increase in air leakage over 1995. If air leakage reduction activities are relaxed even for a short time, leakage increases, so in the future these activities will be carried out without any backtracking.

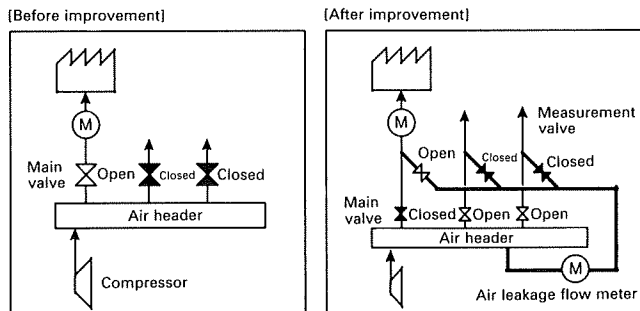


Fig. 6 Improvement of Air Leakage Measurement

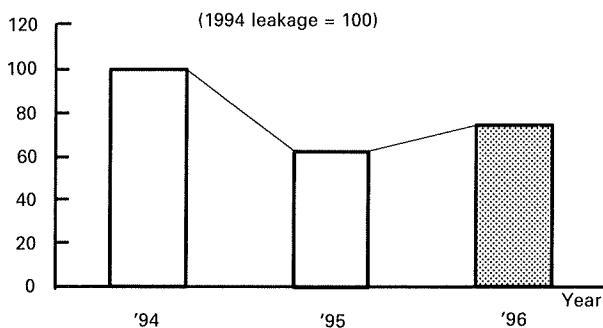


Fig. 7 Air Leakage

(2) Correction of air supply pressure

The air supply pressure at the Tahara Plant is higher than that at other plants, as shown in **Table 4**, due to the Tahara Plant's high level of automation.

Activities were therefore undertaken to bring the pressure down to the level of the other plants.

Table 4 Comparison of Air Supply Pressures (kPa)

	Tahara Plant	Plant A	Plant B	Plant C	Plant D
High-pressure system	833	764	764	786	—
Medium-pressure system	539	539	539	490	490
Low-pressure system	490	490	—	363	392

• Introduction of terminal pressure control

As **Fig. 8** shows, the air supply pressure is constant at the air header. However, while the terminal pressure was controlled in some shops, not all shops did so.

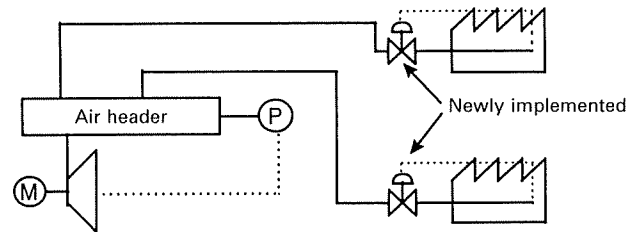


Fig. 8 Air System Diagram

(3) Reduction of compressor generation pressure

It was thought that implementing terminal pressure control in all shops would make it possible to reduce the air supply pressure. This in turn might make it possible to lower the pressure on the generation side, which is to say the compressor, thereby reducing the electricity consumed by the compressor.

The compressors at the Tahara Plant are all turbine models. The relationship of compressor pressure to air flow and shaft power is shown in **Fig. 9**.

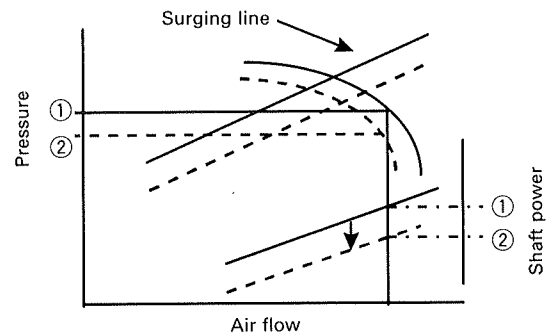


Fig. 9 Compressor Characteristics

It can be seen that if the compressor's generated pressure drops from ① to ②, the shaft power, i.e., the amount of electricity consumed, also drops from ① to ②. The set pressures of the high-pressure and low-pressure systems were therefore lowered as shown in **Table 5**, making it possible to save 990 MWH of energy per year.

Table 5 Compressor Generation Pressure (kPa)

	High-pressure system	Low-pressure system
Before improvement	838	519
After improvement	809	431

(4) Control of the number of compressors

In the past, the starting and stopping of compressors, and the choice of which ones to run, was determined manually by the operators. As shown in **Fig. 10**, this made it difficult to know how many compressors were actually required during periods when the load changed rapidly, such as between shifts.

Also, because frequent starting and stopping of the compressors would adversely affect electrical equipment, more compressors than necessary were being operated. When a compressor exceeds its set pressure, it operates without a load, but even then it consumes about 300 kilowatts of electricity per hour, a considerable waste. Therefore, in conjunction with the updating of the Toyota Energy Control System (TECS), a system to control the number of low-pressure compressors was implemented as a first step. This resulted in an energy savings of 140 MWH per year.

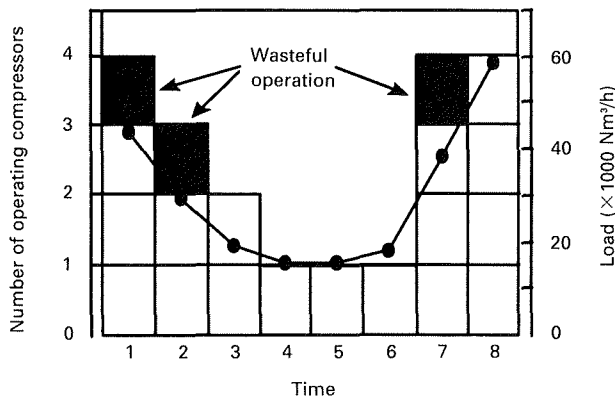


Fig. 10 Compressor Usage

4.2 Motomachi Plant

Theme: Saving energy by making air blowers more efficient

4.2.1 Establishment of Air Blower Theory

Although air blowers are used daily in many locations in the

production process, in many cases they are used instinctively, without a clear theoretical understanding of their specifications, resulting in much wasted energy. Therefore, a first step was to investigate the optimum conditions for air blower operation.

It is the nature of air blowers that the force of the air is proportional to the pressure at the blower outlet. Because it is difficult on the shop floor to control the blower force by measuring the pressure at the nozzle tip, the conventional approach has been to control the source air pressure. The investigation of existing equipment therefore focused on the actual air pressure at the nozzle tip versus the source air pressure. As **Fig. 13** shows, approximately 80% of the equipment showed an air pressure ratio (nozzle pressure/source pressure) below 70%.

Two factors are thought to lie behind the pressure loss described above.

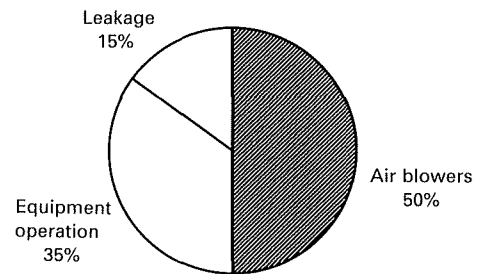


Fig. 11 Compressed Air Usage

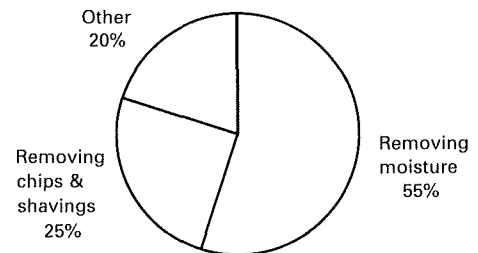


Fig. 12 Air Blower Usage

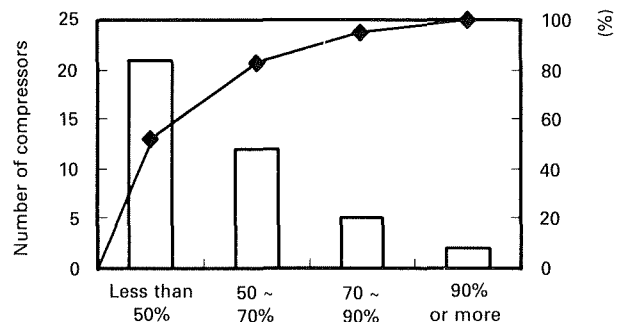


Fig. 13 Comparison of Equipment and Pressure

- ① The effective sectional area of some of the piping used upstream is small.
- ② Because of the large number of nozzles, the total effective

sectional area of the nozzles is greater than that of the piping.

An analysis of the relationship between the nozzles and the upstream piping reveals a relationship between the pressure ratio (P_b/P_a) and the effective sectional area ratio (S_1/S_n), as expressed by the graph in **Fig. 14**.

- P_a : Source pressure
- P_b : Nozzle pressure
- S_1 : Total effective sectional area of piping
- S_n : Total effective sectional area of nozzles

The graph indicates that when the effective sectional area ratio is 1.0 or greater, the pressure ratio exceeds 70%.

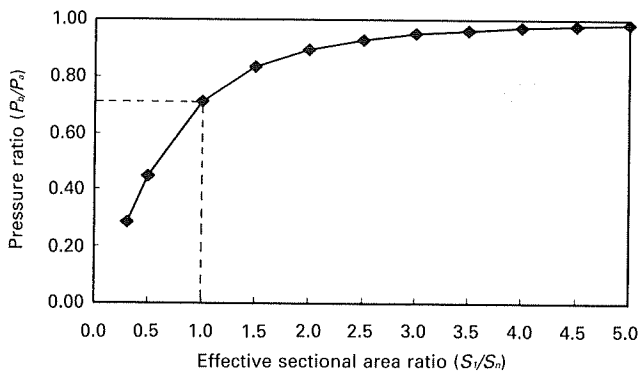


Fig. 14 Effective Sectional Area Ratio and Pressure Ratio

- Verification on model machine

Table 6 Blower Force Comparison with Same Flow (g)

		Effective sectional area ratio (nozzles:piping)			
		1 : 3	1 : 1	1 : 0.5	1 : 0.3
Source pressure	392kPa	175	155	125	70
	294kPa	130	110	80	45
	196kPa	90	70	45	25

Table 7 Flow Comparison with Same Blower Force

		Effective sectional area ratio (nozzles:piping)			
		1 : 3	1 : 1	1 : 0.5	1 : 0.3
With Blower force at 70 g	Flow (NI/min.)	64	77	99	137
	Source pressure (kPa)	147	196	265	392
	Flow ratio (%)	65	78	100	138

Increasing the effective sectional area ratio makes it possible to obtain greater blower force from the same volume of air flow. Also, if the required blower force is constant, increasing the effective sectional area ratio makes it possible to reduce the amount of air consumed, which translates into energy savings.

4.2.2 Drafting of Improvement Measures

The investigation results made it possible to issue guidelines for improvements, mainly in terms of the nozzle diameter (i.e., the effective sectional area). The concept of this improvement is shown by the flow chart in **Fig. 16**.

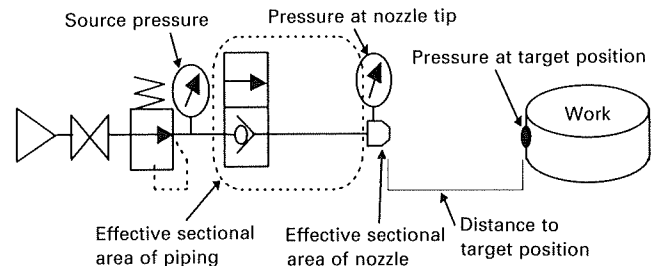


Fig. 15 Diagram of Experiment

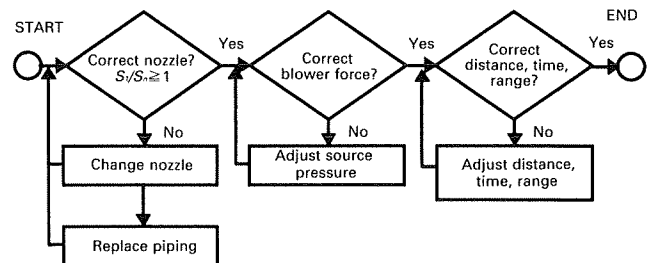


Fig. 16 Flow Chart of Improvement

4.2.3 Example of Improvements

Table 8 shows a representative example of the improvements made, in this case to the moisture-removal air blower for the undercoating hanger in the paint shop.

Measures taken: Attachment of 24 3-mm diameter nozzles
Replacement of collapsed hoses.

Table 8 Before/After Comparison of Improvements

		Before improvement	After improvement
Regulator pressure (at setting)	[kPa]	764	735
Regulator pressure (blower in use)	[kPa]	608	706
Pressure at nozzle tip	[kPa]	304	666
Effective sectional area ratio	—	0.7	3.0
Pressure at target position	[kPa]	5.88	7.84
Distance to target position	[mm]	200	200
Nozzle diameter	[mm]	6.5	3.0
Number of nozzles		24	24
Instantaneous flow	[Nm ³ /h]	1903	839
Rate of reduction	[%]	—	56

4.2.4 Effects

The effects of the measures taken were calculated as shown in **Table 9**. A flow meter was installed at the entrance to the paint shop, and it was confirmed that the actual effects match the calculated values very closely.

(Measured reduction: $1,560 \times 10^3 \text{Nm}^3/\text{year}$)

Table 9 Effects

	Before improvement	After improvement
Blow time per use [sec.]	55	
Blower uses per day	430	
Operating days per year [day/year]	244	
Yearly flow [$\times 10^3 \text{Nm}^3/\text{year}$]	①3040	②1340
Yearly flow reduction (① - ②) [$\times 10^3 \text{Nm}^3/\text{year}$]	1700	

The same sort of measures were implemented for a total of 150 pieces of equipment, bringing the total energy savings to 3,490 MWH per year.

The following secondary effects of these improvements were also noted:

- ① Noise has been reduced when multiple nozzles are in use, because the blower force is more uniform.
- ② Fluctuation in source air pressure has been reduced.

5. Future Efforts

Seeking to be a good corporate citizen, Toyota has sought to achieve its self-imposed energy conservation targets and has steadily expanded its activities to the entire company. The global warming problem will not simply come to an end in the year 2000, but will require long-lasting efforts. For this reason, Toyota intends to promote further energy conservation activities (including new technology development, fuel conversion, etc.), based on the direction of each country's efforts to prevent global warming. Our aim is to make our plants the pride of the world for their low environmental impact.

■ Authors



H. ONO



W. SATO



T. NAKAGAKI



T. SAKAI

An Automatic Offsetting Method of Composite Surfaces

HiroYuki Kawabata*
Yukitaka Fujitani**
Junji Ishida***
Hiromi Morisaki****

Abstract

In the process of modeling the inner surface of resin parts for an automobile, we have usually offset competent surfaces of the outer model and relied on tedious joining operations to guarantee the integrity of the result. Consequently, considerable amount of manpower has been required for this process.

It is well known that conventional methods based on repetitive offset of component surfaces have weakness of causing geometric deviation from neighboring surfaces. We believe that the technique of offsetting a whole composite surface, which consists of geometric surfaces representing the object shape and their topological relationship, is highly effective to overcome the weakness. Our investigation, however, shows that no commercial CAD system using this technique has reached a practically satisfactory level in view of numerical stability.

This report presents our own technique which we have developed to overcome the problem and meet the practical requirements. It includes global modification and recognition of topological changes in the offset composite surface. We believe that it has realized automatic modeling of inner surface for specific parts.

Keywords: *offset, composite surfaces, global modification, calculation of surface intersection, and topological relation*

1. Introduction

Modeling of complicated inner surfaces of resin parts such as a bumper for an automobile has remained unsolved and we had to offset the outer surfaces repetitively surface by surface and underwent tedious joining operations using CAD. Particularly, for resin parts such as bumper, etc., variable offset is an important requirement from the viewpoints of improved strength for the mounting flanges and openings, material cost reduction, improvement of fluidity and so forth. Thus far we failed to have an effective means and have been obliged to concentrate CAD operation man-hours.

Principally speaking, repetitive offset of component surfaces requires excessive manpower for adjusting geometric deviation of surfaces after the offsetting. Consequently, it is thought effective to make an overall offset of an object shape by expressing it with geometric and topological information (relations of connectivity between points, lines and surfaces, hereinafter referred to as the composite surfaces). On the basis of the fundamental studies⁽¹⁾⁽²⁾ on this method, commercial CAD systems have lately begun to materialize this idea. Our investigation shows, however, that these a system has not reached a practical level of application because of the following problems (see

Table 1):

- (1) Variable offset cannot be handled.
- (2) If source surfaces are in continuity of tangent planes (continuity of the first derivatives), crack on the offset surfaces, if any, cannot be avoidable or repaired.
- (3) The technique is not fully capable of handling cases where the topological relation changes before and after the offset.

Problem (1) means the lack of an essential function for the modeling of resin parts and problem (2) is unavoidable as long as error is present in the connection of the source surfaces. Problem (3) occurs when the offset exceeds the radius of curvature or the width of a surface. This is the problem that always accompanies the modeling of resin parts such as bumpers.

This report presents our own overall offset algorithm which we have developed for practical application by overcoming the shortcomings of conventional method, reducing the surface modeling manpower and subsequently realizing the shorter lead time.

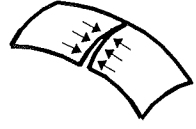
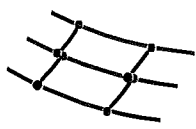
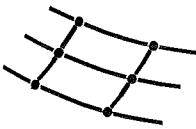
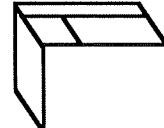
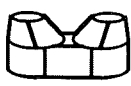
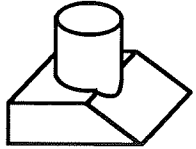
* Information Systems Development Div.

** Machinery Engineering Administration Div.

*** Toyota Soft Engineering, Inc.

**** Intelligent Vision & Image Systems, Inc.

Table 1 Problems of Overall Offset of Composite Surfaces and Countermeasures

#	Problem	Reason	Countermeasure	Actual example	
				Source surface	Offset surface
1	Variable offset cannot be handled.	If the source surfaces are in continuity of tangent planes, cracks are generated on the offset surfaces if error is present in the connection of the surfaces. Calculation of surface intersection is difficult because the surfaces are overlapping even if extended.	Cracks are corrected by making a global modification of the surface.		
2	If source surfaces are in continuity of tangent planes, crack on the offset surfaces, if any, cannot be avoided or repaired.				
3	Cases where the topological relation changes before and after the offsetting cannot be fully handled.	It is difficult to offset the source surfaces which are subtly dislocated preserving their topological relation.	Subtle dislocation can be absorbed by modifying the surface globally.		
		It is difficult to foresee surfaces that become invalid or whose adjacent relation changes as the result of the offsetting.	Virtual image surface (offset exceeds a radius of curvature of the surface) is deleted and the adjacent surfaces are combined.		
			Buried surface (caused by the offset exceeding the width of the surfaces) is deleted and the adjacent surfaces are combined.		
			Reversed surface (the outside and inside of the surface become inverted by the offset) is deleted and the adjacent surfaces are combined.		
			(Algorithm) copes with the separation of intersection point. (Ex. 5-surface intersection point → 3-surface intersection point x 3)		
			(Algorithm) copes with the loop interference. (Ex. Inner loop exceeds the outer loop.)		

2. Problems and Countermeasures

Table 1 indicates the measures taken for solving the shortcomings of the conventional method as found in the commercial CAD systems.

3. Algorithm

Fig. 1 shows the processing flow that incorporates all of the measures indicated in **Table 1**.

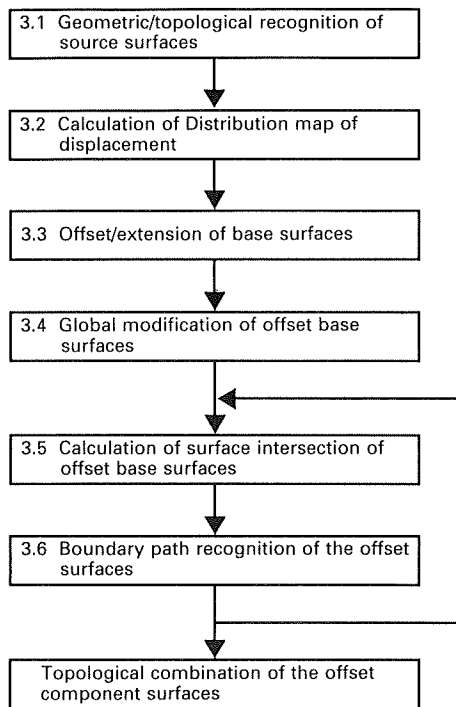


Fig. 1 Processing Flow

3.1 Geometric/Topological Recognition of Source Surfaces

Folding angles of respective component surfaces are detected from the geometric relation of the source surface and the direction of offset to judge whether the surfaces are of convex, concave or AF (Almost Flat) combination. The AF combination refers to a combination of surfaces that can be regarded as being approximately in continuity of tangent planes. An offset base surface is an object global modification. The offset base surface refers to a surface expressed with its geometric information only. A surface expressed with its base surface and its boundary information is called a component (trimmed) surface.

If a surface combination is judged as convex, the length of

extension of the offset base surface is calculated from the folding angle, the offset value and the distance from the component surface boundary to the base surface boundary.

The sequential recognition of the global modification of a surface and the boundary path are made from the topological relation of the source surface.

3.2 Calculation of Distribution Map of Displacement

When a composite surface whose offset varies from d_0 to d_1 is laid out as shown in **Fig. 2**, distances r_0 and r_1 from a vertex **V** of the component source surface to the constant-offset boundary edge of d_0 and to that of d_1 are obtained respectively. Then offset $d_0 + \delta(r)$ of the vertex **OV** is obtained by defining a distribution map of displacement $\delta(r)$ using a cubic polynomial. These offset values of **OVs** of each source surface are averaged to determine its constant-offset value.

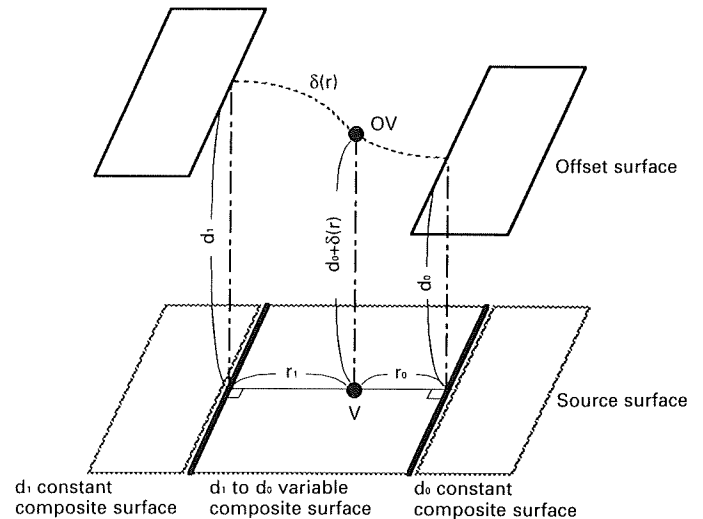


Fig. 2 Variable Layout of the Vertex

3.3 Base Surface Offset/Extension

The base surface is constant-offset and if the result is an virtual image, the offset surface is deleted. Then the offset base surface is extended according to the extension obtained from the preceding item **3.1**.

3.4 Global Modification of Offset Base Surface

An offset surface that corresponds to the AF combination boundary in the source surface as detected in the preceding item **3.1** is globally modified.

Global modification refers to obtaining $OS'(u,v)$ by deforming the offset base surface $OS(u,v)$ as shown in **Fig. 3** through

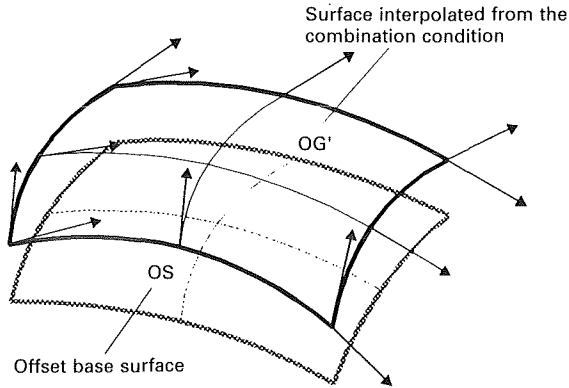


Fig. 3 Constraint Conditions of Global Modification

the following equation which uses the boundary edges and their cross-boundary derivatives of the surfaces to be combined as its constraint conditions:

$$\mathbf{OS}'(u,v) = \mathbf{OS}(u,v) + (\mathbf{OG}'(u,v) - \mathbf{OG}(u,v))$$

Where:

$\mathbf{OG}(u,v)$ and $\mathbf{OG}'(u,v)$ represent the Gordon surfaces interpolated from only the boundary edges and their cross derivatives of $\mathbf{OS}(u,v)$ and those of $\mathbf{OS}'(u,v)$ respectively.

The global modification is applied to correct cracks and misalignment between the constant/variable offset surfaces. However, once combined surfaces become cracked again as become cracked as shown in **Fig. 4(a)** unless the global modification is made in an appropriate sequence. To prevent this, a deformation sequence has to be established in advance so that a condition that the surfaces to be combined never be deformed again may be satisfied as illustrated in **Fig. 4(b)**. This is the meaning of the recognition of the sequence of a global modification.

3.5 Calculation of Surface Intersection of Offset Base Surface

An AF combination boundary edge is formed through the processing described in the preceding item **3.4**. In the case of an offset surface where a mixture of AF combination and convex/concave combination is present, it occurs that the surface intersection cannot be obtained from a generally used calculation of surface intersection or, even if the edge is obtained, it has subtle dislocation from the AF boundary edge, which may fail the boundary loop of a component surface from being closed. This is because the AF combination portion is in the overlapping state and the calculation of surface intersection becomes unstable in the vicinity of this singular point.

This problem is solved by a pincer movement calculation of surface intersection. This method obtains a component point **OP** on the intersection of the offset surfaces of $\mathbf{OS}_0$ and $\mathbf{OS}_1$ from the surface normals $\mathbf{N}_0$ and $\mathbf{N}_1$ at a component point **P** on the intersection of the source surfaces of $\mathbf{S}_0$ and $\mathbf{S}_1$ shown in **Fig. 5** applying a pincer movement calculation iteratively. This is a robust calculation method of surface intersection proper to the offsetting.

3.6 Boundary Path Recognition of the Offset Surfaces

Topological relation of the AF combined section of the offset surface remains basically unchanged from the source surface (with minor dislocation being absorbed, however). Conversely, topological relation of the convex/concave combinations change and it is difficult for us to foresee the topological relation after the change.

In the first place, a primary loop is formed on the own sur-

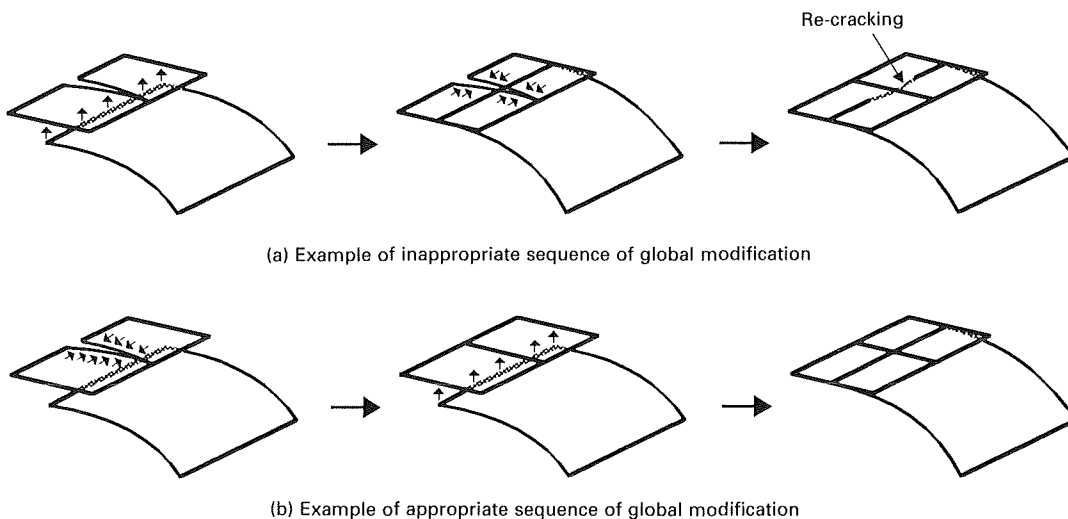


Fig. 4 Difference in the State of Combination by the Sequence of Global Modification

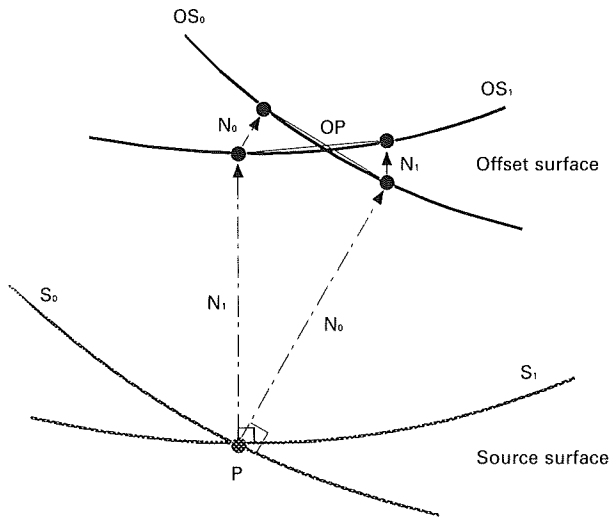


Fig. 5 Caliper Calculation Method of Surface Intersection

face (offset base surface **Fig. 6(c)(d)**) by sequentially calculating the intersection points of the intersection curves between the own surface and its adjacent offset surfaces according to the sequence of the component surface boundary path (**Fig. 6(b)**) as recognized in the preceding item 3.1. Now, if the adjacent surface is either a virtual image surface or reversed surface, it is already deleted. So the intersection with further adjacent surface is obtained and added to the primary boundary loop. If the intersection fails to be obtained notwithstanding the presence of the adjacent surface or if the intersection point of the surface intersections fails to be obtained, the surface intersection with further adjacent surface and its addition to the primary boundary loop are done likewise. Surfaces where the primary boundary loop is not closed should be deleted as the buried surfaces.

Next, detect the intersection on the primary boundary loop of the own surface and separate the loops (**Fig. 6(e)**). As the result, leave those loops having identical direction to the boundary loop of the source surface as the secondary boundary loops and delete all other loops in reverse direction (**Fig. 6(f)**). The secondary boundary loops become the component surface boundary loops of the own surface. Here, delete the surface where all the loops are in reverse direction as a reverse surface.

4. Application Results

Photo. 1 shows the result of application of this algorithm to the front bumper. It shows that the offset surfaces vary smoothly without being cracked under the global modification. Moreover, as much as 71% of the offset surfaces to the source

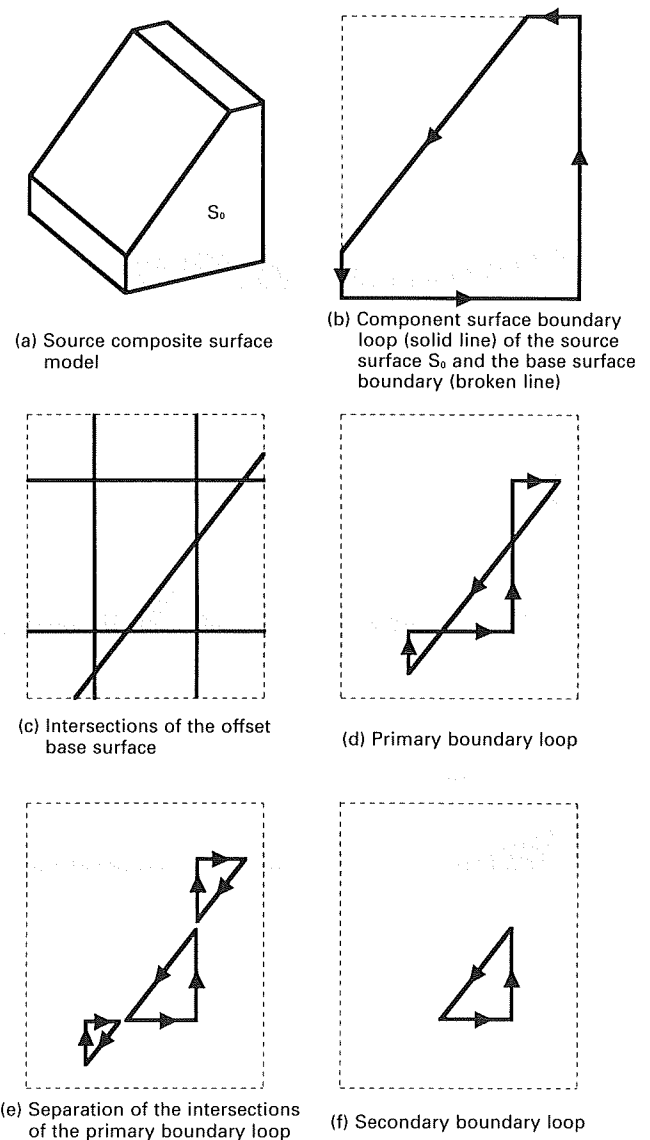


Fig. 6 Recognition Process of Boundary Path

surfaces underwent topological changes, where the boundary path recognition detects the topological change correctly, enabling overall offset of a composite surface.

Fig. 7 shows that the allocated manpower is by far reduced compared to the conventional case. In the present stage, however, approximately 6% of surfaces to the number of source surfaces fail to be formed. Therefore it is necessary to include the manpower for repairing the failed sections.

Principal causes for the failure are as follows:

- (1) Source surfaces are cracked.
- (2) Fine-detailed source surfaces cannot be offset.

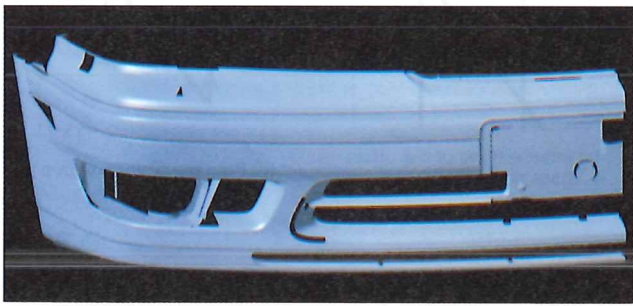
All of those source surfaces are the component surfaces of some complex sections and these problems cannot be taken merely as the accuracy problems of the source surfaces. In

other words, it must be taken up as the problem of the composite surface application technology in the future.

We have reviewed the commercial CAD systems but none of them could make an overall offset of the bumper surfaces successfully.



(a) Surface shape (design surface)



(b) Rear surface shape (overall offset of composite surface)
3.0 to 3.3 mm variable offset

Photo. 1 Application Result to the Front Bumper

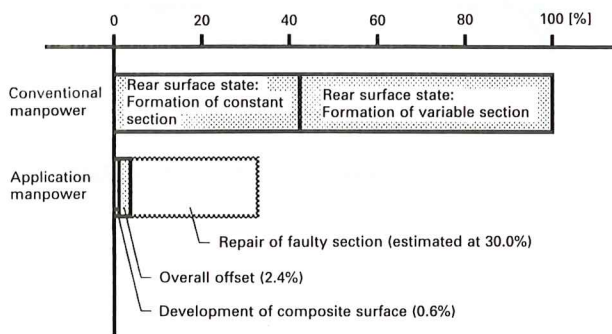


Fig. 7 Comparison of Modeling Manpower for Front Bumper

5. Conclusions

We have devised an overall offset algorithm of composite surfaces and started applying it for practical use. We are confident that the algorithm contributes much to the reduction of the surface modeling man-hours and the lead time, which were the initial target for our studies.

We will be grappling with the following problems in the future:

- (1) Application of global modification technology to the suturing of cracks in the composite surface.
(Partial repair needed for the cracks of the source composite surface model or the cracks due to design modification)
- (2) Improved quality of variable offset surface.
(Elimination of waving in the surface or foldings between surfaces)

The authors wish to thank members of Toyota Soft Engineering, Inc. and IVIS, Inc. for the efforts given in installing the present algorithm for actual application.

■ References

- (1) R. Farouki: Exact offset procedures for simple solids. *Computer Aided Geometric Design*, Vol. 2, No. 4, P.257-279 (1985)
- (2) J. Rossignac, A. Requicha: Offsetting operations in solid modeling. *Computer Aided Geometric Design*, Vol. 3, No. 2, P.129-148 (1986)

■ Authors



H. KAWABATA



Y. FUJITANI



J. ISHIDA



H. MORISAKI

Development of TOYOTA New BEAMS 1UZ-FE Engine

Kenji Watanabe*
Tetsuji Asahi*
Minoru Iwamuro*
Kunihiko Satou*
Tsutomu Hiyoshi**
Shigeo Kikori**

Abstract

The 4-liter, V-type, 8-cylinder engine installed on the new CELSIOR and CROWN released in July 1997 is an improved version of the renowned 1UZ-FE engine mounted on high luxury vehicles. Many new features including Intelligent Variable Valve Timing (VVT-i) system, slant squish combustion chamber, Acoustic Controlled Induction System (ACIS), air-assisted fuel injector, Intelligent Electronic Throttle Control System (ETCS-i) were adopted. Through these features this new 1UZ-FE has achieved overwhelming acceleration and smoothness, and yet highest level of fuel consumption and quietness among the same displacement engines. This paper reports on the newly developed 1UZ-FE engine.

Keywords: V-type, 8-cylinder engine, VVT-i, slant squish combustion chamber, ACIS, air-assisted fuel injector, Electronic Throttle Control System

1. Introduction

In recent years, grappling with the prevention of global warming through energy-saving and the reduction of CO₂ emission has become one of the most important social challenges as part of global environmental measure. Improved fuel economy is related to this challenge on the part of vehicles.

At TOYOTA, we are grappled with various environmental protection activities under the general name of "Eco-Project." On the other hand, achieving smooth acceleration and quietness appropriate for luxury vehicles is the universal theme for the development of engines from the viewpoint of user needs. To meet these requirements, we have sharply improved the basic performance of 1UZ-FE engine renowned for its high total performance by giving major improvement to almost every component including Intelligent Variable Valve Timing (VVT-i) system, slant squish combustion chamber, Acoustic Controlled Induction System (ACIS), Intelligent Electronic Throttle Control System (ETCS-i) and many other latest technologies. By installing this new engine on the new CELSIOR and CROWN, we have achieved the highest level of fuel consumption among the same displacement engines, simultaneously achieving the driving performance and quietness appropriate for the luxury vehicles. This paper reports on the details of improvements and the outline of major technologies adopted to this engine.

2. Selection of Displacement

The world's mainstream of displacement for a V-type, 8-cylinder engine installed on a luxury vehicle is 4.0 to 4.5 liter, and it tends to be expanded. This but indicates certain manufacturers' intention to achieve a greater output performance requirement with an expanded engine displacement. On the contrary, this leads to the deterioration of fuel economy due to an increased friction loss. Upon making the present improvement of the new 1UZ-FE engine, the main objective is placed on the improved fuel consumption while keeping the engine displacement at the low limit among the competitive vehicles. Our concept is based on achieving torque improvement for realizing the driving with ample allowance for power through a drastic improvement of basic performance.

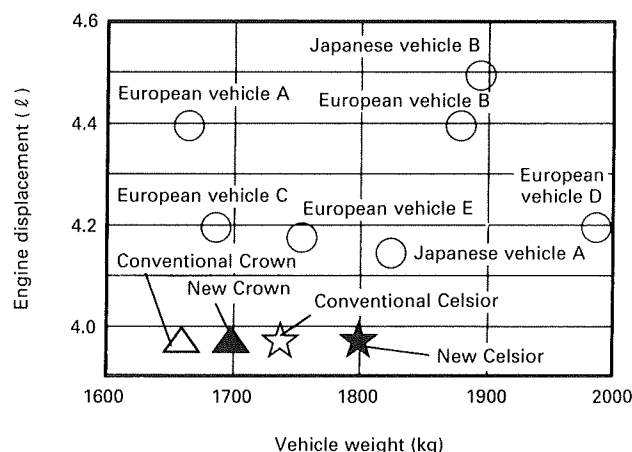


Fig. 1 Vehicle Weight and Engine Displacement among Competitive Vehicles

*Power Train Engineering Div. I

**Engine Engineering Div. I

3. Design Concept

The present development is based on the following three major points:

(1) Leading low fuel consumption

To realize an epoch-making low fuel consumption top among the same class engines with a maximum consideration given to the environment protection and fuel economy.

(2) Power with allowance and smooth acceleration

To realize power of overwhelming margin and the smooth acceleration that are becoming to a luxury car.

(3) Maintenance of the world's highest level of quietness

To realize the highest level of quietness already on the world level along with (1) and (2) above.

4. Principal Specifications and Engine Performance

Table 1 outlines the principal specifications, **Fig. 2** shows the engine performance curves and **Fig. 3** the engine section.

Table 1 Principal Specifications of the Engine

	New type	Conventional type
Arrangement, cylinder number	V-type (90° bank), 8 cylinders	←
Valve train	DOHC 4-valve, belt and gear drive	←
Displacement (cc)	3968	←
Bore×stroke (mm)	87.5×82.5	←
Compression ratio	10.5	10.4
Variable system	VVT-i, ACIS	None
Maximum power (PS (kW) /rpm)	280 (206) /6000	265 (195) /5400
Maximum torque (kgfm (Nm) /rpm)	41 (402) /4000	37 (363) /4800
Full-load minimum fuel consumption rate (g/PS (kW) h/rpm)	190 (258) /2400	190 (258) /2600
Fuel system	EFI	←
Fuel	Unleaded premium	←

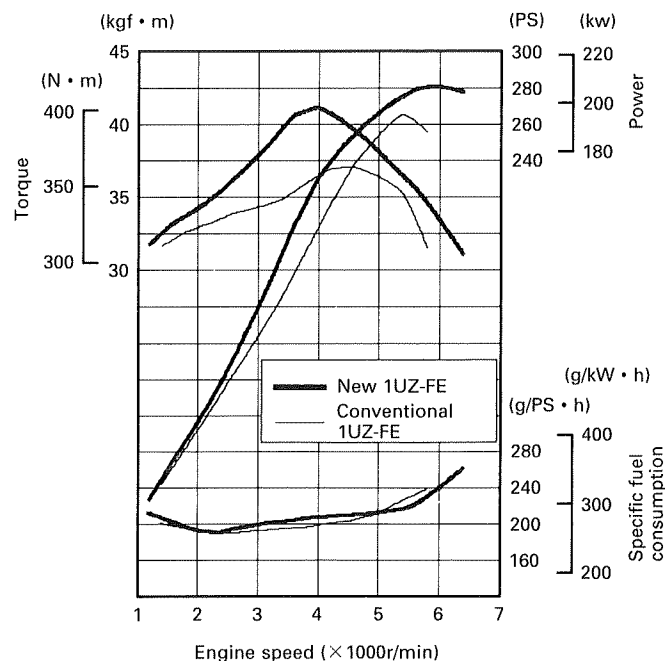


Fig. 2 Performance Curves

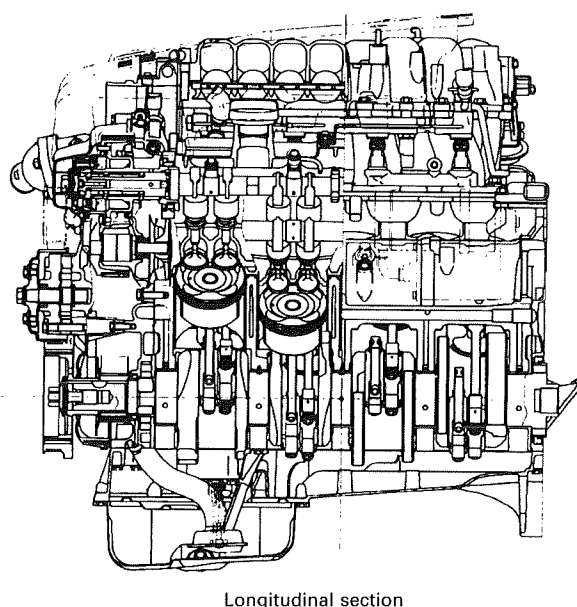
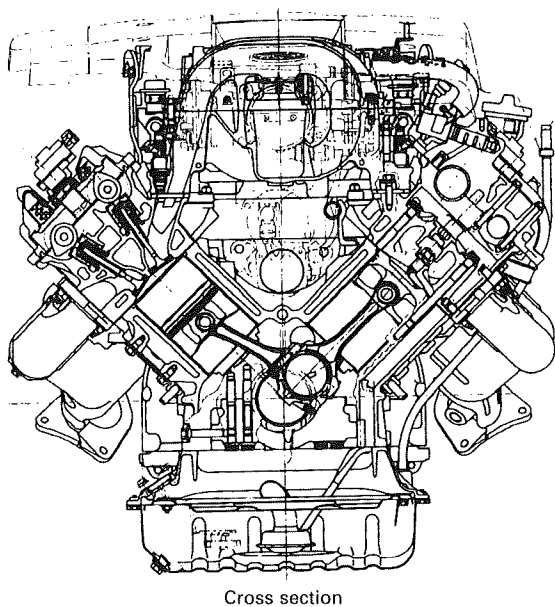


Fig. 3 New 1UZ-FE Engine Section

5. Technical Features

5.1 Leading Low Fuel Consumption

5.1.1 Adoption of VVT-i

We have adopted VVT-i which has been already adopted to the in-line 6-cylinder engine series to win high popularity. For the new 1UZ-FE, a VVT-i controller is newly developed. **Fig. 4** shows its construction. This controller is used to vary the phase of intake camshaft in a combination of the intake camshaft drive with the timing belt and the exhaust camshaft drive using the scissors gear. This enables to set optimal valve overlap in response to the engine operating condition. It can reduce pumping loss by easing depression at engine manifold with an increased internal exhaust gas recirculation (EGR) under partial load. At the same time, this controller raises combustion efficiency to the better fuel economy by an early closing of the intake valve that raises the actual compression ratio. During the idling of engine, combustion is stabilized with reduced internal EGR by eliminating the valve overlap, and the set idle speed is lowered to improve the idling fuel economy.

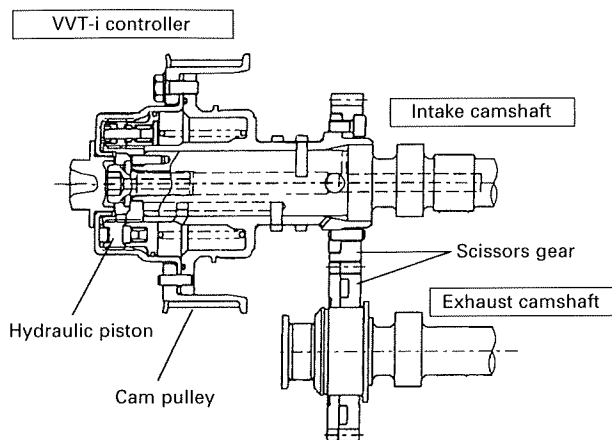


Fig. 4 VVT-i Pulley Structure

5.1.2 Adoption of Slant Squish Combustion Chamber

The combustion chamber shape has been changed as shown in **Fig. 5** to improve S/V ratio from 3.46 to 3.20. Moreover the slant squish combustion chamber as first installed in the world to a V-type, 12-cylinder 1GZ-FE engine is adopted to have strong squish flow generated close to the bore wall surface for stable combustion and improved anti-knock performance. These have improved fuel economy with the development of low idling and higher compression ratio.

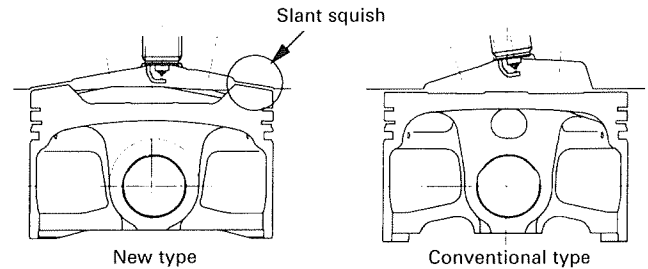


Fig. 5 Combustion Chamber Shape

5.1.3 Adoption of Air-assisted Type Fuel Injector

We have adopted an air-assisted type fuel injector to use negative pressure generated in the inlet port as the auxiliary air for realizing a high atomization of injected fuel to the inlet port. We have developed a new shape of adapter at the end of the injector which determines a high atomization of the fuel (**Fig. 6**). This has succeeded in making finer atomization by reducing the spray mean diameter (SMD) during idling from approximately 240 μm of a conventional type to approximately 40 μm . It particularly reduces fuel deposit on the wall surface during cold operation to improve the fuel economy.

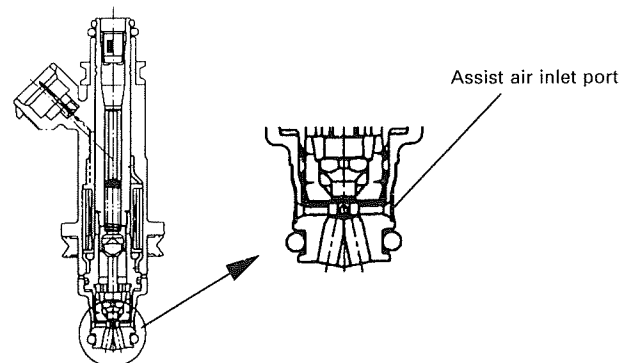


Fig. 6 Structural Drawing of Air-assisted Type Fuel Injector

5.1.4 Adoption of Barrel-type Valve Lifter

As shown in **Fig. 7**, crowning process is provided on the side of the valve lifter to develop a barrel-shaped contour. This is intended for easing impact between the cylinder head and improving lubricating performance to better fuel economy through friction reduction. This barrel-type valve lifter is also effective in reducing noises from the valve system.

Table 2 outlines a number of the latest technologies adopted for the development including the afore-mentioned low-fuel consumption design. Those technologies contribute to the development of low friction of course and the low idling and im-

proved combustion, subsequently realizing the leading low fuel consumption, top among the classes of the same engine displacement in the world as Fig. 8 shows.

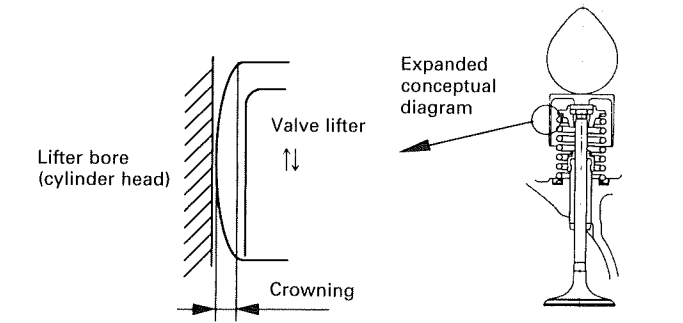


Fig. 7 Barrel-type Valve Lifter

Table 2 Low Fuel Consumption Technologies Adopted on the New 1UZ-FE

Technology	Objective
VVT-i	- Improved idling stability → Lower idle speed - Pumping loss reduction during partially loaded drive
Slant squish combustion chamber	- Improved idling stability → Lower idle speed - Improved anti-knock performance (combustion) → Higher compression ratio
Higher compression ratio	Improved combustion
Metal cylinder head gasket	Bore deformation reduction → Reduced friction
Resin-coated pistons	Reduced friction
Barrel-type valve lifter	Reduced friction
Oil pump without spigot joint	Reduced friction
Air-assisted furl injector	Finer atomization of injected fuel → Reduced fuel deposit on wall surface
Ignition plug with iridium electrode	Improved idling stability → Lower idle speed

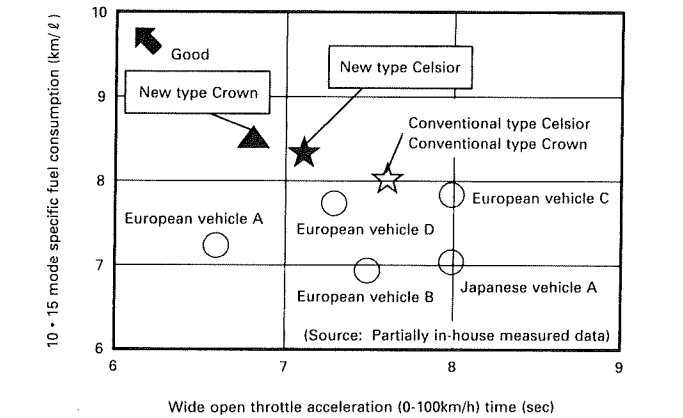


Fig. 8 Comparison of Vehicle Performance (Power Performance and Fuel Economy)

5.2 Power with Ample Allowance and Smooth Acceleration

5.2.1 Sharply Improved Torque

(1) Adoption of VVT-i

During high load, the valve timing is continually controlled to attain a maximum torque in response to the engine speed. During low speed, the VVT-i controller timing is advanced to set the intake valve close timing to the vicinity of the bottom dead center. The close timing can be delayed during high revolution to attain an intake pulsation effect for an improved power.

(2) Adoption of ACIS

We have adopted Acoustic Controlled Induction System that opens/closes 8 intake air control valves provided in the intake manifold in response to the engine speed and load. During the low to medium speed revolution, the system closes the intake air control valves as shown in Fig. 9 and takes in the air from opening A. Then the length of intake pipe will be approximately 600 mm. The intake pulsation effect improves the inlet efficiency to the low to medium speed range with subsequent torque improvement. During high speed, the intake air control valves open, mainly taking the air in through opening B. Then the intake pipe length actually becomes shorter to approximately 350 mm to improve the torque in the high speed range. Both openings A and B are designed in funnel shape to reduce the intake air resistance.

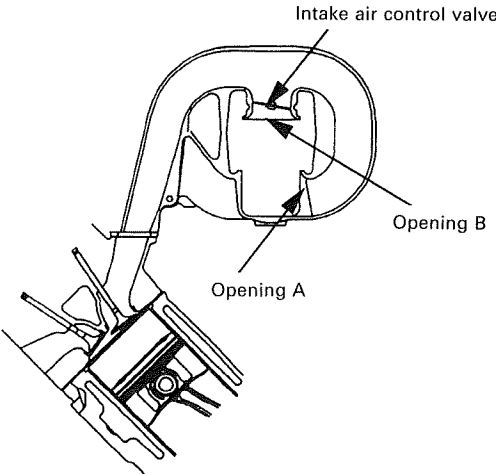


Fig. 9 Structural Drawing of ACIS

(3) Adoption of slant squish combustion chamber

This chamber increases the amount of intake air and improves torque because the opening becomes wider when the intake and exhaust valves are open, in addition to the development of high compression ratio attained from the aforementioned anti-knock performance.

(4) Improvement of intake system

As shown in **Fig. 10**, the throttle body mount position is changed to the front of the engine from the side, simultaneously optimizing the shape of various section. This has reduced the intake air resistance between the air cleaner inlet and the throttle body and improved the torque.

In addition, the following improvements have suppressed the intake air temperature from rising and prevented the drop of intake air density, that is the deterioration of the engine power:

- ① Change of the throttle body mount position to the front of the engine has made it less susceptible to the effect of the heat from the exhaust manifold.
- ② Adoption of the intake manifold heat insulator gasket
- ③ Adoption of the throttle body hot water control valve

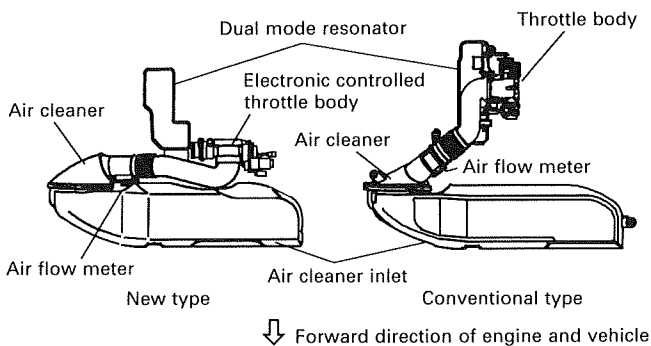


Fig. 10 Intake Layout Drawing

We have attained a net mean effective pressure (in proportion to the torque per displacement), the top for the class as shown in **Fig. 11** by incorporating various technologies outlined in **Table 3**. As the result of subsequent improvement of

the torque, a sharp development of high gear has become possible as a vehicle (differential ratio: 3.916 to 3.266) and the fuel economy has also improved.

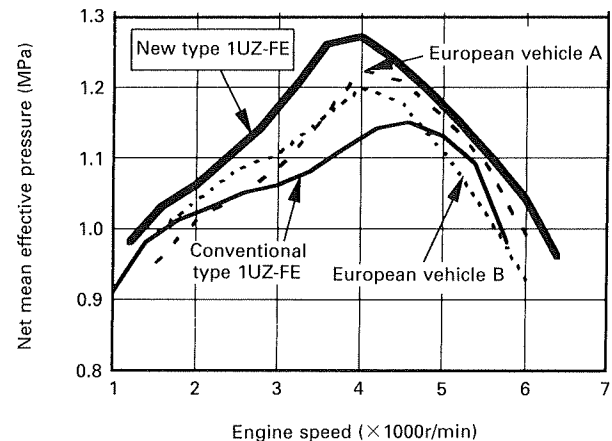


Fig. 11 Comparison of Net Mean Effective Pressure with Other Vehicles of Competition

5.2.2 Realization of Comfortable Drivability

We have adopted Electronic Throttle Control System-intelligent (ETCS-i) with the objectives of the ease of driving, improved comfort, and the vehicle stability proportional to improved torque. In the ETCS-i, electronic parts (such as CPU, sensors and power supply) are provided in redundancy to establish a high level of reliability with structure that allows driving if any of these parts should fail. (**Fig. 12**)

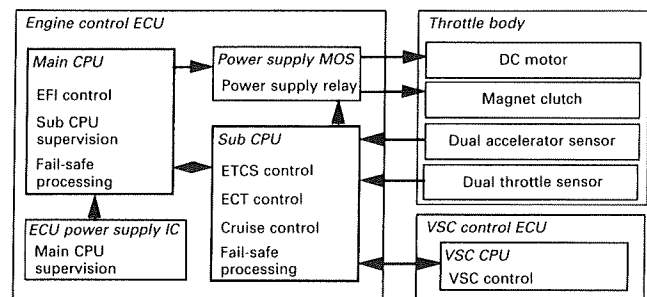


Fig. 12 System Configuration

(1) Throttle body (**Fig. 13**)

- ① A single-valve type is adopted for controllability in all of the driving ranges.
- ② DC motor has been adopted for the responsiveness and better efficiency.

Table 3 Torque Improvement Technologies Adopted to the New 1UZ-FE

Technology adopted	Objective
VVT-i	· Increased air intake
Slant squish combustion chamber	· Improved combustion · Increased air intake
High compression ratio	· Improved combustion
Vertical type intake port	· Increased air intake
Extended valve diameter and reduced shaft diameter	· Increased air intake
Inner shim	· Increased valve lift → Increased air intake
Front air intake & reduced intake air resistance	· Increased air intake
ACIS	· Increased air intake
Heat insulator gasket	· Suppression of intake air temperature rise → Suppression of drop of output
Hot water control valve	· Suppression of intake air temperature rise → Suppression of drop of output

- ③ A structure is adopted to ensure the driving under an abnormal condition by operating the emergency drive lever.

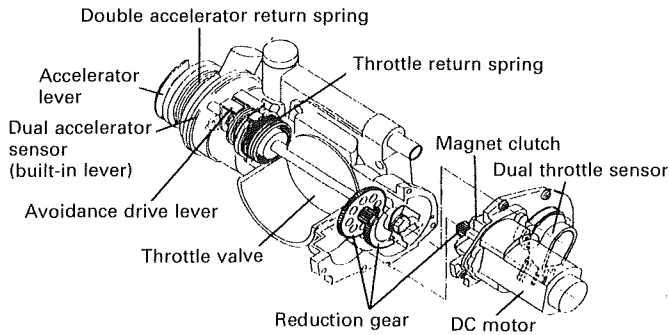


Fig. 13 Structural Drawing of the Throttle Body

- (2) Integrated control of the power train system (EFI, ECT, ETCS)

Overwhelming acceleration and smooth driving have been realized by establishing coordination with EFI and ECT and controlling the throttle valve so as to attain an optimal drive force that meets all types of driving condition on the basis of the reflection of driver's accelerator pedal operation.

- (3) Vehicle stability

- ① Snow mode control (**Fig. 14**)

Throttle valve reaction to the accelerator pedal operation is changed from normal mode. Better accelerator controllability on a slippery road is realized to better avoid the tires from slipping.

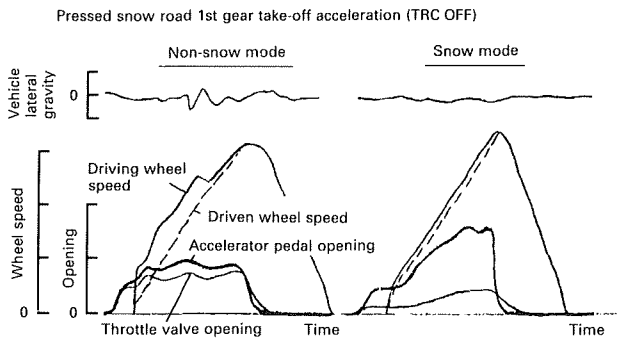


Fig. 14 Effect of Snow Mode Control

- ② Coordinated Control with VSC

Engine power is fine-controlled in coordination with the VSC system to realize the better vehicle stability.

5.3 Maintenance of the Top Level Quietness in the World

5.3.1 Reduction of Power Plant Vibration

To realize both the increased power and quietness for the new vehicle, a weak point of twisted structure is improved by analyzing the vibration mode of the power plant (**Fig. 15**). Accordingly, we have realized a power plant of high rigidity having a high weight efficiency. The improved aluminum oil pan (**Fig. 16**) is an example of high rigidity.

Fig. 17 shows a comparison of the engine mount vibration level.

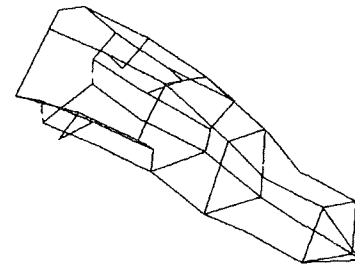


Fig. 15 Power Plant Vibration Mode

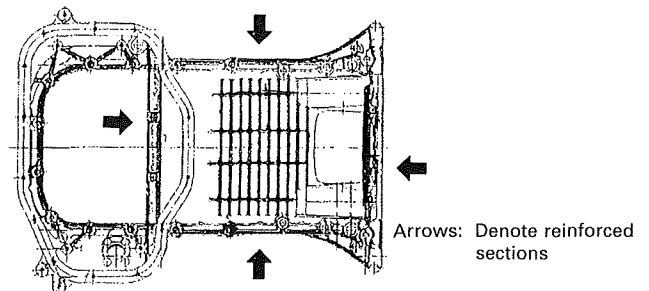


Fig. 16 High Rigidity Oil Pan Contour

5.3.2 Thorough Elimination of Noises

It is necessary to pay attention to low-level noise as the engine noise becomes lower. Thorough noise detection is made for the engine of the highest class and various measures are taken as outlined by Table 4 to provide the high class vehicle with quality appropriate to it.

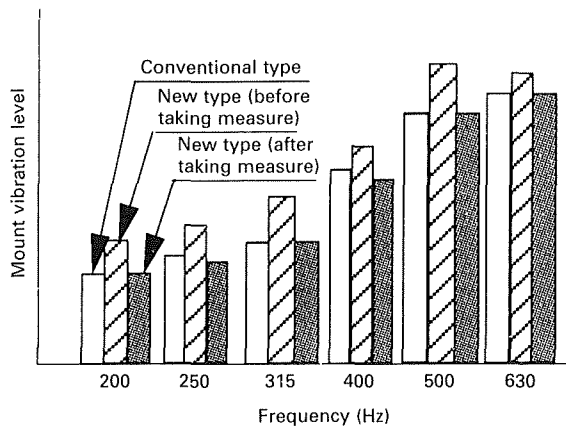


Fig. 17 Comparison of the Mount Vibration Level

Table 4 Noise Reduction Measures

Item	Reduction method
Cam bearing hammering	- Aluminum timing belt cover - Selective matching of cam cap
Valve system noise	- Optimization of cam profile - Barrel-type valve lifter - Increased surface rigidity of cylinder head
Fuel system noise	- Increased rigidity of delivery pipe - Improved acoustic absorption performance of large designed cover

6. Conclusion

We have reported on the outline of BEAMS 1UZ-FE engine installed on new CELSIOR and CROWN.

We believe that we have succeeded in presenting an answer for the engine mounted on high luxury vehicles. We have achieved overwhelming power allowance, smooth acceleration and appropriate quietness while giving full consideration to preventing the global warming through resource-saving and CO₂ emission reduction. We are confident that the result of our development will meet the full satisfaction of the customers.

Before closing, we wish to express their appreciation to individuals within and without this company for valuable assistance in developing and manufacturing this engine.

References

- (1) H. Kawamura, Nakakubo, Asahi, Endou, Kawai, Okumura: Development of New 1GZ-FE Engine, TOYOTA Technical Review, Vol.47, No.1, P.10-17 (1997)
- (2) Yoshito Moriya, Saitou, Kawatake, Yoshioka: VVT-i System, TOYOTA Technical Review, Vol.47, No.1, P.48-53 (1997)

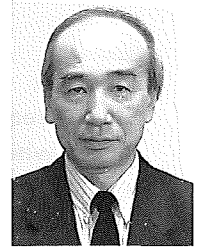
Authors



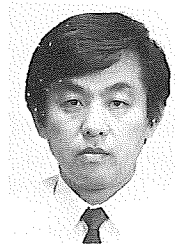
K. WATANABE



T. ASAHI



M. IWAMURO



K. SATOU



T. HIYOSHI



S. KIKORI

A Development of Easy-Column Shift

Yoshitaka Sato*
Harumi Minoshima*
Minoru Makiguchi**

Abstract

By the recent trends of MPV (Multi-Purpose Vehicle) increase and AT (Automatic Transmission) increase, vehicles which have mounted column AT shift levers are increasing as transmission operation. To be more familiar with column AT shift levers for passenger car users on the development of Town-Ace Noah and Lite-Ace Noah, we have developed Easy-Column Shift which can be operated as passenger car feeling.

Keywords: shift lever, operability, MPV, AT, weight reduction, cost

1. Introduction

In recent years, the ratio of AT (Automatic Transmission) vehicles is increasing. Particularly, the vehicles that adopt the column type AT shift lever are increasing among the so-called RV (Recreational Vehicle) and MPV (Multi-Purpose Vehicle).

The reason for this trend is that since the column type AT shift lever is installed to the front seat steering column different from the normal floor AT shift lever, more room space is available for the ease of walk-through. Moreover, with the expanding markets for MPV and RV, production of the column AT shift lever itself is rapidly increasing (Fig. 1). On the other hand, the expansion of the MPV and RV market is supported by those users who have switched from the passenger vehicles. Generally speaking, passenger cars are mainly installed with the floor type AT shift levers. Therefore, passenger car users are not familiar with the column AT shift lever. In this connection, it has been urgently required to develop a column type AT shift lever that can be easily handled by the passenger car users (Fig. 2).

In the development of Town-Ace Noah and Lite-Ace Noah, one of the important items of the vehicle concept is to "appeal on the driving feeling as if a passenger car" along which our development has been promoted. This paper reports on Easy-Column Shift that we have developed under the above concept.

2. Outline of Column AT Shift (Fig. 3)

Column AT shift lever refers to a shift lever installed on to the steering column for the ease of so-called walk-through (a function to allow a passenger to access to the rear seat through the front driver's and passenger's seats) developed along with the expansion of room space in a vehicle. The shift lever on the steering column is connected to the lever on the AT via a push-pull cable (or link) to shift the transmission appropriately

to each position (P, R, N, D, 2, L).

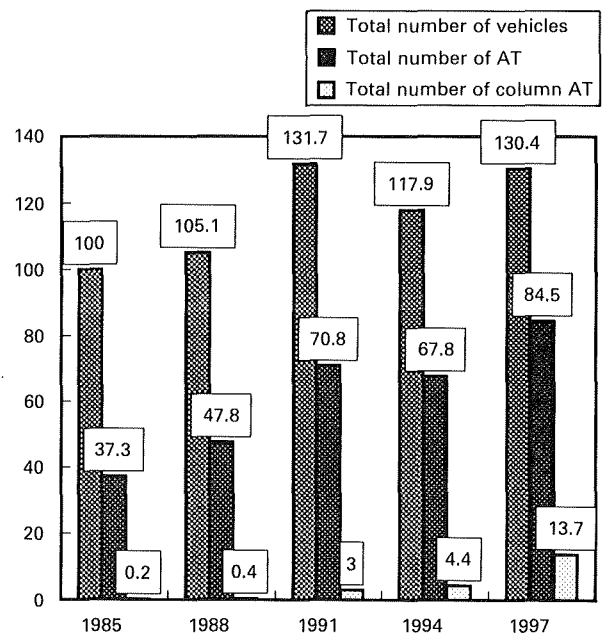


Fig. 1 Comparison of Total Production, Total Number of AT Vehicle, and Total Number of Column AT Vehicle for Each Year with the Total Toyota Vehicle Production for '85

2.1 Operating Direction of Conventional Type Column AT Shift

It is general for a conventional type column AT shift lever to be operated in the direction of the circumference of the steering wheel for shifting and in the direction toward the driver for selection (Fig. 4). (One lever is operated in two different directions.)

* Chassis Engineering Div. III

** Vehicle Evaluation & Engineering Div. III

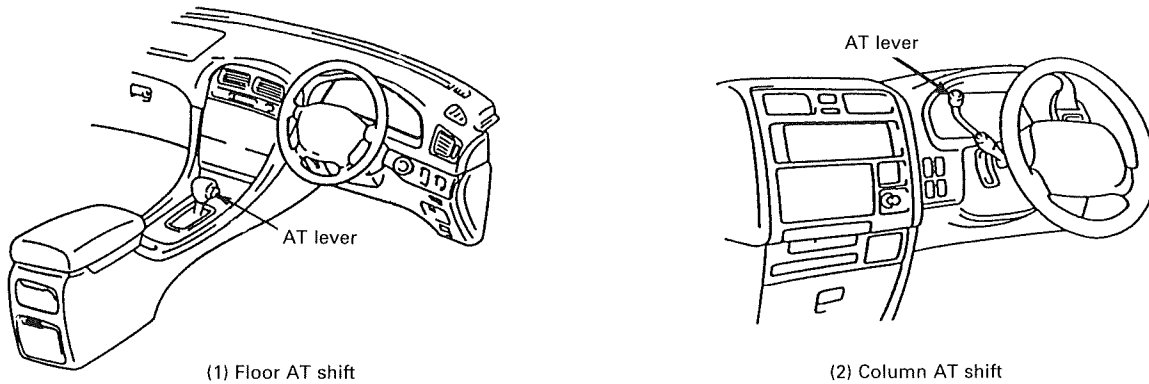


Fig. 2 AT Shift Types

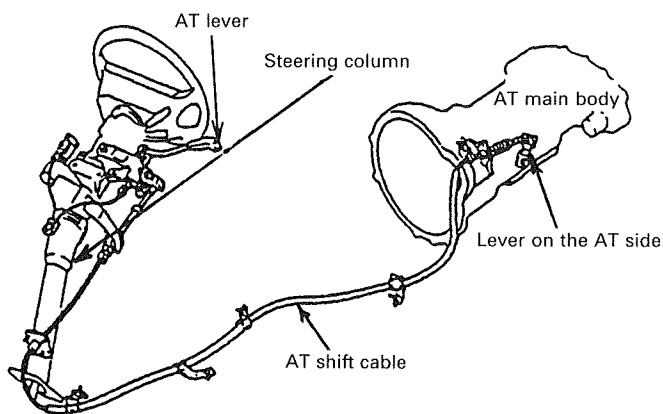


Fig. 3 Outline of Column AT Shift

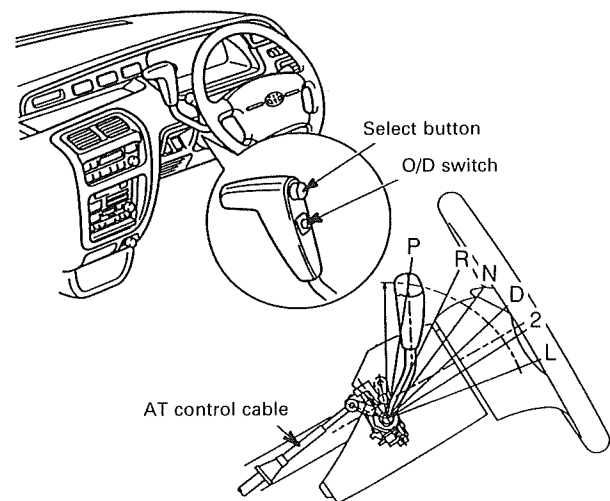


Fig. 5 Easy-Column Shift

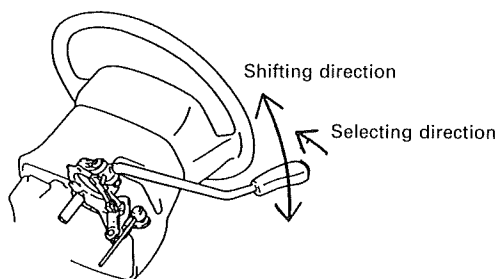


Fig. 4 Conventional Type Column AT Shift

2.2 Objective of Easy-Column Shift

Under one of the vehicle concepts for Noah that reads to "appeal on passenger-car-like operability", we have studied a system that operates the same way as the floor AT shift lever; in other words a system to push button to make selection and move the lever in the longitudinal direction of the vehicle to make shift (**Fig. 5**), and our objective is to realize this system installed on the column.

3. Structure and Operation of Easy-Column Shift

3.1 Outline

We have settled on a select button type shift knob that well resembles the floor AT knob. It is connected to the main body via the shift lever pipe and supported to ensure that the shifting direction is longitudinal.

The main body is mounted on the lower surface of the steering column. We have adopted mechanical type shift lock and key interlock devices.

Actually, shift lock cable is arranged from the main body to the brake pedal to effect the shift locking. Key interlocking is effected with the link system. **Fig. 6** shows the section of the overall shift lever and **Fig. 7** principal components.

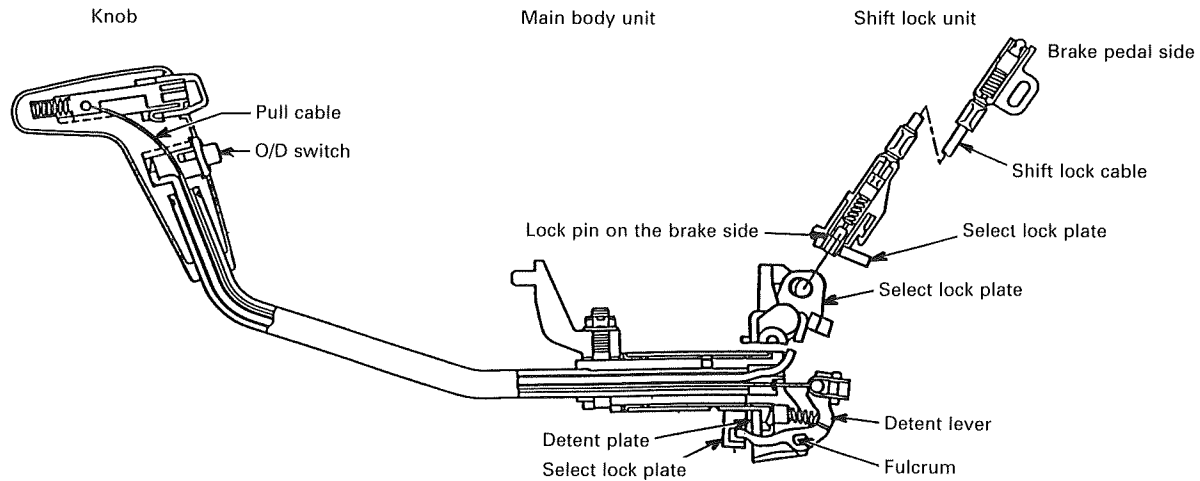


Fig. 6 Easy-Column Shift Section

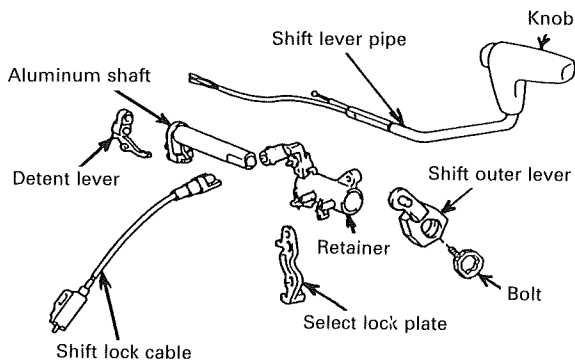


Fig. 7 Principal Components of Easy-Column Shift

3.2 Shift Knob Unit

Select button and Over Drive (O/D) switch are installed to the knob main body in compact arrangement.

Pressing the select button puts the detent lever of the main body in select state with the pull cable that runs through the shift lever pipe.

In consideration of the O/D switch operability, the O/D switch is mounted below the select button. The wire harness is led from inside the shift lever pipe to the main body unit and connected to the harness on the vehicle side.

The inside of the knob main body is formed with polyacetal (POM) resin and the surface with soft vinyl chloride to improve texture.

3.3 Main Body Unit

3.3.1 Retainer

The retainer is a lightweight and compact aluminum struc-

ture with the steering column mount, aluminum shaft support, shift lock mount, detent plate mount, etc. composite-formed.

3.3.2 Aluminum Shaft

The retainer supports the aluminum shaft rotational in the shift direction. The aluminum shaft has an internal space for inserting the shift lever pipe. It is composite formed with the shift outer lever fix section on one end and the detent lever support on other end.

3.3.3 Shift Outer Lever

The shift outer lever is a connecting section for the AT shift cable. It fixes both the direction of rotation of the shift lever pipe and the aluminum shaft and the axial direction of the aluminum shaft. The shift outer lever is composite-formed with aluminum to allow fixing with a single bolt.

3.3.4 Detent Plate

The detent plate is provided with the convex and concave to allow correct selection of respective shift positions (P, R, N, D, 2, L). It is press-formed and fixed to the retainer with screws.

3.3.5 Detent Lever

Pressing the select button on the knob rotates the detent lever via the pull cable, and releases it from the convex and concave on the detent plate to enable shifting. Although it is a part that requires precision in the making, it is composite formed with lost-wax casting.

3.4 Shift Lock and Key Interlock Units

The select lock plate that controls the operation of shift lock and key interlock is mounted to the retainer in sliding condition.

The select lock plate is made from fiber glass reinforced

polyacetal resin (POM) composite-formed with the sections for controlling the operation of detent lever at the bottom, the shift lock cable pin at the top and the key interlock pin in the middle.

Fig. 8 shows the operation of shift lock and key interlock devices.

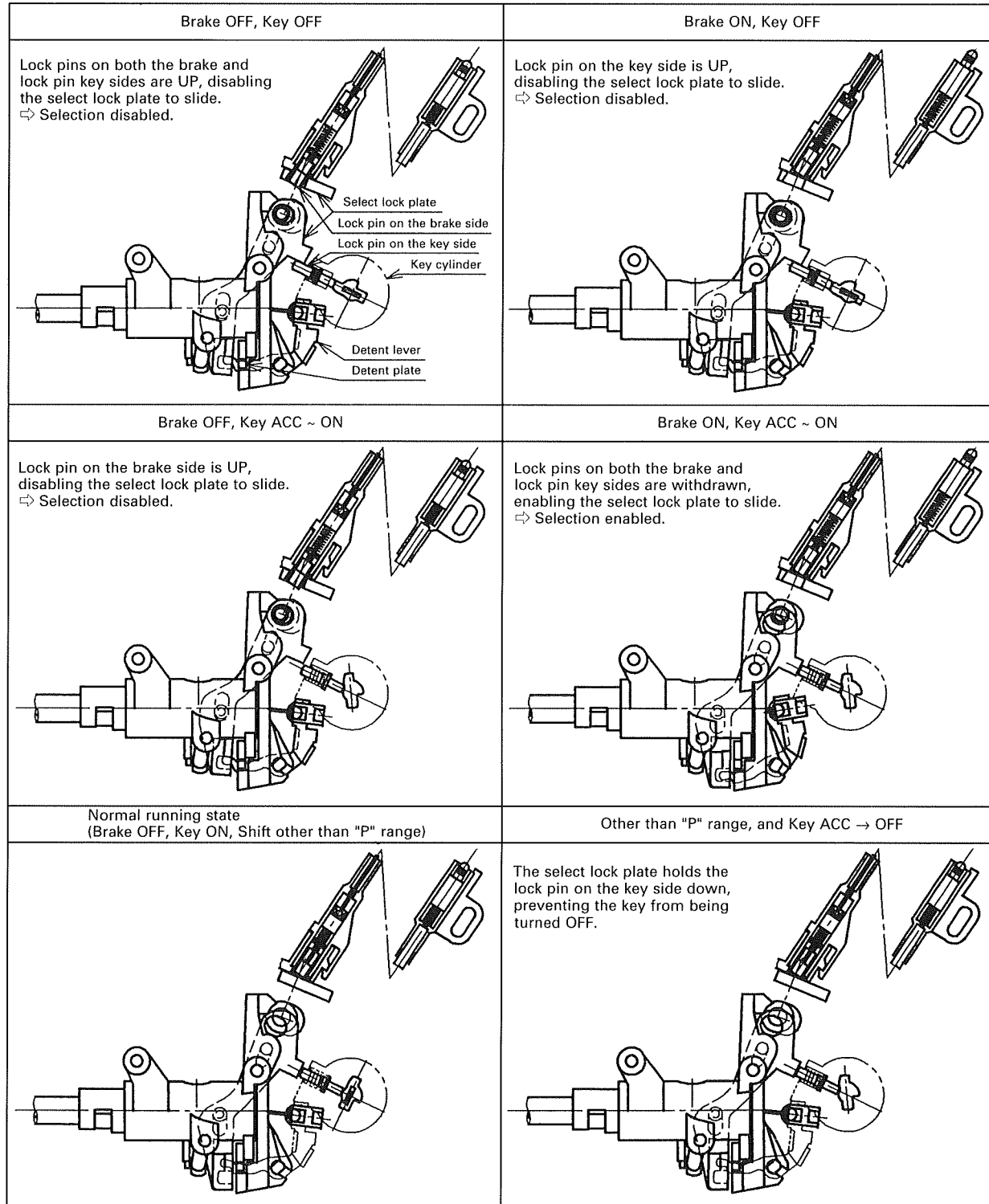


Fig. 8 Explanatory Drawing of Shift Lock and Key Interlock Devices

4. Effect of Easy-Column Shift

4.1 Improved Operability

4.1.1 Reach

Comparison is made of the Easy-Column Shift with the column AT shift levers of other vehicles. **Table 1** indicates the rear from the standard male Japanese shoulder point to the end of the shift lever knob. The table indicates that the D range position of the Easy-Column Shift is particularly closer and easier to reach than other AT shifts. Travel distance from the steering wheel is much more closer, proving the effectiveness of the Easy-Column Shift in making a sudden shift-down.

Table 1 Comparison of Reaches by AT Shift Type

Shift lever type	Reach to D range (mm)	Travel distance from steering wheel (mm)
Easy-Column Shift	561	96.5
Column AT shift on other vehicles	637	130
Other floor AT shift	573	281.4

4.1.2 Comparison of Operating Time

Comparison is made on the shift lever by types among a. floor shift (see **Fig. 2-1**), b. conventional column shift (pull toward you) and up-down (see **Fig. 4**) and c. Easy-Column Shift (see **Fig. 5**).

<Method of comparison> Twelve in-house panel members conducted a shift operation analysis using three units of vehicles each having a different type of AT shift lever from others. Each panel member is verbally instructed to operate the lever to a shift position promptly and correctly. Their shifting operation is VTR recorded for later analysis. Each member made shift operation 60 times per unit of vehicle.

<Result> Regarding the operating time, Easy-Column shift requires short time for touching the shift knob while the conventional pull-toward-you type column shift requires longer

time before completing a shift because of more number of strokes and selection (**Fig. 9**). The Easy-Column shift is equal to or slightly more advantageous than the floor shift type.

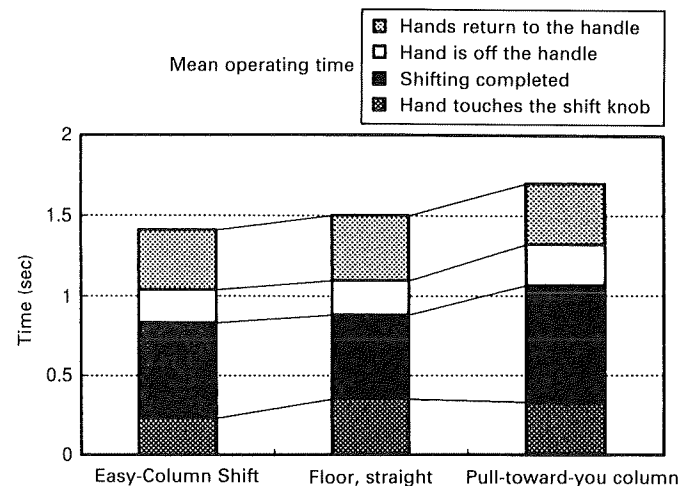


Fig. 9 Comparison Table of Operating Time by AT Shift Type

4.2 Weight Reduction and Downsizing

We have reduced the size and weight of retainer by installing the A/T shift lever to the lower part of the steering column. We have done away with the bell clank by changing the shifting direction. Moreover, we have reduced the sectional area of the column cover also from the above development.

4.3 Reduction of Number of Parts

By developing composite aluminum casting of the retainer, shaft, lever, etc., we have been able to concentrate functions and reduce the number of parts. We have discontinued to use the bell clank by changing the direction of shift.

We have reduced the number of parts by simplifying the shift lock and the key interlock systems.

Table 2 Comparison Table of Cost, Weight and Total Parts Number

		Easy-Column Shift	Vehicle A	Vehicle B
Cost index (100 for vehicle B)		73	80	100
Mass (AT lever + shift lock cable)		800g (−36%)	1000g (−20%)	1250g (Standard)
Total number of parts	AT lever main body	28	29	36
	Shift lock cable	12	25	26
	Total	40 (−35%)	54 (−13%)	62 (Standard)

4.4 Cost Reduction

We have promoted cost reduction through the weight reduction and miniaturization (item 4.2 above), parts number reduction (item 4.3), abolition of machining with the close-tolerance forging of aluminum, etc., and the simplified shift lock and key interlock devices (a single cable plus a link system).

Table 2 indicates comparison with other TOYOTA MPVs.

5. Conclusion

We have this time developed the Easy-Column Shift that can be operated as if operating a passenger vehicle in relation with the development of Town Ace Noah and Lite-Ace Noah. Authors wish to express their appreciation to Mannoh Industrial Co., Ltd. for valuable assistance to the present development.

■ Authors



Y. SATO



H. MINOSHIMA



M. MAKIGUCHI

Development of Catalyst for Diesel Engine

Hideaki Ueno*
Toshinobu Furutani*
Tetsuo Nagami*
Norihiro Aono**
Hideyuki Goshima**
Kouichi Kasahara**

Abstract

The new concept catalyst for diesel engine has been developed. When the exhaust temperature is low, SOF and HC are temporarily absorbed by the absorbent within the catalyst and are oxidized as the temperature rises. The process of this development has manifested the following:

1) The coating material is important factor to govern the oxidation activity. 2) SOF is reduced by the coating material in low temperature less than 200°C. 3) The coating material, which has low SO₂ adsorbing rate, suppresses the sulfate formation at high temperatures.

Keywords: catalyst, diesel engine, oxidation, HC, particulate

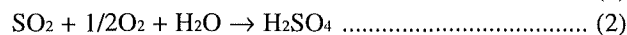
1. Introduction

Recently the diesel engine has drawn particular attention from the viewpoint of global warming prevention because of its low CO₂ emission. Conversely, diesel engines emit a large amount of particulate matters (hereinafter referred to as "PM") consisting of Soot, Sulfate, SOF (Soluble Organic Fraction) and NO_x. Hence, the development of measures to reduce emission has been centered on improvement of combustion and EGR. Increasing the amount of EGR with decreasing NO_x increases the amount of PM, HC and CO, thus, attempts at emission reduction by improving engines have an innate limit. In order to achieve still cleaner exhaust gas from diesel engines in the future, it is essential to provide them with exhaust cleaning catalysts. To achieve a clean diesel engine, however, a number of problems must be solved. For instance, diesel engines do not emit exhaust gas hot enough to activate catalysts; the catalysts deteriorate relatively quickly since the high proportion of sulfur (S) contained in the fuel gives rise to sulfur oxides, which attack the catalysts; and the atmosphere in which diesel engines are operated contain oxygen in excess of the amount necessary for fuel combustion, which makes it impossible to maintain NO_x reduction. Thus the emergence of new techniques has been awaited. We, at Toyota Motor Corporation, have developed a new diesel catalyst embodying a new concept that can reduce SOF and HC emission at low exhaust temperature, while improving the durability of the catalyst. This new concept diesel catalyst will be installed on our new models, marketed this summer, ahead of other auto makers. Vehicles with this catalyst are expected to meet the domestic long-term regulations, and the catalyst is scheduled to be applied to products bound for Europe as well.

2. Development Tasks

Table 1 lists tasks to be achieved in the present development of the subject diesel catalyst. Reactions in tasks ① and ② in the **Table 1** are oxidizing reactions considered to occur on the catalyst noble metal.

Loading a large amount of noble metal in order to improve catalyst low-temperature activity is good for task ①. However, this is detrimental to task ② since heavy loading of noble metal, giving rise to sulfuric acid mist and a sulfate in reactions indicated by equations (1) and (2), increases the amount of PM in exhaust gas. This poses a difficult problem, namely expanding the temperature range where the catalyst can be most effective while meeting two contrary requirements: to promote the oxidization of HC and SOF and at the same time to inhibit sulfate formation.



Task ③ is to develop or find a new coating material that does not decrease the specific surface area as a result of reaction with the sulfate formed when SO₂ in exhaust gas is oxidized. Of particular consideration for tasks ② and ③ is the lessening of SO₂ adsorption to the coating material so as to prevent the sulfate from occurring. In tasks ④ and ⑤ the chief

Table 1 Characteristics of Diesel Exhaust Gas and Development Subject

Characteristics	Development subject
1) Low exhaust gas temperature	① Development of HC and SOF oxidation catalyst at less than 200°C
2) Excessive surplus oxygen content in diesel exhaust gas	② Suppression of the SO ₂ oxidation activity and low sulfate formation ③ Development of sulfate tolerance coating material
3) Presence of excess oxygen	④ Development of NO _x reduction catalyst in excess oxygen
4) Small amount of HC and CO	⑤ Development of catalyst effectively applying adsorbed HC to NO _x reduction

* Material Engineering Div. I
** Cataler Industrial Co., Ltd.

technical problem is to enhance reaction between HC and NO_x while inhibiting reaction between HC and O₂ in an atmosphere with an excessive amount of oxygen (or oxidizing atmosphere).

3. Objectives of the New Concept Catalyst

3.1 SOF Reduction Effect of the Coating Material

Fig. 1 illustrates the HC and PM conversion characteristics of two catalysts: one loading Pd on the SiO₂-Al₂O₃ coating material and the other consisting of the coating material alone. The two catalysts turned out to have equivalent PM reduction rates at low temperature of 300°C or lower, whereas the catalyst with Pd exhibited high PM reduction rate over 300°C. The effect of Pd, however, deteriorated over 500°C because of an increased amount of sulfate.

As for HC conversion, on the other hand, the catalyst without Pd performed 10% or lower at 500°C, whereas the catalyst with Pd showed a high HC conversion rate over 250°C. A possible cause of such a difference between the two types of catalyst is as follows: at low temperature, whereat a major portion of SOF is in the liquid phase, the coating material works to reduce SOF; and at high temperature, whereat SOF is gasified, Pd oxidizes SOF.

Fig. 2 shows time-course changes in the PM reduction effect of the coating material without noble metal. The PM reduction rate is kept at 10 to 20% for 23 hours. This result indicates that PM reduction at low temperature is attributable to not only adhesion to the coating material but the oxidation of SOF, totally or partially, by the coating material as well. These results suggested that the coating material plays an important role in SOF reduction at low temperature, a new view opposing con-

ventional wisdom which holds that noble metal is necessary to oxidize SOF.

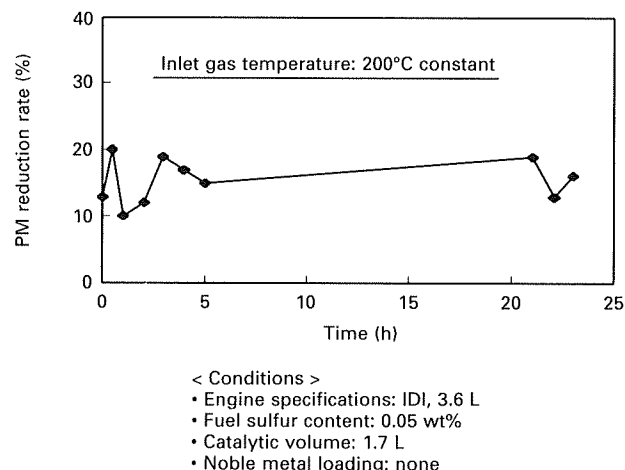


Fig. 2 PM Reduction Effect of Coating Material

3.2 Objectives of the Development of the New Concept Catalyst

Our study revealed that the coating material not only helps noble metal promote oxidation but also serves to reduce SOF at low exhaust gas temperature. This finding made it possible to design a catalyst with two separate functions: one provided by the coating material to reduce SOF at low exhaust gas temperature, and the other provided by the noble metal to remove HC, CO and NO_x. Hence the present study set two goals, viz.: to further improve the coating material performance, and to develop a new coating material durable against exhaust gas containing a high level of SO₂. To achieve these goals, we considered the following items:

- 1) Improving durability
 - ① Developing or finding coating materials unlikely to adsorb SO₂ (i.e., materials unlikely to generate sulfates)
 - ② Developing or finding coating materials resistant to heat of 700°C or higher (the maximum temperature of diesel exhaust gas)
- 2) Improving performance
 - ① Adding a zeolite (HC adsorbent) to reinforce the HC and SOF trapping capacity at low exhaust gas temperature whereat noble metal is difficult to activate.

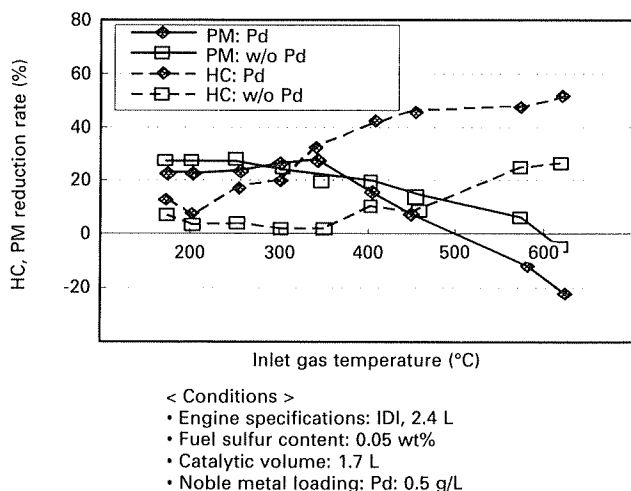


Fig. 1 Difference in Reduction Characteristic Between Presence and Absence of Noble Metal

4. Results of Considered Coating Materials

4.1 Sulfate Adsorption Characteristics of Various Coating Materials

Fig. 3 presents the sulfate adsorption characteristics of various coating materials. The graph indicates that SiO_2 and TiO_2 adsorb 1/4 or less as much sulfates as does alumina, a conventional coating material. **Fig. 4** shows the HC 50% conversion temperature of a catalyst with Pt(0.5 g/L) loaded on SiO_2 and TiO_2 . TiO_2 exceeds SiO_2 in low-temperature activity. Since diesel exhaust gas contains a high proportion of SO_2 and its temperature is low, we concluded that TiO_2 was more appropriate as a coating material for diesel catalyst and therefore should be used as the chief coating material.

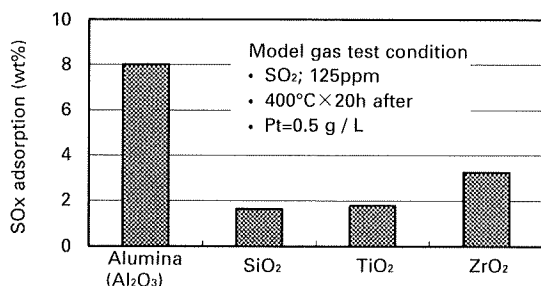


Fig. 3 Comparison of Sulfate Adsorption Characteristics of Various Coating Materials

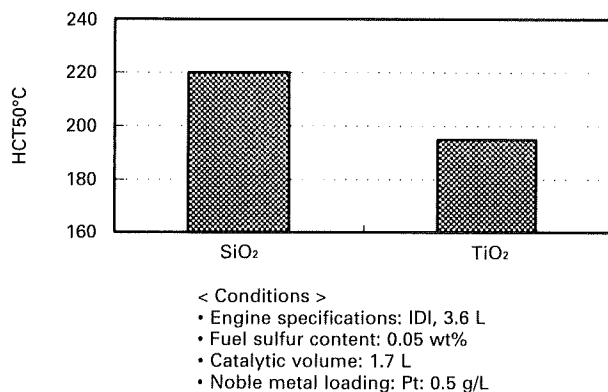


Fig. 4 Comparison of the HC Oxidation Activity of SiO_2 and TiO_2

4.2 Improving TiO_2 Heat Resistance

Over 600°C the crystal structure of TiO_2 transforms from anatase type to rutile type, and grain growth significantly deteriorates a specific surface area. Thus, to use TiO_2 as coating material, higher heat resistance is absolutely necessary. Hence, we examined additives to see if they could improve the heat re-

sistance of TiO_2 . **Fig. 5** presents the results regarding the effect of additives on TiO_2 heat resistance.

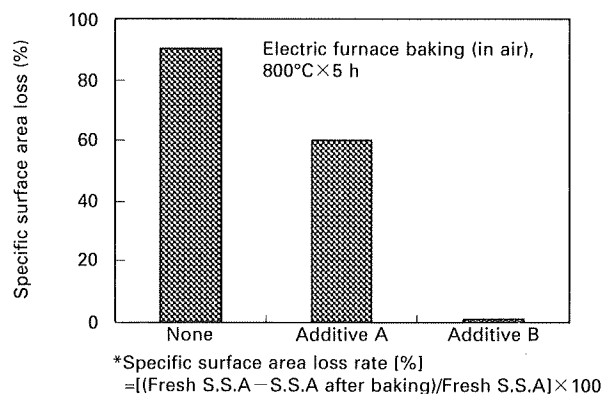


Fig. 5 Effect of Additives on TiO_2 Heat Resistance

4.3 Selecting Zeolites

Required of zeolites used for the subject catalyst are: ① a high capacity to trap HC and SOF; ② a detachment temperature for trapped HC and SOF within the activity temperature range of the catalyst noble metal; and ③ a high resistance to heat. Zeolites with a high $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio are hydrophobic and can selectively adsorb organic molecules⁽²⁾. Moreover, the higher the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio, the less likely aluminum is to detach and the higher the heat resistance. Hence we chose zeolites with a high $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio for the present development.

5. Basic Characteristics of the Developed Catalyst

5.1 HC Adsorption Performance

Fig. 6 compares the developed Pt catalyst (0.5 g/L) with conventional catalysts for HC adsorption performance. The diagram illustrates changes in HC reduction rate when the exhaust temperature was continuously elevated and lowered in engine bench tests. The developed catalyst showed substantial improvement in HC adsorption performance over the conventional catalysts at low temperature.

5.2 Inhibiting Sulfate Formation

Fig. 7 presents the relationship between the amount of Pt loaded on the developed catalyst and the catalyst temperature that rapidly increased the formation of sulfate. The sulfate rapid formation temperature of the developed catalyst is higher than that of the conventional. This is probably attributable to the low adsorbency of sulfates to the coating material, as men-

tioned in Section 4.1 above. This finding implies that coating materials are an important factor in determining the amount of sulfate formation.

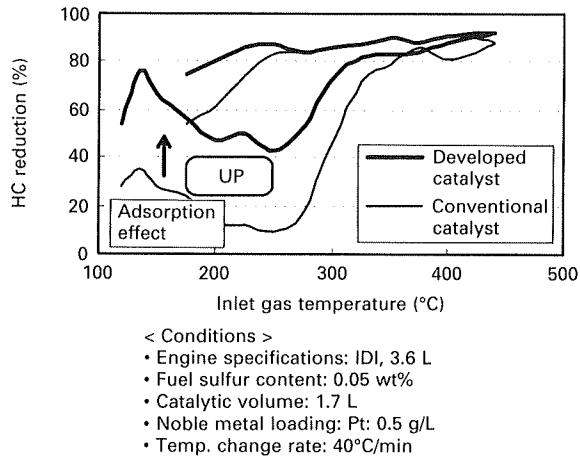
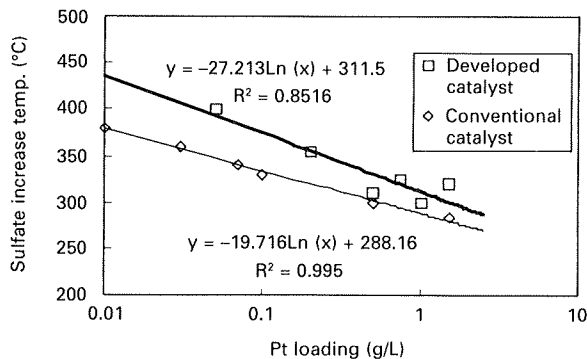


Fig. 6 HC Adsorption Effect of Developed Catalyst



*Sulfate increase temp.: Temperature of PM reduction rate at 0%

< Conditions >

- Engine specifications: IDI, 2.4 L
- Fuel sulfur content: 0.05 wt%
- Catalytic volume: 1.7 L
- Steady state measurement

Fig. 7 Sulfate Suppression of Developed Catalyst

5.3 Durability of the Developed Catalyst

Fig. 8 shows the temperature characteristics of HC and CO conversion rates before and after high temperature durability tests (650°C×50 h). The graph demonstrates that the conversion performance of the developed catalyst remained virtually unchanged after durability tests, thus proving the superior durability of the catalyst.

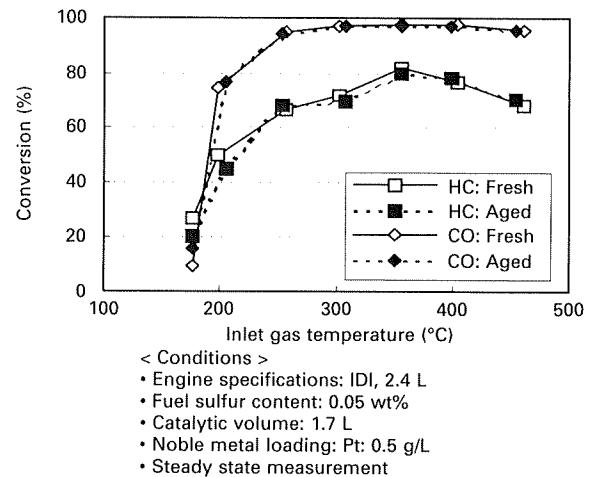


Fig. 8 High Temperature Durability of Developed Catalyst (650°C×50 h)

6. Catalyst Performance on the Vehicle

Fig. 9 indicates the conversion performance of the developed catalyst as tested on vehicles with different engine displacements and exhaust temperatures. The conversion performance depends on how far the exhaust gas temperature in each evaluation mode extends into the catalyst's high activity temperature range. The temperature windows of the developed catalyst vary with the amount of Pt loading. Thus, to allow the catalyst to fully perform conversion, the amount of Pt loading must be optimized for the subject vehicle. In addition, optimizing the exhaust temperature as well as the temperature of the whole exhaust system, including the engine, could possibly induce still higher conversion performance.

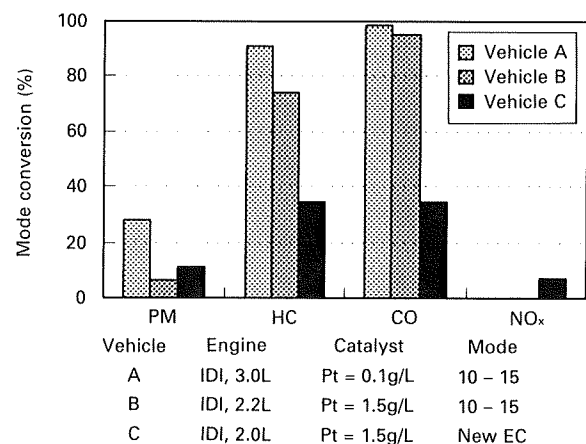


Fig. 9 HC, CO, NOx Conversion of Developed Catalyst

7. Discussion

7.1 SOF Reducing Effect of Zeolites

Fig. 10 presents the result of a heat generation study conducted on zeolites A, B and a conventional catalyst during temperature elevation. Pt load for the samples was at 0.2 g/L, and the catalysts were mixed with n-hexadecan ($C_{16}H_{34}$) simulating SOF. SOF adsorbed to the zeolites began to be oxidized at a lower temperature, generating more heat than did SOF adsorbed to the conventional catalyst. This may be because the SOF, having a large molecular size and unlikely to be oxidized by Pt, was converted by zeolites into more combustible HC with a smaller number of carbons. **Fig. 11** shows the analysis results of SOF trapped on the coating material resulting from feeding engine exhaust gas at 150°C . The distribution of the numbers of carbons of SOF adsorbed on the conventional cata-

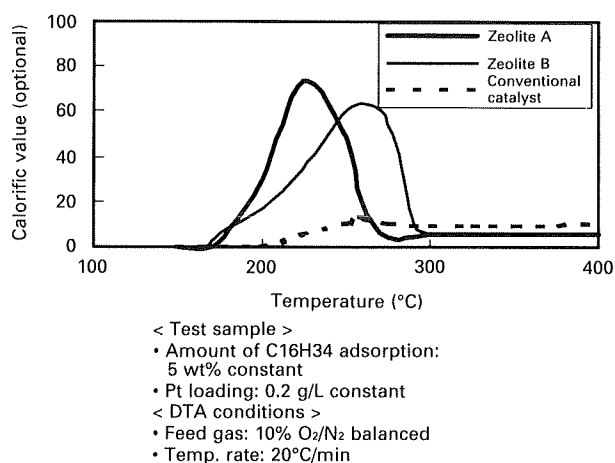


Fig. 10 SOF Combustion Performance by Use of Zeolites

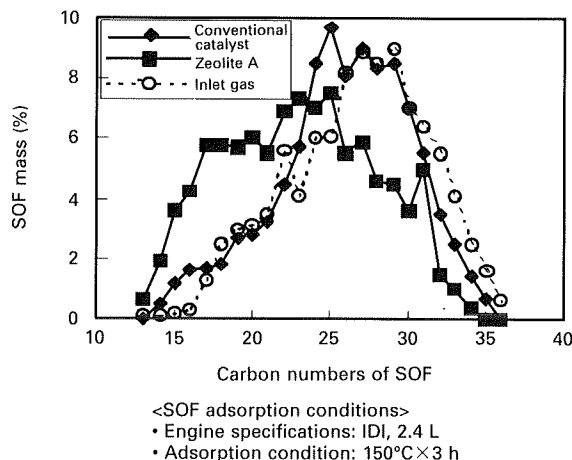


Fig. 11 Distribution of Carbon Number in Absorbed SOF

lyst is nearly equal to the distribution of those before adsorption by the catalyst (or the numbers of carbons in the inlet gas). Thus, the conventional catalyst does not convert SOF. SOF adsorbed on zeolite A, however, exhibited a shift in the C-number distribution toward the smaller, which indicates that zeolites can convert SOF.

These results suggest that zeolites trap SOF at a low temperature and convert it into more combustible gaseous HC at higher temperature, subsequently detaching the resulting HC. Zeolite A is shown to have a greater such capacity than zeolite B.

7.2 Potential to Decrease NO_x

Vehicle C in **Fig. 9** shows slight removal of NO_x . **Fig. 12** presents changes in NO_x concentration during the measurement of emission from this vehicle. The diagram indicates that NO_x decreased as the inlet gas temperature increased from 170°C to 240°C . With diesel engines during normal driving, it is difficult to reduce NO_x solely with HC present in the exhaust gas. Substantial NO_x reduction requires an HC concentration higher than a certain level. Thus, a probable mechanism of NO_x reduction in this vehicle is as follows: HC and SOF adsorbed at a low exhaust gas temperature and detached as the gas became hotter during acceleration, temporarily increasing the concentration of HC present in the vicinity of the catalyst and as a result reducing NO_x . Such a mechanism implies that the capability of the developed catalyst to adsorb and detach HC can be applied to NO_x removal.

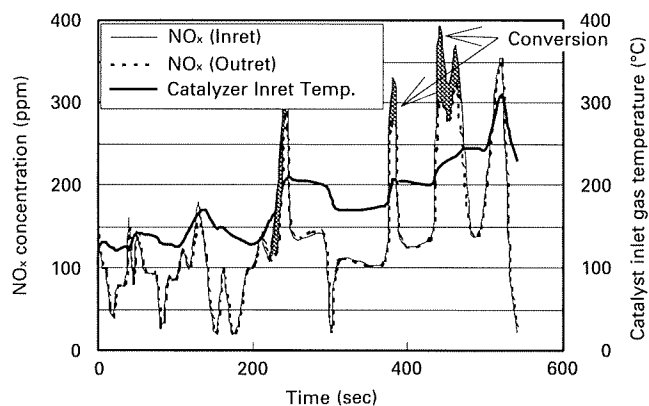


Fig. 12 Data of NO_x Concentration During the Test Mode of Vehicle C

8. Conclusion

A new concept catalyst, superior in converting HC and SOF at low exhaust gas temperatures and in inhibiting the genera-

tion of sulfate at high gas temperatures, was developed. The present developmental activities have brought about the following findings:

- 1) At a low exhaust gas temperature of 200°C or lower the coating material oxidizes SOF, totally or partially.
- 2) The addition of an HC adsorbent in the coating material significantly enhances HC and SOF conversion at low exhaust gas temperature.
- 3) Sulfate formation at high exhaust gas temperature can be inhibited by using a coating material that does not adsorb SO₂.
- 4) Zeolites are effective in converting SOF into HC with a low C-number.
- 5) The developed catalyst, with an HC adsorbent added, has a potential to decrease NO_x if optimum service conditions are met.

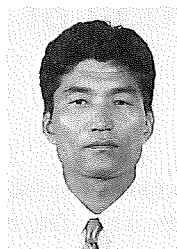
9. Acknowledgements

The authors thank the staff in the Catalyst and Analysis Department and the Measurement Departments of Toyota Central Research Institute for their cooperation regarding analysis in the present development.

References

- (1) Yoshitsugu Ogura et al: Development of Oxidation Catalyst for Diesel Engine, SAE Paper No. 940240 (1994)
- (2) Toshihisa Fukushima et al: Properties of the HSZ Series, Tosoh Research Report Vol. 33, No. 2 (1989)

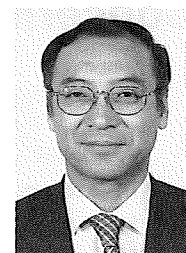
Authors



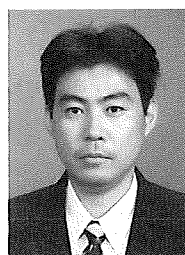
H. UENO



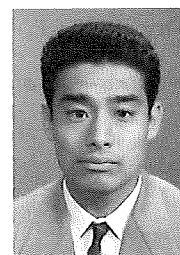
T. FURUTANI



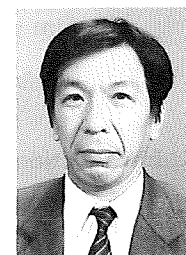
T. NAGAMI



N. AONO



H. GOSHIMA



K. KASAHARA

Molecular-Level-Analysis on Water Behavior Concerned to Degradation of Paint Film

Nobuaki Takazawa*
Yoshihiro Yamamura*
Ryuji Shimazaki*

Abstract

In late years, some paint film damage cases have been reported that are considered to have been caused by falling objects such as acid rain, pollen, etc. The outbreak factor is classified into the main factor which is falling objects themselves and environment factors such as water, air, heat and light. The countermeasures for environment factors are effective to the main factors as well. In this study, we focused on water among the environment factors. The water behavior in the premonitory stage of paint film degradation was analyzed in molecular level by Atomic Force Microscopy (AFM). As the result, the water molecule influence on paint film was partly clarified.

Keywords: degradation of paint film, water, atomic force microscopy (AFM), molecular structure

1. Introduction

In recent years, several paint film damages were reported probably caused by acid rain, pollen or other falling objects. **Fig. 1** represents the causal factor consisting of the main factor that is the falling objects themselves and the environmental factors such as water, atmosphere, heat, light and so forth. Hitherto, countermeasures were mostly directed to acid rain⁽¹⁾ and other specific falling objects that constitute the main factor. However, there are many other falling objects⁽²⁾ that are likely to cause paint film damages. Thus it is difficult to take overall measures against those objects. On the other hand, environmental factors relate to the matter by accelerating reactions initiated by the falling objects. For example, as **Table 1** indicates, water content in the paint film makes it more susceptible to damages by acid. It is known to cause extensive paint film degradation. Thus water is considered to be particularly important a factor among the environmental factors.

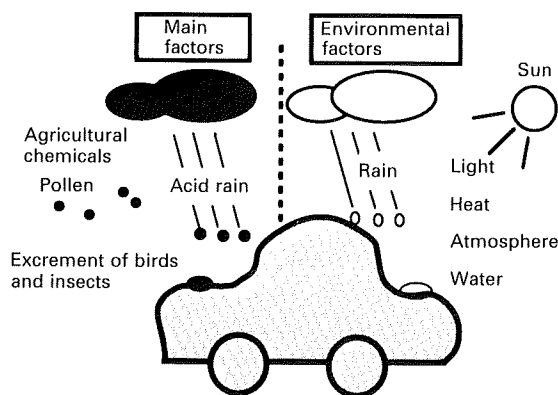


Fig. 1 Causes of Paint Film Staining

Table 1 Water Content in Paint Film and Susceptibility to Acid Damages

Paint film	Decomposition of paint film (Melamine decomposition)
Dry paint film	2%
Paint film with water absorption	52%

Decomposition of paint film after 10% sulfuric acid dripping and 2 hours of drying

2. Objectives

Of the environmental factors for the degradation of paint film, we have paid attention to the water in the present study since it is common to the main and the environmental factors. In this report, we analyze and clarify the behavior of water that affects the paint film degradation.

3. Point of Attention

Fig. 2 shows the relationship between the paint film deterioration level and the evaluation and analytical methods.

At present, visual inspection and analytical methods are used for the evaluation and analysis of paint film damages. We thought it is necessary to make analysis on the molecular level (=nm order) by advancing one step forward from the conventional μm order to analyze the behavior of the water molecules and subsequent paint film deterioration, particularly the water behavior in the premonitory stage to the paint film degradation.

In the present study, we use an atomic force microscope (AFM) as the analytical method in nm order. **Fig. 3** shows the conceptual diagram of AFM. The AFM visualizes the atomic behavior in 3-dimension by scanning the probe held close to a

* Material Engineering Div. III

specimen surface to nanometer level and keeping the atomic force between the probe and specimen constant.

We paid attention to the paint film change from the premonitory to the early stage of degradation. We conducted analysis mainly with the AFM observation and proceeded with the discussion on the behavior of water molecules on the basis of the analytical results.

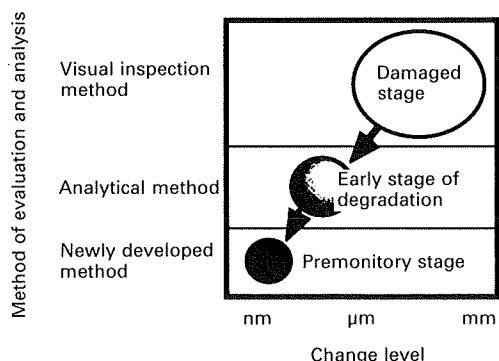


Fig. 2 Paint Film Deterioration Level and the Methods of Evaluation and Analysis

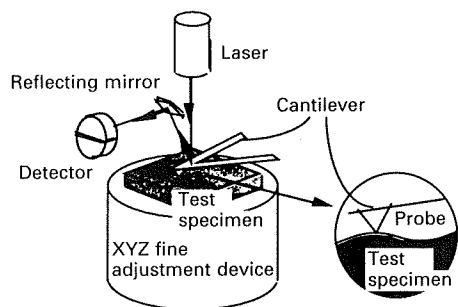


Fig. 3 Conceptual Diagram of Atomic Force Microscope

4. Test Method

4.1 Paint Film Test Specimen

We used two types of specimen; conventional paint film (melamine cross-linked) and acid resistance paint film (acid-epoxy cross-linked).

4.2 Analytical Method

(1) Analysis on the chemical change of paint film

The test specimen was dried by heating ($60^{\circ}\text{C} \times 100 \text{ min}$) after being immersed in the water for two days. The film was then analyzed under the infrared spectroscopy (IR) to examine the paint film change caused by the water alone.

(2) Analysis on the physical change of paint film

The test specimen was dried in the open air after being immersed in the water for 4 days. During this course of process, changes in the paint film weight, length and hardness (Vickers hardness) were examined.

(3) Analysis on the surface contour change of paint film to the order of nanometer

The test specimen was dried in the open air for 3 days after being immersed in the water for 4 days, then dried in the vacuum state for 4 hours. During this course of process, we observed the paint film surface with AFM (magnification: 50,000 times).

5. Test Results

5.1 Analysis on the Chemical Change of Paint Film

Fig. 4 presents the IR spectrum of the (conventional) paint film in the initial state and after immersion in the water and drying. No difference is detected in the spectrums of both specimens (melamine peak, etc.) and it is found that water alone does not give any chemical change to the paint film. The same result was obtained from the analysis of acid resistant paint film.

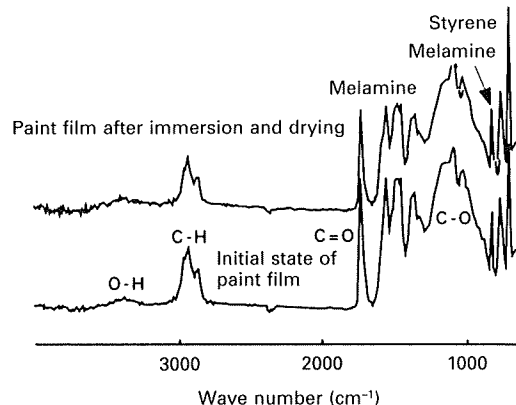


Fig. 4 IR Spectrum of Conventional Paint Film in the Initial State and after Immersion and Drying

5.2 Analysis on the Physical Change of Paint Film

Fig. 5 shows the changes in the (conventional) paint film weight, length and hardness during the immersion and drying processes. During the immersion process, immediate change occurred to the weight, length and hardness, which immediately began to recover during the drying process. Although the water content was not desorbed completely on the second day of drying, the paint film shrank and became hardened. From

this it was known that water freely goes in and out of the paint film to give physical change to it. The same behavior of change was observed with both the conventional and acid resistant paint films.

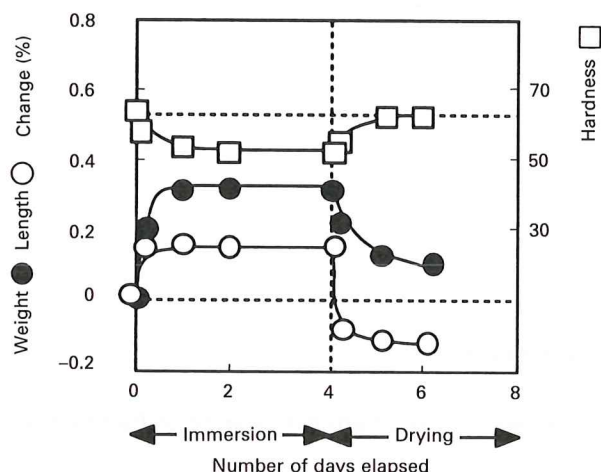


Fig. 5 Relationship between the Number of Days for Immersion and Drying and the Changes in Weight, Length and Hardness (for Conventional Paint Film)

5.3 Analysis of Surface Contour to Nanometer Order

Fig. 6 shows the AFM observation result of the (conventional) paint film surface during the immersion and drying processes. Brighter spots represent blistered sections the size of rising is indicated in surface roughness R_z to the order of nanometer. The paint film surface before immersion was smooth by the nm order. But the surface roughness gradually increased as the number of days in immersion passed. Then the breadth or intervals of the roughness were several tens of nm. After drying the specimen in the open air for 3 days, the surface roughness remained almost unchanged. But after subjecting the specimen to the vacuum drying (for 0.2 day), the surface roughness became smaller. **Fig. 7** shows the relationship between the number of days elapsed and the surface roughness R_z to the nm order by arranging the results of observation. Test specimen for acid resistant paint film indicates the similar surface change behavior, but the change is minor compared with the conventional paint film.

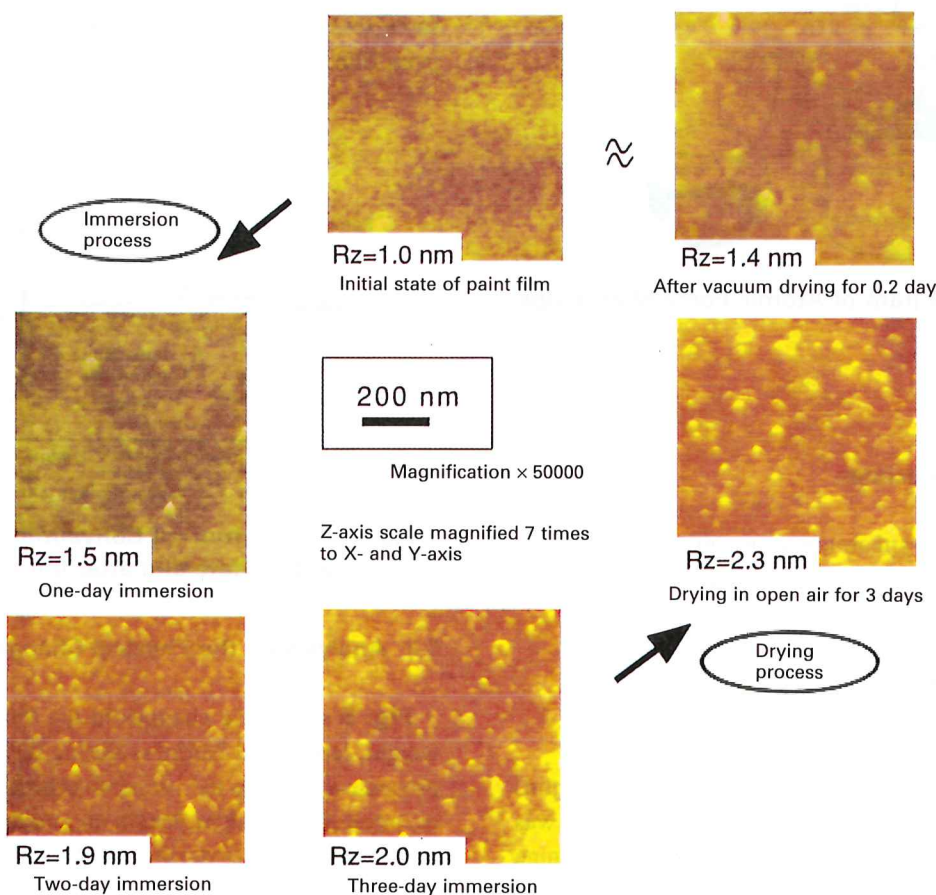


Fig. 6 Result of AFM Observation of Paint Film during the Course of Continual Immersion and Drying Processes

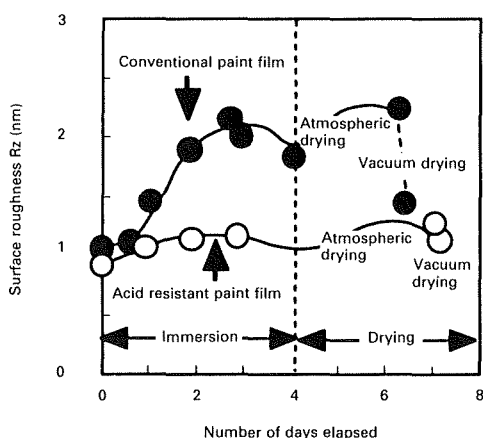


Fig. 7 Relationship between the Number of Days for Immersion and Drying and Surface Roughness R_z

6. Discussion

6.1 Paint Film Change Model

Fig. 8 shows the model presentation of the above-mentioned test results. The modeling was preconditioned on the following three points:

① Changes generated during the immersion and drying processes consist of macro physical change and surface waviness change. ② Since changes in the surface waviness are detected in the AFM images, we thought that the ease of filtration of water to the paint film differs by the section, that is the paint film consists of hydrophilic and hydrophobic parts. ③ **Fig. 5** and **7** show that the paint film size (length) changes rapidly within several hours while the surface roughness changes slowly, taking several days. Thus we thought that there are two types of hydrophilic part; one is hydrophilic part A which has a large size and allows free filtration/exit of water. The other is hydrophilic part B to which water can filtrate with difficulties. Precondition ① is a fact while ② and ③ are assumptions all based on the test results.

In the first stage of immersion, the water molecules first infiltrate into the hydrophilic part A. During this process, the paint film expands macroscopically. Later the hydrophilic part A reaches saturation. In the second stage, the water molecules infiltrate the hydrophilic part B as well, causing changes to the surface waviness.

On the other hand, during the drying process, the water molecules desorb themselves from the hydrophilic part A and the paint film contracts macroscopically. In the second stage, the water molecules desorb themselves from the hydrophilic part B, causing the surface waviness to become smaller. Using this

model, we can explain a series of paint film changes as shown in **Figs. 5** and **7**.

Fig. 9 shows the paint film and water molecule model we considered to construct the above-mentioned model in the level of molecule (this model represents the above-mentioned assumptions ② and ③ themselves). The paint film has a 3-dimensional network structure of molecular chain. The network does not have neat regularity and may form irregularly sized voids. Hydrophilic part A represents a large sized void in and out of which go a number of water molecular groups (clusters). Hydrophilic part B represents a smaller void in and out of which go a small number of water molecular groups (dimer, trimer, etc.) induced by hydrophilic group in the structure. A

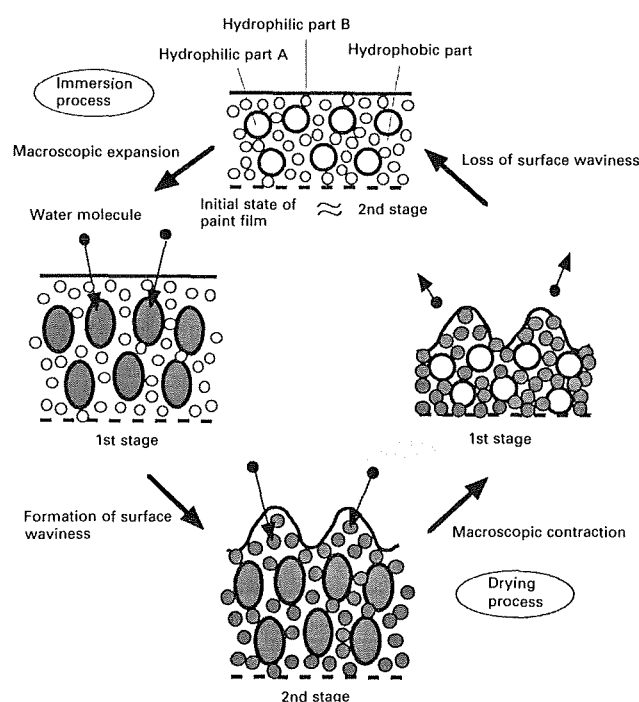


Fig. 8 Paint Film Change Model

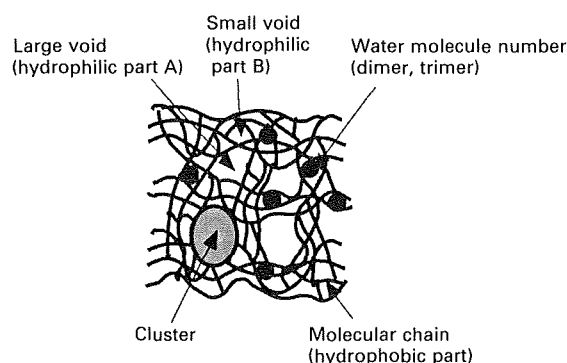


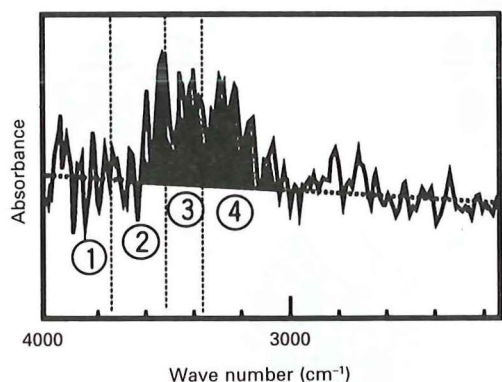
Fig. 9 Paint Film and Water Molecule Model

hydrophobic part represents the alkyl and hydrophobic group in the molecular chain. If this model is compared to a piece of sponge, a pore of sponge represents the hydrophilic part A, the smaller pore in the sponge fiber does the hydrophilic part B, and the fiber itself representing hydrophobic part. By incorporating this to the model in **Fig. 8**, effect of water on the paint film can be explained on the molecular level. In this connection, validity of this paint film and water model can be verified as follows.

6.2 Validation of Paint Film and Water Molecular Model

6.2.1 Analysis of State on Water Molecule

Fig. 10 shows the result of IR analysis of water content in the paint film. According to this result and the view of Takaoka et al ⁽³⁾, water exists in the paint film as the dimer and trimer water molecules and as the cluster water of a larger molecular weight. From this, we can explain that water molecules infiltrate the hydrophilic part A in the form of clusters and the hydrophilic part B, dimer or trimer.



Assignment of absorption band		
Absorption band	Assignment	
①	Monomer	One water molecule
②	Dimer	Two water molecules
③	Trimer	Three water molecules
④	Cluster	Four and over of water molecules

Fig. 10 IR Spectrum in the Paint Film

6.2.2 Analysis of Molecular Structure of Paint Film

Fig. 11 shows the paint film cross-linking structure assumed from the monomer composition of the paint and a cross-link to cross-link mean molecular weight (=500) obtained with visco-elasticity measurement and Bauer's model ⁽⁴⁾. **Fig. 12** shows

the steric cross-linking structure obtained with the simulation of the molecular operation on the basis of the above structure. A void of a size that allows simultaneous infiltration of several water molecules is present in this steric cross-linking structure, and the width of molecular chain and cross-link intervals were 1 to 2 nm. The width and intervals of waviness as detected in the AFM image (**Fig. 6**) are several tens of nanometer, however. Therefore this waviness does not match with individual molecular chains.

And thus the waviness is supposed to have been configured with a number of network of molecular chains. To verify this, we observed the film surface with the AFM at a higher magnification (3 million times). **Fig. 13** shows the result of this observation. Network-like waviness of a much finer nm size is detected in this AFM image. The intervals of the waviness are about 1 nm, which matches the assumed cross-link intervals of the paint film molecules. In other words, we judge that the molecular cross-linking structure was observed as the network

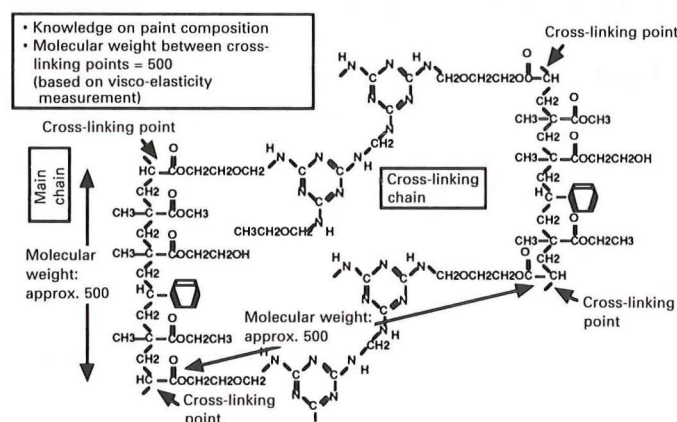


Fig. 11 Molecular Structure of Paint Film

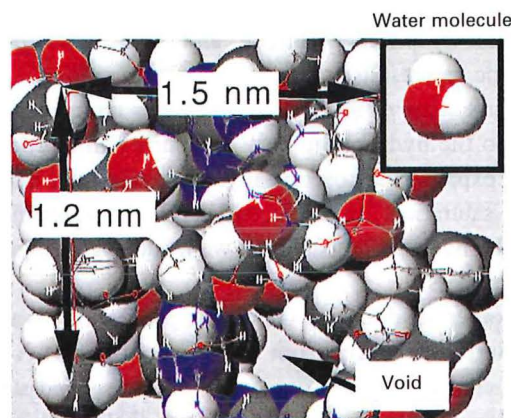
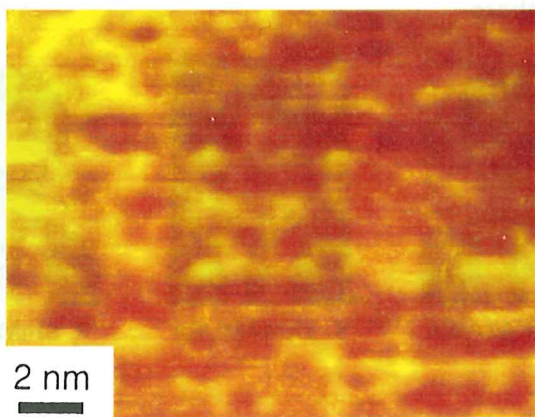


Fig. 12 Paint Film Steric Cross-linking Structure



**Fig. 13 Paint Film Molecular Level Observation
(Conventional Paint Film)**

of nm size. This forms the hydrophilic part B. The hydrophilic part A falls on the concave between the waves as seen in the preceding AFM image. (Fig. 6) We have been able to validate the paint film and water molecule model as thus explained.

6.3 Paint Film and Water Molecular Behavior Model

Fig. 14 shows the paint film and water molecular behavior model as proposed by us. It is constructed by incorporating the

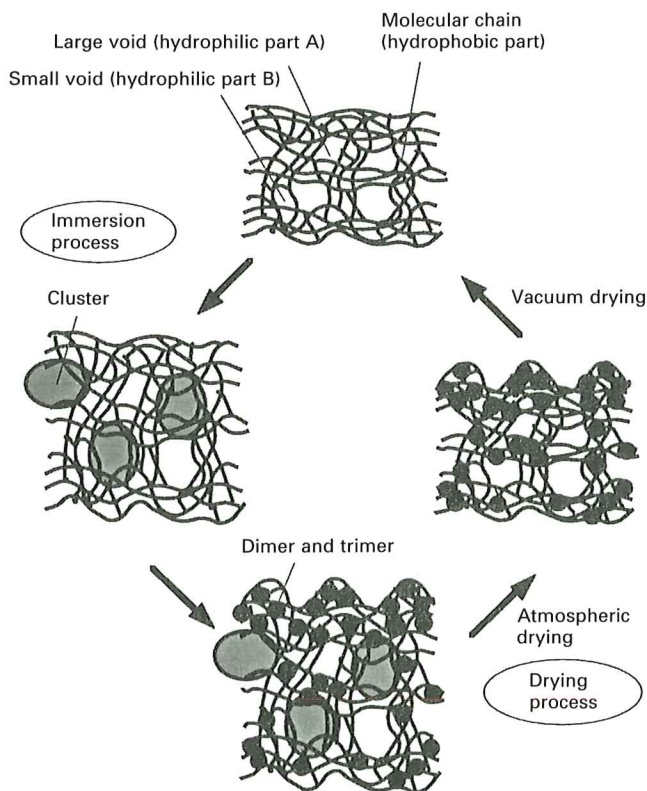


Fig. 14 Paint Film and Water Molecule Behavior Model

paint film and water molecular model (**Fig. 9**) to the paint film change model (**Fig. 8**). As the result, we could explain the paint film changes caused by water infiltration in the level of molecule.

This model implies that the traffic of water molecules in and out of the paint film and subsequent expansion and contraction of the paint film structure are concerned with the degradation of paint film caused by the falling objects.

In other words, residual water molecules in the structure tend to fix the falling objects in their vicinities and accelerate the degradation of paint film. Expansion and contraction of the structure caused by the water molecules deposit internal stress in the paint film. The presence of the content of falling objects, if any, may accelerate the release of internal stress with the breakage of the cross-linking.

7. Conclusions

- ▽ We have found that water moves in and out of paint film to cause physical change to it macroscopically, simultaneously bringing surface contour change of nanometer order.
- ▽ We have proposed a paint film and water molecular behavior model on the basis of the analysis conducted on the molecular level and clarified part of water behavior that affects the degradation of paint film.

8. Future Task

We will continue to conduct behavior analysis under the environment where water that constitutes an environmental factor and the falling objects that form the principal factor coexist. We will make analysis on the molecular level from the viewpoints of the infiltration and desorption of water molecules and the suppression of paint film expansion and contraction so as to accumulate basic knowledge that leads to the development of high durability paint film.

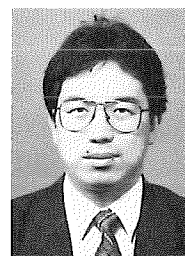
■ References

- (1) Koji Buda: Analysis of Paint Film Degradation Mechanism by Acid Rain, Paper presented at Toyota Society of Engineering Studies (1995)
- (2) Takahiro Tsubouchi, Masataka Muramatsu and Hisato Takeuchi: Paint Film Damage Generation Mechanism by Natural Falling Objects, the main purport of the lecture presented at 32nd All Toyota Research Presentation Meeting (1997)
- (3) Kyo Takaoka, Yasunori Taru, Masayoshi Arai, Kunio Kohiyama and Kazuyuki Mihara: Behavior of Water Molecules in the lacquer film, the main purport of the lecture presented at the General Research Meeting on the Paint and Coating Techniques (1990)
- (4) David R. Bauer: Chemical Criteria for Durable Automotive Topcoats, Journal of Coatings Technology, Vol. 66, No. 835, 1994

■ Authors



N. TAKAZAWA



Y. YAMAMURA



R. SHIMAZAKI

Construction and Implementation of Internal Management System for Hazardous Substances

Kengo Ando*
Yoshihisa Nakagawa*
Yuji Kiyono*
Chikashi Ogura*

Abstract

Environment issues involving a great diversity of chemicals have been discussed both domestically and internationally in recent years, and internal management and voluntary reduction of the release and transfer of potential hazardous chemicals, even though they are not regulated, in the environment have been required. This paper states the internal management system of hazardous chemicals at Toyota Motor Corporation.

The internal management system of hazardous chemicals should be considered at consumption and discharge phases. The main structures of the consumption phases are (1) The Toyota Hazardous Chemical List which were developed by a survey of domestic and overseas environmental laws and regulations and (2) the collection system of chemical content data from the suppliers of raw material.

The main structures of the discharge phase are (1) Data base of environmental potential impact chemicals and compounds, (2) Information system of raw materials consumption at each department, (3) Data base of transition factors between and in the manufacturing process, and (4) Data base of meteorology for dispersion model.

Keywords: hazardous substance, internal management system, prior environmental inspection system, reduction of potential hazardous substances

1. Introduction

In recent years, environmental issues involving a great diversity of chemicals have been discussed both domestically and internationally. **Table 1** indicates the change of control measures for the environmental issues caused by hazardous substances. Conventionally, such measures were promoted mainly for the environmental problems that affect the health of human beings with heavy pollution, and today, control measures are being taken accordingly under various laws and regulations. The environmental issues caused by chemicals as being discussed today (problems of hazardous substances) are centering around the long-term effect of low concentration of various chemicals on the health of human beings and ecosystem. Thus

it is required to voluntarily manage and reduce potentially hazardous substances not yet legally controlled from being released and transferred into the environment.

2. Prior Environmental Inspection System

To realize environmental protection, it is important to take appropriate measures by assessing effect on the environment in advance when newly expanding the plant or introducing new materials and or new processing technologies. We, at Toyota Motor Corporation (hereinafter called Toyota) established the prior environmental inspection system in 1984. We implemented prior inspections and took countermeasures on various projects from the aspects of environmental protection (against air pollution, odor, water pollution, noise, vibration and wastes) and the safety and health (of the working environment) (see **Table 2**). Moreover, with the objectives of implementing appropriate management of chemicals, we revised the above system partly in 1994 to make it applicable to the management of chemical substances (see **Fig. 1**).

2.1 Outline of Prior Inspection System

Material and auxiliary material (hereinafter referred to as indirect material, see **Table 3**) consumed in the plant are provided with part number for each merchandise name and assembled

Table 1 Change of Environmental Issues Caused by Hazardous Substances

	Pollution problem	Hazardous chemical problem
Number of chemical	Few	Many
Contamination level	High concentration	Low concentration
Exposure period	—	Long
Impact	Human health	Human health and ecosystem
Measures by enterprise	Conformity with laws and regulations	Voluntary management and reduction efforts

* Plant Engineering Div.

Table 2 Contents and Items for Examination under the Prior Inspection System

●: Subject of examination

Item		Project	Green field project	New equipment installation, modification and expansion	New adoption/substitution of materials
		Content	• Building specifications • Process layout	• Equipment specifications • Abatement equipment	• Check acceptability of use • Abatement method
Safety and health Environment	Working environment		●	●	●
	Air emission		●	●	●
	Odor		●	●	●
	Waste water			●	●
	Noise and vibration		●	●	
	Wastes			●	●

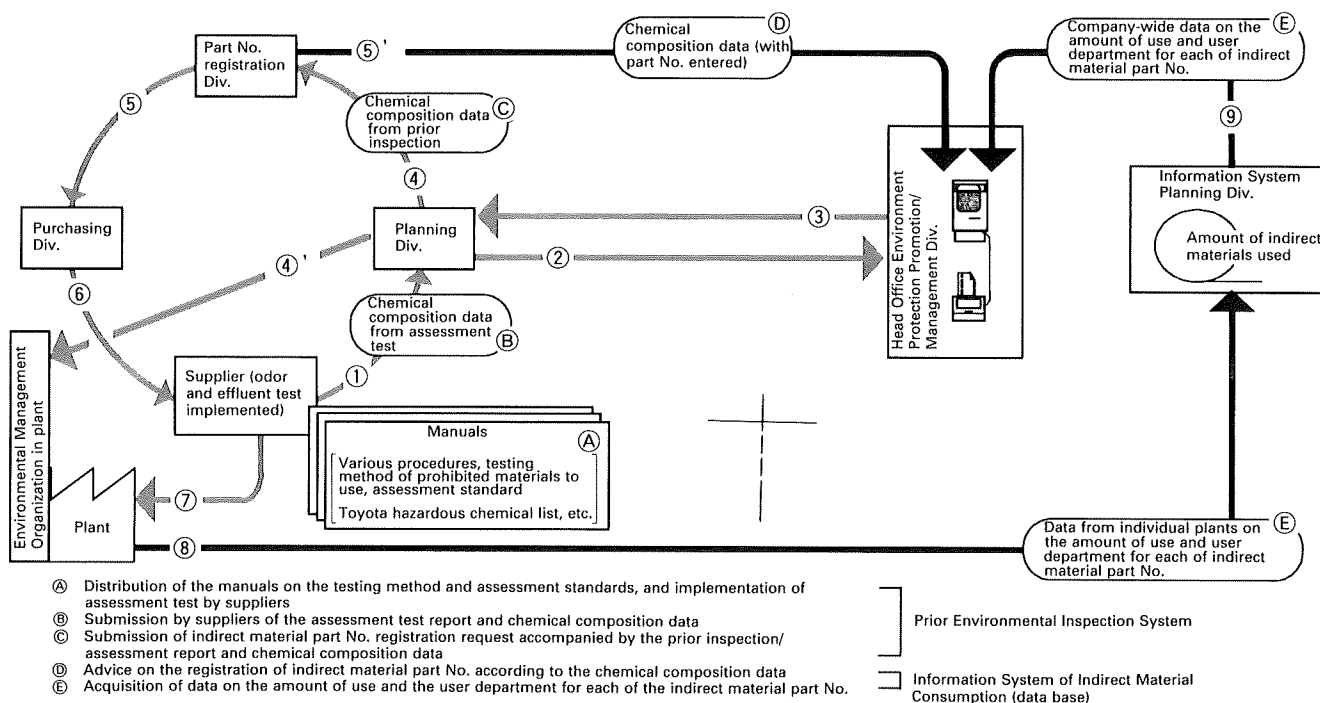


Fig. 1 Outline of Prior Environmental Inspection System for Indirect Material (Including Information System on Indirect Material Consumption)

Table 3 Classification List of Indirect Material

Paint	ED	Antirust wax	Cleaning and de-greasing agent	Resin, polyol and isocyanate
	Primer	Exterior wax	Antirust chemical	Waste water treatment chemical
	Interior	Thinner	Plating agent	Antiscales
	Solid	Paint killer chemical	Electro-chemical machining agent	Semiconductor
	Metallic	Paint strip chemical	Surface treatment agent	Reagent for laboratory
	Blackout	Lubricant and operation oil	High pressure gas	Indirect casting material
	Anti-chip	Cutting and grinding oil	Adhesive	Others
	Others	Stamping process oil	Mold release solvent	
	Body sealer	Quenching oil	Stamping and lubricant oil	

form. This makes it possible for the departments in the plant to purchase and use material they need.

The Prior Inspection System incorporates the part number registration divisions in the system. This prevents a new Request Sheet for Part No. Registration from being assigned a part number unless the request is accompanied by an assessment results report issued by the division concerned. Thus this system checks and prevents unassessed or rejected indirect material in the prior assessment from being used for manufacturing.

2.2 Chemical Substance Management in the Prior Inspection System

Toyota extracted 2,232 chemical substances for its internal management from the domestic and foreign laws and regulations related to the safety, health and environment protection (see **Table 4**). The company listed them in the "Toyota Hazardous Chemical List." We request our suppliers of indirect material that contains a fixed amount and over of the listed substance to submit their chemical composition data (or statement to the effect that their material does not contain the listed substance in the event their material is free of such substance). (For the existing indirect material the chemical composition data were submitted during the period from July 1994 to December 1995, and for the new indirect material, from July 1994.)

Registration of used chemical substances makes it possible to create the "Data Base of Chemicals Used in Toyota" by which the user section or department of any specific chemical substance within the company can be retrieved. Moreover, the chemical composition data provided by the suppliers on newly introduced indirect material enables to implement a permanent prohibition of listed material by checking the indirect material containing in-house prohibited chemical substances.

Table 4 Sources for Toyota Hazardous Chemical List

Classification		Source
Domestic	Safety and health	Regulations for the prevention of injury from designated chemical substances; Regulations for the prevention of poisoning by organic solvents; Laws for the regulation of poison and toxic substances
		Guidelines for the prevention of damage to health from epoxy resin curing agents
		Substances suspected of being carcinogenic by the International Agency for Research on Cancer (IARC), etc.
		Substances for which the ACGIH permissible concentration is less than 100 ppm (or less than 100 mg/m ³)
Environment	Laws related to the regulation of inspection and manufacture of chemical substances	
	Basic environmental laws: Water Pollution Control Law; Air Pollution Control Law; and Odor Regulation Law	
	Laws related to waste disposal	
	Municipal and prefectural regulations, plans and guidelines in areas where Toyota Motor Corporation and its affiliates are located	
	Priority list for the second general inspection and examination of the safety of chemical substances	
	Clean Water Act (Clean water act and restriction of discharge)	
North America	Clean Air Act (Clean air act; restriction of discharge and abnormal effluent prevention)	
	Proposition 65 (New environmental control for California; restriction of discharge)	
	SARA Section 313 (Citizens' right-to-know law; disclosure of information on chemical substances and response in the event of a chemical release)	

3. Grappling with the Reduction of the Release and Transference of Potentially Hazardous Chemicals

This section and the following sections devote to describing our grappling with the environment-related aspects while omitting the safety and health matters for the present time.

Toyota strengthens voluntary management of chemical substances by giving consideration to their effect on the environment.

By this time, it has almost completed the reduction of the release and transference of regulated substances to the environment through the application of the internal prohibition measure or controlled method of use. As to non-regulated substances, we are investigating the state of application of candidate chemicals for the listing as a hazardous substance selected on the basis of "Data Base of Environmental Potential Impact Chemicals and Compounds." We are carrying on the calculation of the environmental target concentration. At the same time, we need to investigate the dispersion rate that relates the allowable discharge level to the environmental target concentration both as the management index. To this end, we, at a model plant, conduct the observation and recording of the direction of the wind, velocity and atmospheric stability (solar radiation intensity and differential radiation).

3.1 Basic Conception

Toyota has thus far grappled mainly with the management of regulated chemical substances in conformity with the current laws and regulations concerning toxic chemicals, but it now gives priority in managing non-regulated chemicals (see **Table 5**).

Table 5 Basic Conception on the Reduction of Release and Transference of Hazardous Chemicals to the Environment

Basic conception		Related laws and regulations	Examples of subject substances
Regulated substance	Prohibition of in-house use of chemical substances whose manufacture is prohibited	Regulation of Ozone Layer Protection; laws related to the regulation of inspection and manufacture of chemical substances (Specific chemical substance Class 1)	Tetrachlorocarbon 1,1,1-Trichloroethane CFCs PCB, etc.
	Prohibition of in-house use of non-treated hazardous chemical substances under regulation	Water Pollution Control Law	Cadmium, cyan, mercury, organophosphorus compound, trichloroethylene, dichloromethane, etc.
Non-regulated substances	Strengthening of voluntary management considering chemical impact to the environment	—	Candidate substances for the listing already selected

Regarding the regulated chemicals, if their abatement measure is difficult, Toyota prohibits in-house use of approximately 150 hazardous chemicals (including compounds) already under legal control, needless to say those whose manufacture is prohibited, by the environmental protection laws and regulations. This is in consideration of the process to the regulation (such as the environmental risk, result of monitoring by the autonomous bodies, etc.). The existing indirect materials are substituted and the newly introduced indirect material is checked under the Prior Inspection System.

On the other hand, with regard to the non-regulated chemicals, candidate substances subject to in-house management are selected on the basis of environmental risk (impact to the environment), amount and the state of use and the countermeasures are presently under examination.

3.2 Outline of Steps Being Taken

Table 6 outlines the steps being taken according to the basic conception as stated in Section 3.1. Different steps are taken for different chemicals involved, but every chemical prohibited to manufacture is automatically prohibited to use. And necessary measures are being taken for substances under control by the current laws and regulations by grasping the state of abatement through the examination on the present state of use.

On the other hand, non-regulated chemicals are subject to a full-course examination for designation as the candidate substances that may release and transfer hazardous substances to the environment, investigation on the state of use, decision on the need for taking countermeasures, and the selection of such measures. This section states the steps we are taking particularly for non-regulated chemicals as follows.

3.3 Steps for Non-regulated Substances for Reducing their Release and Transference to the Environment

3.3.1 Selection of Candidate Substances that May Release and Transfer Hazardous Substances to the Environment, and Calculation of Tentative Target Emission for Management

Table 7 outlines the indexes used for sorting the environmental impact brought by chemicals by the type and rank as these data are needed for selecting the candidate substances. **Table 8** indicates the sources of those index data adopted. The overall ranking of the environmental impact of chemicals will be determined with the top ranking impact of the individual impact types (global environmental factors are to be separately added). The ranking for the individual impact types of chemicals (see **Table 9**) is determined by giving consideration to their exposure performance (such as volatility, bioaccumulation and biodegradation, etc.) but this paper will not go into the detail, however. Using such data base, chemical substances having a high overall ranking are selected as the candidate chemicals that release and transfer hazardous substance to the environment. At the same time, tentative allowable discharge level for the candidate impact substances to the atmosphere and water is calculated on the basis of the environmental target concentration and the tentative dispersion rate.

Table 7 Outline of Environmental Impact Data Base

Type of environment impact		Index
Global environment	Depletion of ozone layer	Ozone layer depletion potential
	Global warming	Global warming potential
Area environment	Odor	Threshold odor number (subject: paint solvent for the time being)
	Human beings [atmosphere and water]	Toxicity (Carcinogenicity, teratogenicity, chronic toxicity (inhalation), and chronic toxicity (oral))
	Aquatic organism [water]	Toxicity (ecotoxicity)

Table 6 Outline of Steps being Taken for the Reduction of Release and Transference of Hazardous Substances to the Environment

●: Subject item

Steps being taken		Regulated substance		Non-regulated substance
		Manufacture prohibited	Regulated hazardous substance	Voluntarily managed substance
Selection of environmental impact substance			●	●
Investigation on state of use	Grasping state of abatement		●	●
	Grasping of shifted media and rate			●
	Calculation of dispersion rate through meteorological observation, etc.			●
Decision on need for reduction		●	●	●
Implementation of reduction	Prohibition to use	●	●	●
	Limitation of amount of use			●
	Limitation on the method of use (abatement, etc.)		●	●

Table 8 Sources for Indexes Adopted for the Environmental Impact Data Base
(Object: Human Beings; Environmental Media: Atmosphere and Water)

Toxicity	Data type	Source of data
Carcinogenicity	IARC ranking of carcinogenicity	IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, International Agency for Research on Cancer (IARC) (1993)
	USEPA ranking of carcinogenicity	Integrated Risk Information System (IRIS), USEPA (1995)
	ACGIH ranking of carcinogenicity	1994 -1995 Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices, ACGIH (1994)
	WHO European air quality guidelines (unit risk)	Air Quality Guidelines for Europe, World Health Organization Regional Office for Europe
	WHO drinking water quality guidelines (concentration)	Guidelines for Drinking-Water Quality, World Health Organization (1993)
	USEPA unit risk	Integrated Risk Information System (IRIS), USEPA (1995)
	USEPA water quality criteria (concentration)	Water Quality Criteria, U.S. Environmental Protection Agency (USEPA) (1984)
Chronic toxicity	WHO European air quality guidelines (concentration)	Air Quality Guidelines for Europe, World Health Organization Regional Office for Europe
	WHO drinking water quality guidelines (concentration)	Guidelines for Drinking-Water Quality, World Health Organization (1993)
	USEPA chronic toxicity and safety coefficient	Integrated Risk Information System (IRIS), USEPA (1995)
	USEPA water quality criteria (concentration)	Water Quality Criteria, U.S. Environmental Protection Agency (USEPA) (1984)

Table 9 Ranking of Chemical Substances on the Basis of Environmental Impact Data Base
(Example for Human Beings and Aquatic Organism)

[Environmental impact; (Large)A>B>C>D(small)]

Toyota List No.	CAS No.	Substance name	Human beings					Aquatic organism				Overall ranking
			Carcinogenicity, etc.	Atmosphere (Chronic toxicity)	Water (Chronic toxicity)	Atmospheric ranking ●	Water ranking ◆	Fish (Acute toxicity)	Water flea swimming disturbance	Algae growth disturbance	Aquatic organism ranking ▲	
111111	1111-11-1	①	B	A	B	A	B	C	B	D	B	A

Table 10 Output Example of Data on the State of Use

[Environmental impact; (Large)A>B>C>D(small)]

Indirect materials in use				Department using indirect materials				Amount of use					
Part No.	Product name	Supplier	Maker	Dept. code	Plant	Div.	Dept. and section	Amount of indirect materials used (kg/month)				Substance A	
								Jan. '96	Dec. '96	Total		Chemical content	Amount of use (kg/year)
Y861500001	□□-◇◇	○○ Trading	△△ Chemical Industry	KX354	◇◇	○○○○	□□□□	1,335	----	1,357	11,608	5.3%	614

3.3.2 Investigation of the State of Use and Decision on the Need for Taking Protective Measures

Toyota has expanded the Prior Environment Inspection System stated in Section 2. It has built the "Information System on Indirect Material Consumption" (see Fig. 1) by which monthly consumption of indirect material by respective departments concerned (location of use) is recorded. This system is linked to the "Data Base of Chemicals Used in Toyota" to allow us to understand the amount of use of the indirect material that contains candidate environmental impact chemical and the plant (departments) using such substance. Table 10 indicates an output example of the usage data. These data help us take efficient measures to the source of hazards.

Fig. 2 shows a flowchart on the reduction steps of the envi-

ronmental impact emission to the atmosphere and water. In the case of the atmospheric risk, impact assessment is made as the first step by comparing the tentative allowable discharge level calculated in advance with the amount of use by whole of a plant concerned under an assumption that 100% of the amount used is emitted to a fixed environmental medium. If the actual amount of use is lower than the tentative allowable discharge level, the material concerned is removed from the list of substances for reduction for the time being.

Then, as the second step, coefficient of the transfer to the environmental medium is grasped from the investigation (measurement) conducted by the user department on the actual state of use of the chemical in question. The amount of transfer is then distributed to the environmental media. For example, suppose that the result of investigation on the state of use should

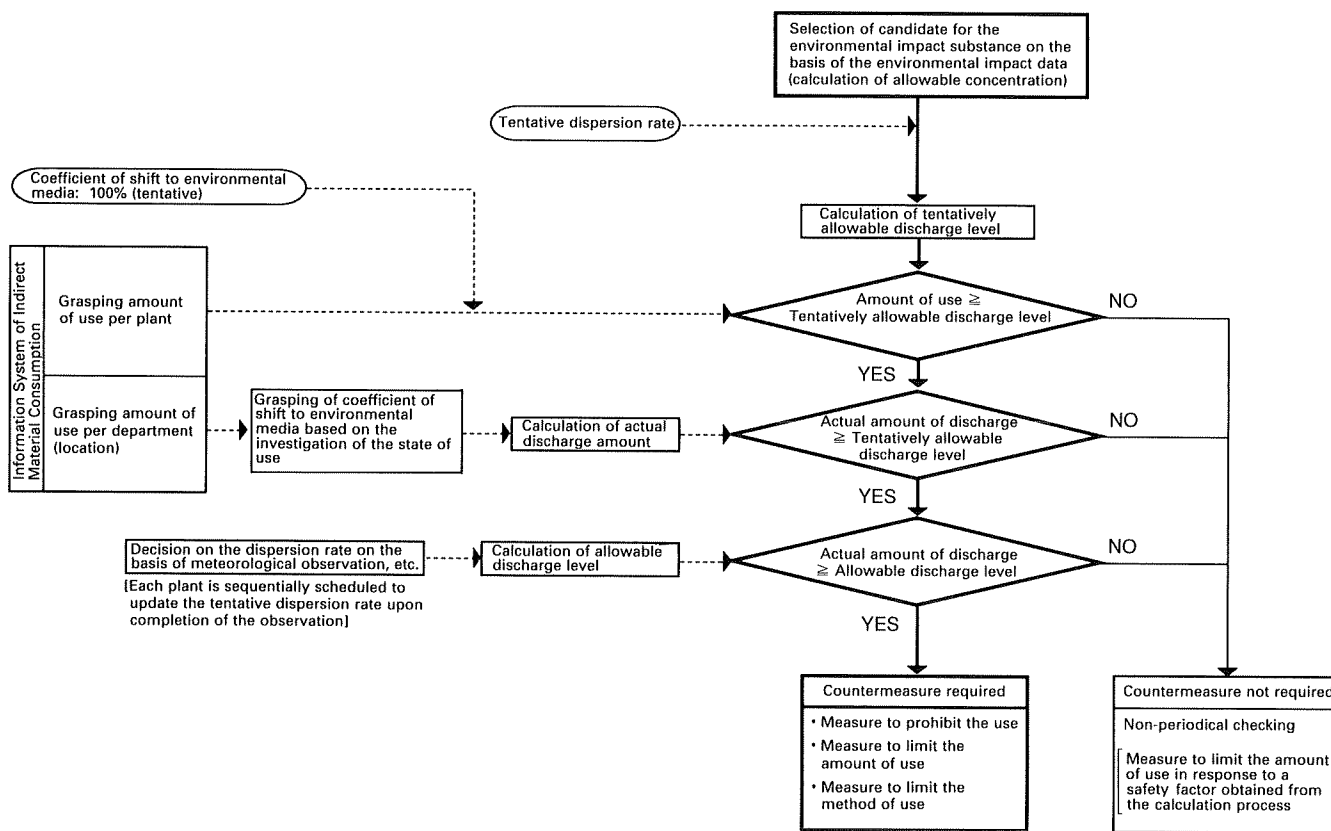


Fig. 2 Recapitulation of Chemical Substance Management for the Reduction of the Release and Transference of Potential Hazardous Chemicals

distribute 40% of transference to the atmosphere, 30% to the effluent (shift from the waste water treatment facilities to the environmental media such as the atmosphere, wastes, etc. is considered) and 30% to the wastes. If 40% of amount used is lower than the tentative allowable discharge level by the atmospheric risk as the actual emission, then the chemical concerned is removed from the list of substances for reduction for the time being.

Lastly as the third step, the allowable discharge level calculated from the dispersion rate determined on the basis of actual measurement in the plant concerned is compared with the actual emission based on the result of investigation on the state of use. If the actual emission is smaller than the allowable discharge level, the substance concerned is removed from the list of substances for reduction for the time being.

We decide whether countermeasure is required for the time being for the environmental impact substance after passing these three steps. The setting level of safety coefficient to the allowable discharge level is a major factor in determining the need for the countermeasure. The identical steps are taken basically in determining the need for countermeasures for the water risk.

On the other hand, in the case of wastes, it is difficult to set

the criteria for the reduction of the release and transference of potential hazardous chemicals which are equivalent to the allowable discharge level in the cases of the atmosphere and water. Therefore, it is necessary for us to promote the reduction of environmental impact from both the qualitative and quantitative aspects by putting up a voluntary reduction target along with, needless to say, appropriate processing and disposal (including the recovery and transport) of wastes to the fullest extent.

3.3.3 Selection of Countermeasures

Reduction of the release and transference of potential hazardous chemicals to the atmosphere and water is based on three types of measures; namely the prohibition of use, limitation on the amount of use, and the limitation on the method of use. However, the measures to select for an early achievement of actual effect differs by the current environmental impact level, environmental media concerned, the method of use and so forth.

For example, if the current level of the release and transference of hazardous chemicals to the environment (actual emission of an object chemical/allowable discharge level) is close to

1, the measure to control the amount of use should have the priority. If the level should exceed 1 and the substance concerned is an object of the atmospheric risk and that it is in use at a number of scattered locations, then the prohibition of use may possibly have the priority to the control of the method of use. In the case of the water risk, however, the measure to control the method of use (abatement measure, etc.) may have the priority to the prohibition measure even if the environmental impact level is the same, because there is less necessity for giving consideration to the dispersion of the hazard within the plant.

4. Conclusion

Toyota is grappled with the reduction of the release and transference of potential hazardous chemicals. As shown in **Fig. 3**, Toyota applies the "Data Base of Chemicals Used in Toyota" stated in Section 2 of this report, the "Data Base of Environmental Potential Impact Chemicals and Compounds" and "Information System of Indirect Materials Consumption" in Section 3, and the data from its investigation on the state of use of actual substances on the worksites concerned and from the meteorological observations for implementing appropriate management of chemical substances.

In the future, we will promote an efficient implementation of the hazardous chemical management through its domestically and internationally related enterprises (All Toyota Environmental Management Committee: 20 member companies and All Toyota Environmental Liaisons Committee: 112 member companies), including the educational activities for our suppliers.

Authors wish to express their deep sense of appreciation to our suppliers for their assistance in submitting the chemical

composition data on their products for the creation of the "Data Base of Chemicals Used in Toyota"; to Mr. Kohei Urano, Professor, Faculty of Engineering, Yokohama National University for his valuable information and assistance in the creation of the "Data Base of Environmental Potential Impact Chemicals and Compounds" and to all other individuals concerned for their cooperation.

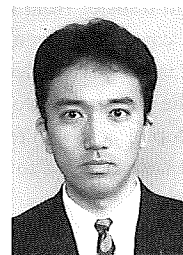
■ References

- (1) Kengo Ando: "Prior Environmental Inspection System and Chemical Substance Management of Toyota Motor Corporation", purport of the 7th Lecture Meeting on the Environmental Chemistry, P.53-64 (1996)
- (2) Tetsuo Iwai and Kengo Ando: "Voluntary Management of Potentially Hazardous Chemical Substances at an Automotive Manufacturing Plant", Journal of the Japan Society of Waste Management Experts, Vol. 8, No. 2, P.128-138 (1997)

■ Authors



K. ANDO



Y. NAKAGAWA



Y. KIYONO



C. OGURA

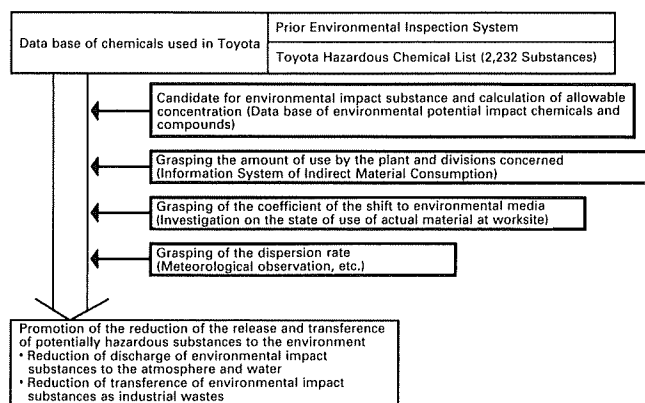


Fig. 3 Recapitulation of Chemical Substance Management for the Reduction of the Release and Transference of Potential Hazardous Chemicals

Development of Improved Appearance Acid-rein Resistant Metallic Paint

Mikio Asai* Akihiro Watanabe* Hitoshi Kato**
Susumu Umemura* Masataka Muramatsu*

1. Introduction

We have developed and applied acid-rain resistant paint to part of vehicles to prevent paint film damages caused by acid-rain to the vehicles in the market. Problem is pointed out, however, that the paint has a narrow workability range to realize good appearance. To solve this problem, we have analyzed the resin characteristics and behavior of viscosity, etc. of the paint and checked the mechanism. On the basis of the analytical results, we have developed a new metallic paint having improved appearance equivalent to that of conventional paint with acid-rain resistance.

2. Outline

Comparison of acid-rain resistant paint with conventional paint on the resin composition reveals that the acid-resistant paint is designed with a larger amount of functional group to provide the paint with acid resistance. We assumed that because of this difference in the amount of functional group, the base coat and clear coat mix with each other more easily and the solvent transfer from the clear layer to the base layer become remarkable, causing difference in the appearance. To reduce the mixture level, it is effective to decrease the amount of functional group contained in the clear paint. A simple decrease, however, is expected to cause the drop of acid-rain resistance and other performance. Consequently, we have decided to blend a new special resin component as shown in **Fig. 1**.

As the result, we could obtain ΔSP (Solubility Parameter), the index of the mixture level, almost equivalent to that of the conventional paint as shown in **Fig. 2**. This led to a sharp reduction of mixture level and an expanded workability range was achieved.

As the result of measuring the 3-dimensional roughness of the film of the developed paint, we have verified that the surface of this paint has an appearance comparable with that of the conventional paint. (**Fig. 3**)

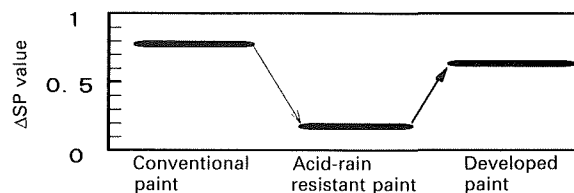


Fig. 2 Mixture Level with Respective Paint Systems (Comparison of ΔSP Values)

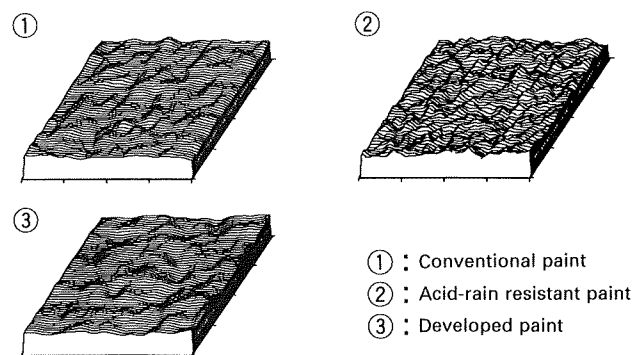


Fig. 3 Paint Film Surface Roughness (Vertical sprayed Surface)

3. Conclusion

- (1) We estimated the appearance formation mechanism with the acid-rain resistant paint and clarified the relationship with the paint characteristics.
- (2) Accordingly, we have developed an epoch-making metallic paint realizing both the acid-rain resistance and the improved appearance.

■ Reference

- Charles M. Hansen, K. Skaarup: Journal of Paint Technology, Vol. No. 511, P.511-514 (1967)

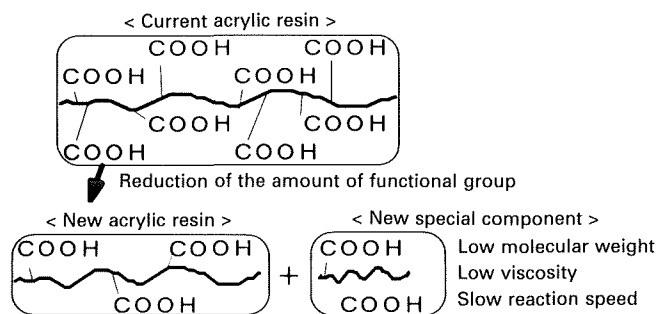


Fig. 1 Introduction of New Resin Component

* Material Engineering Div. II
** Surface Finishing Engineering Div.

Mechanical and Thermal Properties of Si₃N₄ with Oriented Microstructure

Hidemitsu Sakamoto*

1. Introduction

Si₃N₄ material has been adopted for the reciprocating engines. It is now desired that the material manifests compatibility of high fracture strength and toughness, and high thermal conductivity to meet its new application to a sliding component, porous material, heat sink material and so on. In the present study, we have newly synthesized β -Si₃N₄ rod-like powders and attempted to create an Si₃N₄ sintered body with an anisotropic structure where the elongated grains are highly oriented to an axial direction. We have examined possible compatibility of high fracture strength and toughness as well as high thermal conductivity by introducing anisotropy to the structure.

2. Outline

The homogeneous rod-like powders with high aspect ratio were synthesized through heat-treatment of Si₃N₄ powder with Y₂O₃ additive. In the present study, the extrusion as the forming method was applied to make orientate those synthesized rod-like powders. Forming of rod-like particles alone failed to successfully orient them as the aggregated particles were extruded without orientation. To solve the problem, the spherical α -Si₃N₄ powders with lubricating effect were added for the purpose of dispersing rod-like powders. The results showed that the aggregation of rod-like powders were relieved, resulting in a sintered body with high degree of orientation to an axial direction. **Photo. 1** shows the SEM photographs for the sintered body with oriented microstructure.

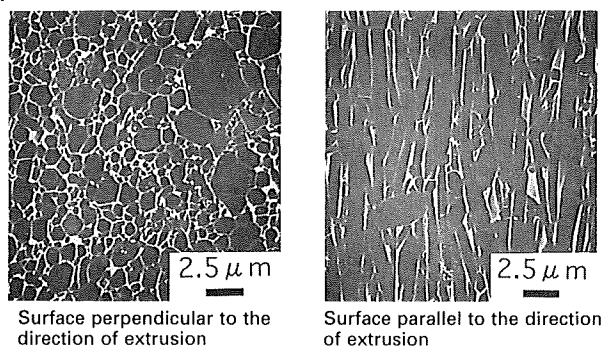


Photo. 1 SEM Photographs for Sintered Body with Oriented Microstructure

Fig. 1 shows the relation between the sintering temperature and fracture strength, and K_{Ic} of the oriented sintered body. A maximum strength of 1310 MPa was observed in rein-forced direction with elongated grains. Particularly we observed a K_{Ic} of approximately 13 MPa $\sqrt{m}$ which is equivalent to two times that of conventional Si₃N₄. We have thus obtained an Si₃N₄ material having both a high degree

of fracture strength and toughness. A large difference was observed with both the strength and K_{Ic} depending on the direction of applied stress, this indicating their apparent anisotropy.

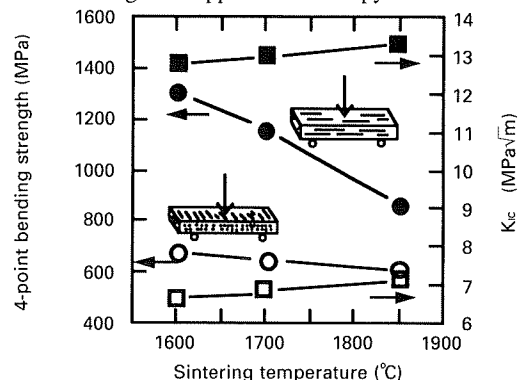


Fig. 1 Change in Fracture Strength and K_{Ic} According to Sintering Temperature

Fig. 2 shows the relationship between the degree of orientation and thermal conductivity of an oriented sintered body. The thermal conductivity in the direction parallel to the elongated grains shows a value approximately three times that of the conventional Si₃N₄. A maximum thermal conductivity of 145 W/mk was observed by sintering with further heat treatment.

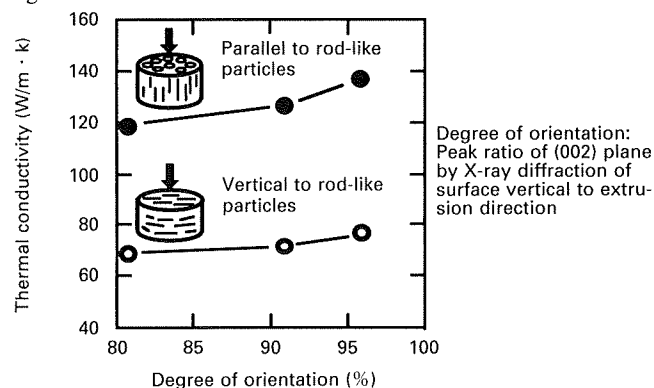


Fig. 2 Degree of Orientation and Thermal Conductivity

3. Conclusion

Sintered Si₃N₄ having controlled orientation of elongated grains has both a high fracture strength (1310 MPa) and a high fracture toughness (12.7 MPa $\sqrt{m}$). Since it shows a high thermal conductivity (145 W/mk) comparable with metal, it is a potential material for new applications.

* Material Engineering Div. III

Development of Lane Change Control Using Yaw Rate Sensor

Tomoyuki Doi* Akihide Tachibana* Toshihiko Suzuki*

1. Introduction

When a vehicle equipped with AHS (Automated Highway System) is tracking the lane by referring to the lane marker, the vehicle comes across a section where it cannot refer to the lane marker during the process of lane change for evading an obstacle, etc. As a method for controlling the vehicle while on such a section, we have developed a lane changing method using a yaw rate sensor.

2. Outline

We decided to realize the lane change control by the following three steps: (1) Generation of the objective trajectory; (2) Estimation of the vehicle position; and (3) Vehicle control.

Objective trajectory : The lane change trajectory is determined by the distance to an obstacle, lateral acceleration generated, and ride quality. **Fig. 1** shows a schematic diagram of evasive maneuver.

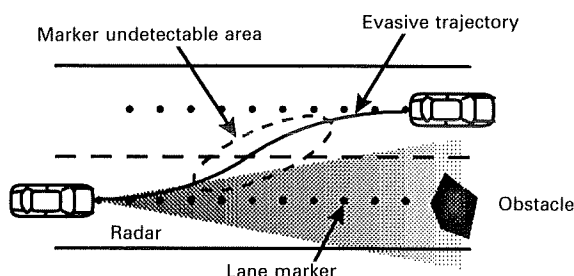


Fig. 1 Schematic Diagram of Lane Change

Estimation of vehicle position : Error factors involved in estimating the vehicle position using the yaw rate sensor output⁽¹⁾ include errors by the slip angle, yaw rate offset γ off, and the initial yaw angle error θ err. Effects of slip angle may be calculated for correction by the vehicle model. We implemented the correction of the yaw rate offset and the initial yaw angle error with Δy and $\Delta \theta$ as shown in **Fig. 2**.

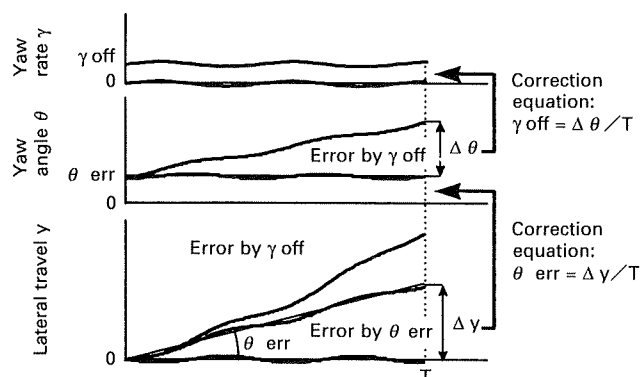


Fig. 2 Position Estimation Error and Correction

These corrections resulted in sharply improving the vehicle position estimation accuracy. (**Fig. 3**)

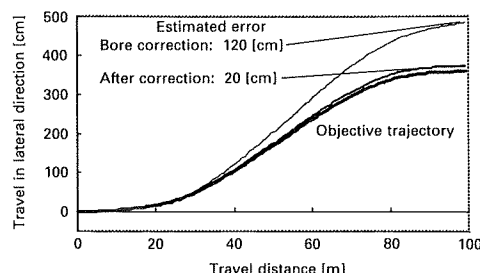


Fig. 3 Simulation Result of Position Estimation

Vehicle control : We implemented vehicle control by applying the sum of the feed-forward steering angle following the objective trajectory and the feedback steering angle by PID control as the steering angle instruction.

Result : To assess the effect of position correction, we compared the lane changes before and after implementing the correction. **Fig. 4** shows the result. The horizontal axis represents the initial yaw angle that constitutes the major error factor for the estimation of the position. The vertical axis assesses the lateral deviation control performance after a lane change. As the result, the correction enables stable lane change irrespective of the initial yaw angle.

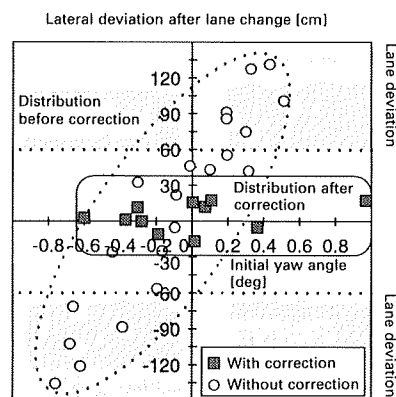


Fig. 4 Result of the Control Implemented

3. Conclusion

We have developed a high accuracy position calculation method and achieved stable lane change control.

■ Reference

- (1) Masato Abe: Sharyo no Undo to Seigyo (in Japanese), Kyoritsu Shuppan, P.37 (1979)

* Future Project Div.

Development of Chip-Absorbing & Compacting-System in Turning

Keisuke Tamura* Takeshi Shibuya* Syoji Kinoshita*

1. Introduction

Conventional cast iron turning requires a large amount of coolant for washing and cleaning chips, which causes in-plant mists, liquid waste and odor. Chips wet with coolant are recycled to the casting process (Fig. 1). To avoid a steam explosion in the molten metal and maintain fusibility, chips are dried and compacted by a subcontractor. During the drying process, approximately 20 to 30% of the chip surfaces are oxidized, possibly generating slag in the molten metal to eventually decrease the recycling rate as metal. To solve these problems, it is necessary to do away with the coolant and develop a new machining method that scatters no chips. With this regard, a chip absorbing and compacting system that sucks (absorbs) chips at the cutting point and completes compaction within the cutting machine has been developed.

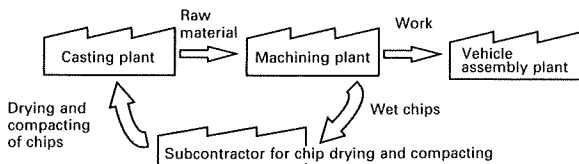


Fig. 1 Recycling Route of Chips

2. Outline

The absorber unit at the cutting point uses a suction hood mounted on the tool holder to absorb chips with a negative pressure (Fig. 2).

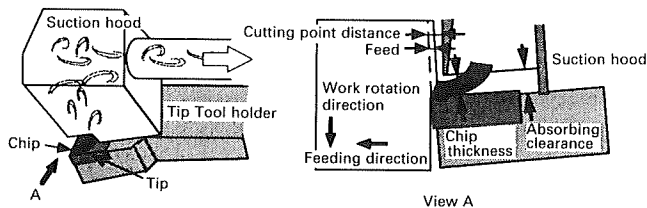


Fig. 2 Absorbing Unit at Cutting Point

To prevent the suction hood from interfering the chips and work, the following conditions have to be met:

Cutting point distance > Feed

Absorbing clearance > Chip thickness ($\cong 2 \sim 2.5 \times \text{feed}$)

A test was conducted to determine the degree of chip-absorb-rate by changing those factors. As the result, it has been found that if the cut point to the holder is close to the feed value, enabling a maximum of 95% of chips to be collected (Fig. 3).

As the result of a phenomenal analysis using a recorded video tape to further raise the chip absorbing rate, it has been found that the chip emitting direction that points to outside the chip-absorb-holder leaves several percent of chips unrecovered.

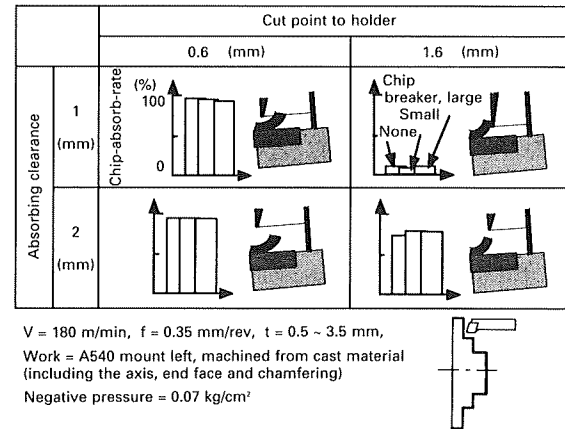


Fig. 3 Effects of Factors to the Chip-Absorb-Rate

As a means to improve the chip-absorb-rate, there is, for instance, a method for separately installing another chip-absorb-holder bite dedicated for cutting slant surface, but this sacrifices general-purpose workability of the machine. Consequently improvement of the chip absorbing rate by increasing the negative pressure was attempted. A vacuum unit that provides practically the highest negative pressure was used but the highest absorbing rate realized was about 97%. It was difficult to achieve 100% collection.

Conversely, it was reconsidered that the scattering of chips can be fairly well controlled by using a negative pressure of about 0.07 kg/cm² which is not so high. Thus a system having a compact vacuum unit in consideration of the cost and space saving was configured. Moreover, to realize a 100% chip recovery rate as the equipment, a system with a secondary absorbing unit was directly coupled to the chip-compacting unit. The chip-absorbing and compacting unit introduced here has been completed in this way (Fig. 4). This system has been in operation since October 1997.

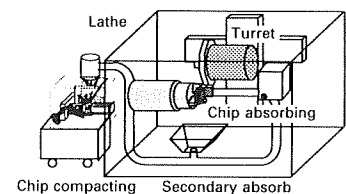


Fig. 4 Chip-Absorbing and Compacting System

3. Conclusions

- (1) A chip absorbing technology for cast iron and has been devised to realize a chip-absorbing and compacting system.
- (2) The plant environment and recyclability are both improved to satisfy the development objectives.
- (3) In the future, the same technology for steel and aluminum is planned to be established.

The authors wish to acknowledge the assistance and cooperation of Mitsubishi Materials Corporation and Fuji Machine Mfg. Co. in the implementation of this development.

* Machines & Tools Engineering Div.

Development of Quantitative Engine Measuring Technology

Naoyuki Maruta*

Nobuaki Suzuki*

Akiji Hayashi*

1. Introduction

Delivery inspection of engines at the engine manufacturing plant was conducted by the inspection staff in a driving test under their own power (firing) using combustible materials during the final process. Unusual noise, vibration and any other defects were detected and the causes were determined by the staff with overhaul, etc. which took fair amount of time. In the present development, we paid attention to the three principal factors for normal combustion; namely the valve timing, arc energy, and the air-fuel-ratio. We measured respective variables in the course of assembly and conducted inspection to specify the cause of abnormalities at the preceding processes. As the result, we could attain product quality better than under the conventional inspection, hence discontinued the firing test.

2. Outline

Defects detected under the conventional firing test are classified by phenomenon into five items including the unusual emission. The defects can be also classified into those that occur under normal combustion and those that prevent normal combustion (Fig. 1).

Since it is difficult to apply a quantitative measurement to engines having defects under normal combustion, we drive an engine with an electric motor and assure its quality with sensory inspection. Normal combustion is assured with the valve timing, arc energy, and the air-fuel-ratio and the sampling inspection by variables are conducted.

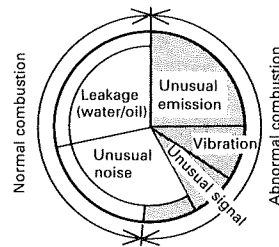


Fig. 1 Classification of Defects

- ① Valve timing: By noticing that the air flow changes with the opening/closing of valves, exhaust pressure changes are measured by driving the engine with the motor (Fig. 2).
- ② Arc energy: We paid attention to the primary voltage of the ignition coil as ignition occurs with the transformation of the ignition coil. We found that defectives such as crushed spark plug gap cause difference in the ignition time (Fig. 3). In addition, to eliminate disturbances of compression pressure, we conducted measurement with the engine in stopped state. This resulted in suppressing dispersion in measurement and we could obtain better detection performance than the firing test.
- ③ Air-fuel-ratio: Instead of combustible materials, compressed air is used as the measuring medium in measuring the injection flow.

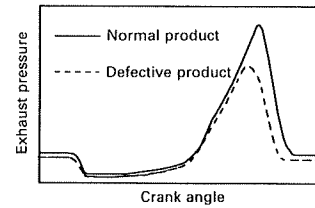


Fig. 2 Exhaust Pressure Wave

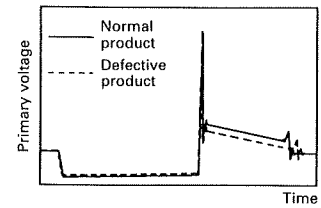


Fig. 3 Primary Voltage Wave

With regard to ① and ② above, inspection process is arranged within the assembly line since engines are not yet assembled with exterior parts and available for inspection at this stage of processing.

We have assessed the detection performance of the developed measuring technology in comparison with the conventional firing test about defects that occurred in past. As the result, we have found that the developed technology has superior detection performance to the firing test and we have been able to discontinue it (Fig. 4).

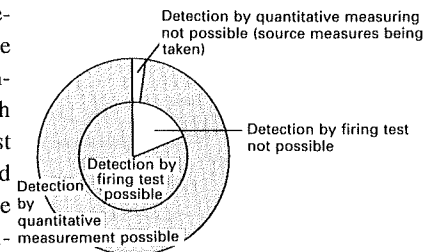


Fig. 4 Comparison of Defect Detection Performance

3. Conclusions

- ① We have established a quantitative measuring technology that can specify the cause of abnormality.
- ② We have arranged an inspection process within the assembly line to enable early detection and feedback of defects.
- ③ We have improved the environment by discontinuing the firing test.

* Machines & Tools Engineering Div. (Instrumentation Engineering Div. Technical Support Group)

Development of Virtual Tryout Technique by Stamping Simulation

Hideo Tsutamori* Toru Kato* Shin Ikura*

1. Introduction

To reduce the production preparation lead time, it is necessary to promote the development of simplified product shape, simultaneously manufacturing panels of high accuracy within a short period of time. In the present research, we have analyzed total processes including deformation after separating the molds and implemented a computerized tryout (virtual tryout) in a simulation of the press forming process. From the result of this study, we indicate that it is fully possible to incorporate defective measures for formability and accuracy through the virtual tryout prior to metal mold casting.

2. Outline

We first conducted a simulation of drawing process, the initial process for the press stamping (Fig. 1, left). The simulation result indicated a wide range of leaning of plate thickness as much as 30% and over, implying the potential risk of splitting in a wide range of area. When A-A section is observed, generation of a wrinkling of 7 mm high is detected in a saddle-shaped section at 10 mm before the bottom dead center and the sagging of material is observed on the top surface of the punch. A virtual tryout was conducted by taking measures as shown in Fig. 2. Fig. 1, right, shows the result of the tryout. It shows considerable reduction of area with major leaning of plate thickness. The height of wrinkling is reduced to 4 mm and the sagging on the punch surface is eliminated. By incorporating these measures, we have cast the actual molds.

We have then conducted the simulation of trimming and bending processes and calculated the spring-back in the respective processes. Fig. 3 shows the distribution of spring-back after the trimming process and the comparison with an actual panel.

To conduct the present virtual tryout, it was an important task to reproduce the simulation result of drawing process with actual forming. If the forming conditions differ largely between the simulation and actual forming, it causes difference in the stress state inside the panel, which makes it impossible to make a direct comparison of the following process and/or spring-back. In the present method, we paid attention to the inflow volume of raw material and set up the conditions for actual forming by matching the inflow to that of the simulation.

3. Conclusions

(1) We have established a technology for making a virtual tryout of the press mold using actual parts. (2) We have sharply reduced molding defects through the application of simulation to the drawing process. (Approximately 160 hours in terms of man-hour for repairing

actual molds) (3) Calculation results of spring-back have coincided qualitatively with the actual panel. (4) In the future, we will apply this technique sequentially to parts that pose problem in accuracy.

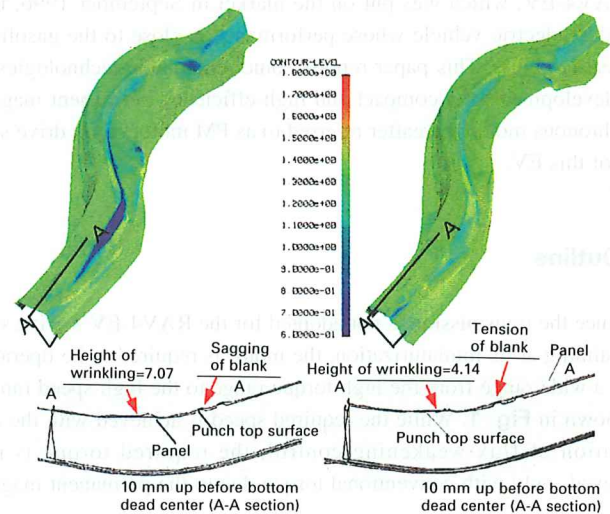


Fig. 1 Comparison of Plate Thickness and Section Before and After Taking Measures

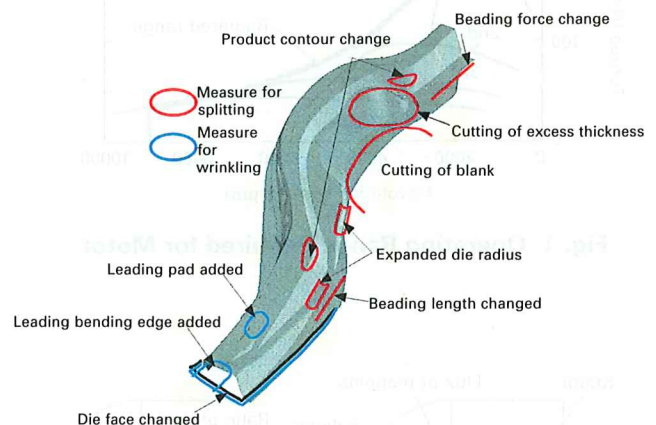


Fig. 2 Measure by Virtual Tryout

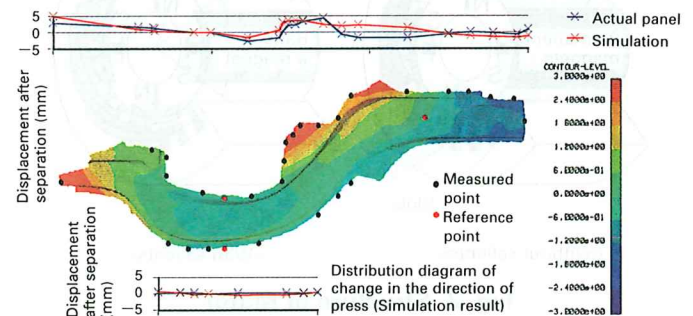


Fig. 3 Spring-back Distribution after Trimming Process and Comparison with Actual Panel

*Stamping Production Engineering Div.

Development of Motor for RAV4-EV

Tetsuya Miura* Yasutomo Kawabata* Kaoru Kubo**

1. Introduction

RAV4-EV, which was put on the market in September 1996, is a practical electric vehicle whose performance is close to the gasoline-powered vehicle. This paper reports some remarkable technologies in the development of a compact and high-efficiency permanent magnet synchronous motor (hereafter referred to as PM motor) for a drive system of this EV.

2. Outline

Since the transmission is not adopted for the RAV4-EV's drive system aiming at its miniaturization, the motor is required to be operated over a wide range from the high-torque range to the high-speed range, as shown in Fig. 1. While the required speed is achieved with the application of flux-weakening control, the required torque is not achieved only with conventional torque due to the permanent magnet flux.

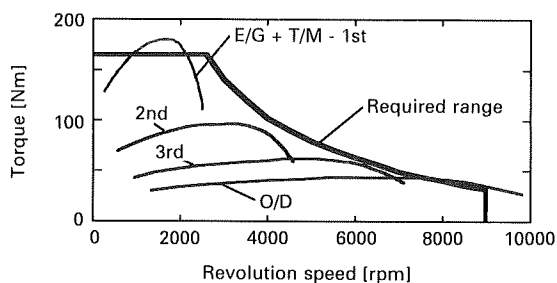


Fig. 1 Operating Range Required for Motor

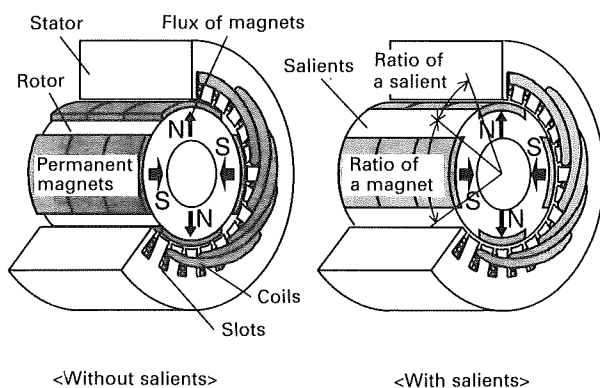


Fig. 2 Structure of Motor

To improve the torque with the application of reluctance torque, salients were added between the magnets around the circumference of the rotor, which was conventionally cylindrical shape without unevenness, as shown in Fig. 2. Further the torque is maximized by equalizing the ratio of a magnet to a salient, as a result of the optimization of the rotor shape.

Due to the addition of the salients, however, the fluctuation of flux concentrated on the salients increased the eddy current inside the rotor, when the motor was operated in the high-speed range, as shown in Fig. 3-(a). Consequently, the increase in temperature of the permanent magnets resulted in irreversible demagnetization which removes magnetic force of the permanent magnet.

To reduce the eddy current, first, the conductivity of the rotor was reduced by changing it into laminated structure of thin electromagnetic iron sheets. While the eddy current in the salients was therefore reduced, the eddy current in the permanent magnets was so increased on the contrary that the increase in temperature was not suppressed below the permitted level, as shown in Fig. 3-(b). Second, both edges of the salients were rounded to reduce the fluctuation of flux inside them and the eddy current inside the permanent magnets was so halved that their temperature was suppressed below the permitted level, as shown in Fig. 3-(c). As mentioned above, the irreversible demagnetization of the permanent magnets was prevented.

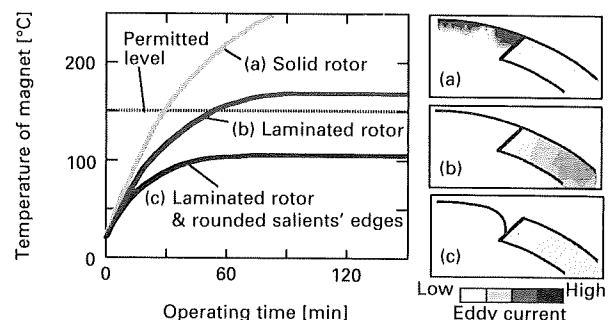


Fig. 3 Eddy Current inside Rotor & Increase in Temperature

3. Conclusions

An optimization of the rotor shape enabled the motor to be operated from the high-torque range to the high-speed range. Further, a laminated structure of the rotor and an optimization of the edge shape of the salients prevented the irreversible demagnetization of the permanent magnets due to the eddy current.

*Information Technology & Engineering Div.

**Electric and Hybrid Vehicle Div.

JSME Medal by The Japan Society of Mechanical Engineers Development of Vehicle Stability Control System (VSC)

Hiroshi Kawaguchi*
Shouji Inagaki***

Toshirou Kurusu**
Yoshiki Fukada***

Akio Okada*

1. Introduction

Studies on the cause of serious automobile accidents reveal that as many as one-fourth of the accidents is due to excessive vehicle side slip that leads to uncontrollability. We found that the excessive vehicle side slip was in many cases due to drivers' misjudgment of road conditions or unexpected traffic behavior, leading to abrupt maneuver of the drivers. It was also verified from the investigation result of actual vehicles that it is quite difficult for drivers in general to control the side slip once it occurred. The safety devices already introduced to the market, i.e., ABS or traction control system, are purposed to establish guards for braking or acceleration for longitudinal direction. Conversely, VSC set target in establishing guards for lateral direction to improve the accident evasive performance.

2. Outline

Fig. 1 shows the principle of the present system. When vehicle tends to spin, VSC calculates vehicle slip angle β and the derivative $d\beta/dt$ from the sensor signals for vehicle velocity, yaw rate and lateral acceleration. VSC calculates instability by relation of β and $d\beta/dt$ in a phase plane. Accordingly, VSC activates outer front wheel brake to induce anti-spin moment.

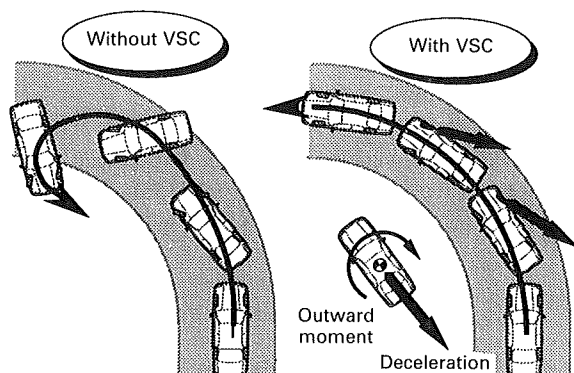


Fig. 1 Function of VSC (in Preventing Vehicle Body from Spinning)

When vehicle tends to drift out, VSC activates each wheel brake individually using the difference between actual yaw rate and target yaw rate to the steer angle to induce more yaw moment and to reduce vehicle velocity. Before VSC activates brakes, driver is noticed that vehicle is approaching to the limit with warning lamp and buzzer.

Photo. 1 shows the spin suppressing effect of VSC during a double lane change test on a slippery road.

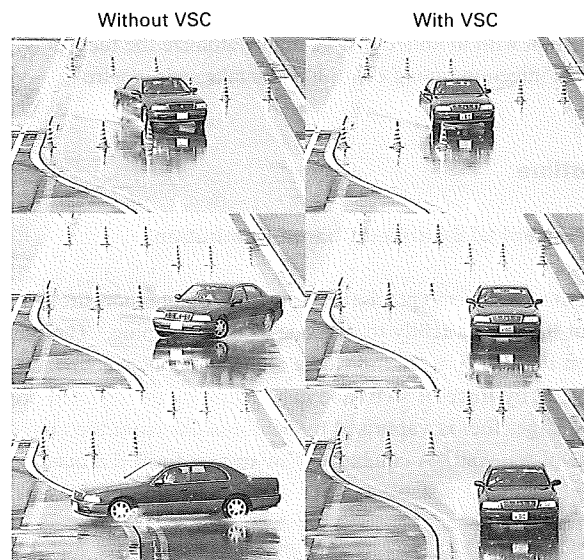


Photo. 1 Spin Suppressing Effect of VSC

3. Conclusion

VSC system has been developed to control the vehicle side slip on the basis of accident investigation and analysis. VSC is adopted to part of vehicles of Crown and Mark II series. Through the present development, we have developed a vehicle stability control system using a new vehicle dynamic behavior estimation technology and a phase plane.

References

- Yamamoto: "Vehicle Stability Control system (VSC) for controlling vehicle side slip", JSAE* Symposium, "The Latest Technology on Tire-Vehicle System", No. 9602, Symposium 1996

* JSAE : Society of Automotive Engineers of Japan

* Vehicle Engineering Div. I
**Somic Ishikawa
***BRVC Dept., Research & Development Group

The JSAE Technological Development Prize by The Society of Automotive Engineers of Japan, Inc. Development of Direct Injection Gasoline Engine (TOYOTA D-4)

Souichi Matsushita* Michikatsu Sato* Takeshi Gouno*
Daisaku Sawada** Akinori Saito***

1. Introduction

Today, reduction of CO₂ emission has become a worldwidetask. When it comes to automobiles, reducing CO₂ mean reducing fuel consumption. Toyota D-4 engine achieved stable stratified charge combustion at an extremely lean air-fuel ratio by injecting fuel directly into the cylinder. The Toyota D-4 Engine achieves stable stratified combustion with modified piston, highly atomize the fuel spray, precision fuel injection timing control, and intake swirl control.

2. Outline

2.1. Concept of Stratified Charge Combustion

The fuel is injected precisely during the compression stroke into the flow of the swirr slightly to one side of the sparkplug. The fuel impings on the cavity wall and flows along the concave surface to the spark plug by force of swirl and penetration by the injected pressure. In this stage, fuel is vaporised by heat transfer from the ambient air and the piston wall. A combustible mixture is formed around a spark-plug which enables stable ignition and combustion of the super lean mixture.

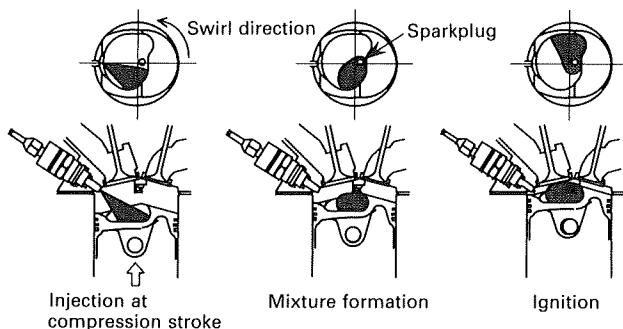


Fig. 1 Concept of Stratified Mixtures Formation

2.2. Configuration of D-4 Engine

Based on an inline 4-cylinder engine with 2-liter cylinder displacement, the portion of the engine from the cylinder head and above has

been modified for direct cylinder injection, thus enabling the D-4 engine to perform stratified charge combustion. To realize this concept, we newly developed the following:

- (1) Deep-dished piston
- (2) High-pressure swirl injector
- (3) One-sided helical port with SCV (swirl control valve)

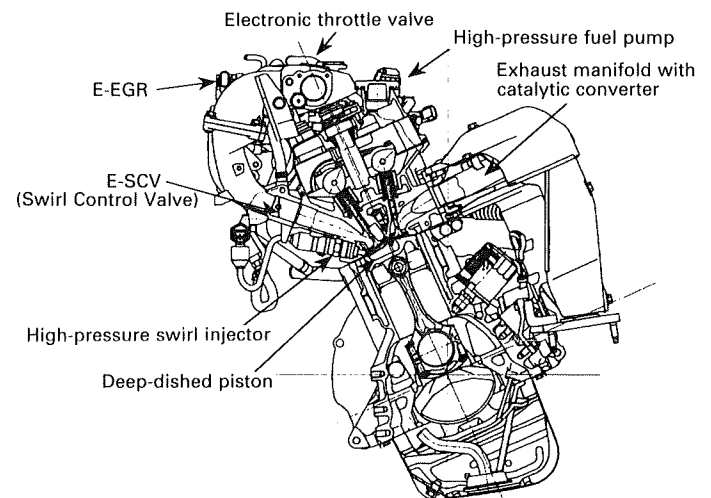


Fig. 2 Toyota D-4 Engine Cross Section

2.3. Fuel Consumption Performance

Vehicles with the D-4 engine shows an improvement of approximately 30% better fuel consumption in the 10.15 mode test cycle, as compared to one with a conventinal engine. (Fig.3)

	Vehicles with automatic transmission	
	10.15 Mode Fuel Efficiency (km/ℓ)	
	10	20
Vehicles with D-4 engine		17.4
Vehicles with conventinal engine	13.0	

Fig. 3 Fuel Efficiency

3. Summary

The Toyota D-4 engine has been used as a commercial product on the Toyota Corona Premio. We believe that the D-4 engine offers a technology that hassignificance in addressing the increasingly stringent worldwide demand for fuel consumption.

* Engine Engineering Div. I
** Engine Engineering Div. III
*** Toyota Central Res. & Develop. Labs.,Inc.

Toyota Awards by Japan Foundry Engineering Society

The Development of Casting Technology for Aluminum Suspension Cross-Member

Yoshiro Hayashi* Yasuaki Hadatsuki** Sadamu Sakamoto***

1. Introduction

With the growing trend for reduced weight in higher performance automobiles, aluminum parts are on increase. Suspension cross-member (hereinafter referred to as "susmem") were used to be made of stamped steel plates. Replacing this part with cast aluminum is expected advantageous in reducing vehicle weight, interior noise, and improving running stability.

However, susmem is a part having a large aspect ratio (long and relatively thin) and is, therefore, difficult to produce (Fig. 1). It has the following problems: ① Misrun due to the thin and long structure; ② Internal porosity at locally thick portions; ③ Warping of the permanent mold due to its large size; ④ Product warp due to the high aspect ratio.

2. Outline

We have recently developed a dedicated casting permanent mold structure to solve problems ① to ③ above (Fig. 2).

To maintain the mold temperature stably at a high level, we adopt-

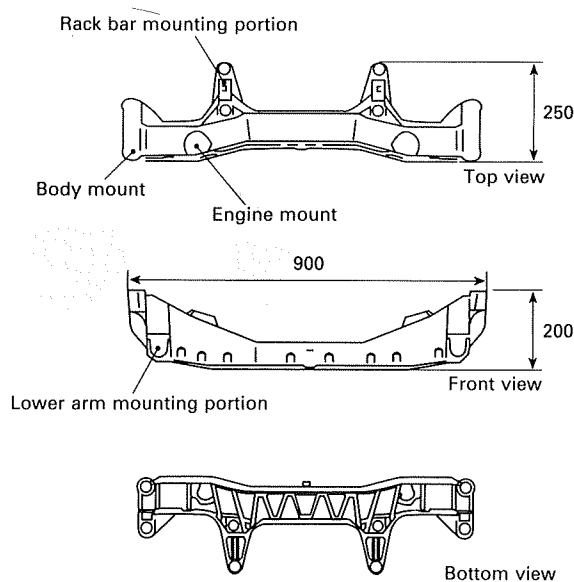


Fig. 1 Outline of Suspension Cross-Member

ed a thin die-insert structure for the product portion (cavity) of the mold. This is also effective in reducing the warping of the permanent mold as a whole.

We then newly developed a feeder and cooling die insert structure as a measure for shrinkage cavities that occur to the engine mount and other locally thick portions.

With the adoption of thin die-insert structure and the tie bolt that suppresses the warping of permanent mold, we have succeeded in controlling the warping of permanent mold to a lower level.

We have clarified and taken measure for the generation mechanism of the product warping stated in ④ above through efficient application of multivariate analysis.

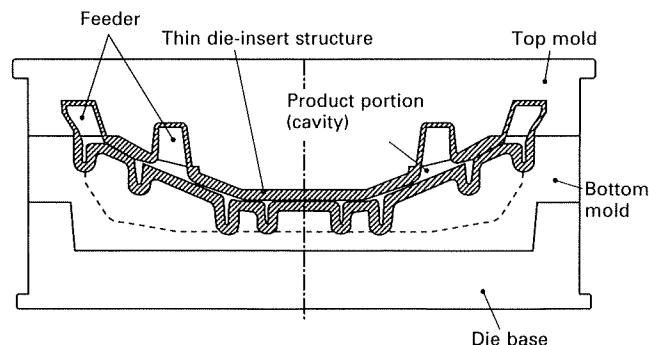


Fig. 2 Outline of Permanent Mold Structure Developed

3. Conclusion

With the technological development thus far outlined, we, at Toyota, have established the manufacturing technique of susmem and adopted aluminum susmem to Lexus LS400, Lexus SC300, and Supra.

With the establishment of mass production engineering for large sized cast aluminum parts using the low pressure die casting process, this technology will contribute not only to the expansion of cast automobile parts in the future, but to further product quality improvement through the upgrading of the low pressure die casting process and to the development of near net shaping. We think the new casting technology would contribute to the advancement of die casting technology to a great extent.

* Manufacturing Div.III, Tahara Plant

** Administration Div., Honsha Plant

*** Production Engineering Planning Div.

The JSAE Thesis Prize by The Society of Automotive Engineers of Japan An Experimental Study of Premixed-Charge Compression Ignition Gasoline Engine

Yasuo Sato* Taro Aoyama** Yoshiaki Hattori**
Jun'ichi Mizuta**

1. Introduction

Better fuel economy and lower NOx emission are the requirements for the next generation engines to realize. We have this time studied multi-point ignition and combustion of premixed lean mixture as a means for realizing the above objectives. It has been experimentally clarified that the better fuel economy equivalent to direct injection diesel engines and much lower NOx emission can be simultaneously realized by injecting gasoline to the inlet port and making combustion by self ignition of gasoline after a compression process (PCCI: Premixed-Charge Compression Ignition).

2. Outline

2.1 PCCI Performance

Using a single cylinder engine having an engine displacement of 915 cc and a compression ratio of 17.4, we injected gasoline to the inlet port with the electromagnetic injector. Fig. 1 shows a comparison of performance between conventional direct injection diesel engine (hereinafter referred to as diesel). Multi-point compression ignition and combustion of premixed lean mixture were realized stably in the shaded A/F range of 33 to 44 in the figure. In the A/F range of stable combustion, the indicated specific fuel consumption was equivalent or a little lower compared with diesel. NOx concentration was

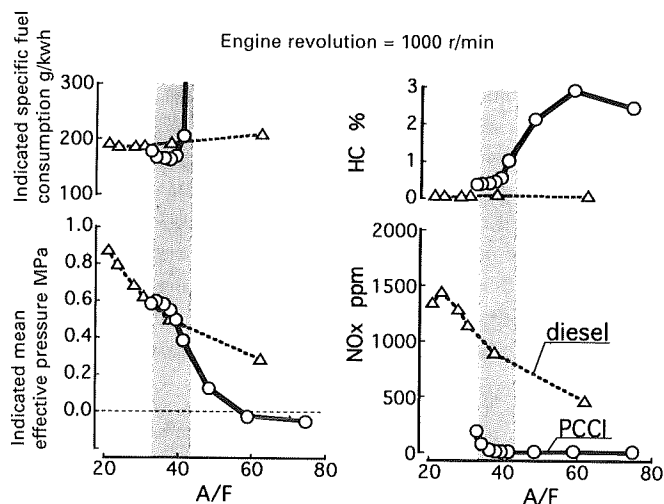


Fig. 1 PCCI Performance

positively low with about 1/100 of diesel or lower. The HC concentration in the PCCI engine was one order of magnitude higher than that of diesel. No smoke emission was discerned, although it is not illustrated here.

2.2 Combustion of PCCI

In-cylinder observation of combustion phenomenon was conducted through the quartz glass-formed at bottom of the piston combustion chamber. No evidence of the flame propagation is shown in the shadow images taken with a high speed camera (Fig. 2). Random start of ignition and subsequent stable combustion are observed from the direct images photographed with a superhigh speed shutter camera equipped with image intensifiers (Fig. 3). Summing up these results, it has been found that multi-point compression ignition and combustion of premixed lean mixture are realized within the PCCI engine.

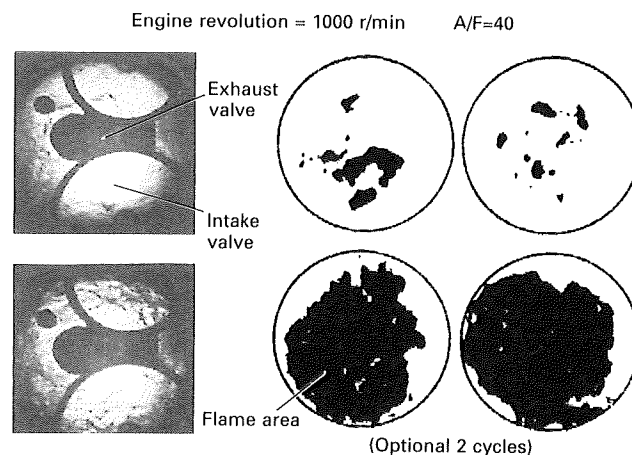


Fig. 2 Shadow Images Fig. 3 Direct Images
(Upper: 2° after the top dead center,
Lower: 8° after the top dead center)

3. Conclusion

Upon presentation of the present study, premixed-charge compression ignition and combustion is briskly taken up as a prospective candidate for realizing clean diesel engines.

We expect that PCCI would become the key technology for the combustion technologies in the future.

*Engine Engineering Div. III

**Toyota Central Res. & Develop. Labs., Inc.

Recent Publications by Toyota Authors (January – June, 1997)

■ International Conferences

Conference	Paper Title	Authors	Comp./Div./Dept.	Date
Fuel & Lubes Asia International 3rd Annual Fuels & Lubes Asia Conference	Lubricity of Low Sulfur Diesel Fuel in Japan	Masanori Okada Nobuhiko Kakeno Hirohiko Hoshi Masahiko Nakada	Engine Engineering Div.I Engine Engineering Div.I Material Engineering Div.I Material Engineering Div.I	Jan.21
Society of Automotive Engineers, Inc. (SAE) International Congress & Exposition	Theoretical Consideration in Rear-Wheel Skid to Steering Input	Hideki Sakai	Vehicle Engineering Div.	Feb.24 -Feb.27
	Handling Analysis with Vehicle Dynamic Simulator	Katsutoshi Horinouchi Takashi Yonekawa Tamio Kanou Seishu Utsumi	Vehicle Engineering Div. Vehicle Engineering Div. Vehicle Engineering Div. Technical Administration Div.	
	Development of a Direct Injection Gasoline Engine	Jun Harada Hiroyuki Mizuno Zenjiro Masuki Yasushi Ito Tsutomu Tomita	Engine Engineering Div.I Engine Engineering Div.I Engine Engineering Div.I Engine Engineering Div.III Director	
	Development of Titanium Nitride Coated Shim for A Direct Acting OHC Engine	Michihiko Masuda Masato Ujino Ikuo Marumoto Kenji Shimoda Koji Nishida	Engine Engineering Div.I Power Train Engineering Div.I Material Engineering Div.I Production Engineering Development Div. Production Engineering Development Div.	
	Development of Exhaust Air Fuel Ratio Sensor for 1997 Model Year LEV Vehicle	Kazuya Mizusawa Kazunori Kato Shigeki Hamaguchi Shinji Hocho Hidetaka Hayashi	Electronics Engineering Div.II Electronics Engineering Div.I Material Engineering Div.I Nippon Soken Inc Nippon Soken Inc	
	Development of Exhaust Air Fuel Ratio Sensor for 1997 Model Year LEV Vehicle	Kazuya Mizusawa Kazunori Kato Shigeki Hamaguchi Shinji Hocho Hidetaka Hayashi	Electronics Engineering Div.II Electronics Engineering Div.I Material Engineering Div.I Nippon Soken Inc. DENSO	
	Development of Sleeve Riveting Method and Making Practicable	Tatsuya Ogawa Seiichi Toyonaga Osamu Tanigawa Tohru Kato	Assembly & Design For Manufacturing Engineering Div. ditto ditto ditto	

Conference	Paper Title	Authors	Comp./Div./Dept.	Date
Society of Automotive Engineers, Inc. (SAE) International Congress & Exposition	Development of Gear Parts for VVT Unit	Hitoshi Nakamura Hideo Aihara Masato Okubo Toshihiro Nakashima	Metal Forming, Welding & Heat Treatment Engineering Div. ditto ditto TMCS*	Feb.24 -Feb.27
	Key Technology of the Future Combustion	Kiyoshi Nakanishi	Engine Engineering Div.I	
	Body Electronics Area Network (BEAN)	Hiroshi Honda Kazunori Sakai Takao Akatsuka Shigeru Uehara Susumu Akiyama	Electronics Engineering Div.I Electronics Engineering Div.I Electronics Engineering Div.I Body Engineering Div.I DENSO	
	Smart Algorithm for a Pneumatic Monitor Embedded in ABS Program	Katsuhiko Iwasaki Masayuki Kawamoto Masahiro Ueda	Electronics Engineering Div.III Electronics Engineering Div.III Electronics Engineering Div.III	
	A Study of CAM System for Super High Speed and Accuracy Machining of Dies For Body Panels	Yoshiki Muta Masahiko Matsumi Haruhisa Higashiyama Mitsuru Kubota	Machinery Engineering Administration Div. Machinery Engineering Administration Div. Machinery Engineering Administration Div. Information Systems Div.I	
	Design of the Gain-Scheduled Observer for the Semi-Active Suspension	Hideo Nakai Satoru Osaku Kiichi Motozono	Toyota Central Res. & Develop. Labs., Inc. Chassis Component Engineering Div. Production Engineering Development Div.	
	Design Development of Energy Absorbing Ribs for Meeting FMVSS201 Extended Head Impact	Gajanan V. Gandhe Yoshinori Noritake Luis Lorenzo	The Dow Chemical Company Material Engineering Div.III The Dow Chemical Company	
	Precision Temperature Control of Ferrous Alloy Melt at Induction Furnace	Katsuhiko Yamada Norihiko Amano Tamotsu Hasegawa Koichi Soda Masuji Oshima	Toyota Central Res. & Develop. Labs., Inc. Production Engineering Development Div. Production Engineering Development Div. Foundry Engineering Div. Toyota Central Res. & Develop. Labs., Inc.	

* TOYOTA MOTOR CORPORATE SERVICES OF NORTH AMERICA INC.

Conference	Paper Title	Authors	Comp./Div./Dept.	Date
IAVSD 2nd.Int.Colloquim on Tyre Models for Vehicle Dynamic Analysis	The Relaxation Length Concept at Large Wheel Slip and Comber	Akira Higuchi H.B.Pacejka	Vehicle Engineering Div. Delft University of Technology	Feb.25
Embedded System Programs Embedded System Conference	Proposal of the On-Chip Debugging Resources for High-Speed Microcontroller	Shigeru Sasaki Ken Asami Jiro Nakano Kazuaki Sasaki	Electronics Engineering Div.III Electronics Engineering Div.III Electronics Engineering Div.I Yokogawa Digital Computer Corporation	Mar.10
Science and Technology Agency, Japan Work Shop on S & T Human Resource Development to Support Industrialization and Scientific Dvelopment	Current Situation of Securing Engineers in Manufacuturing Industries In Japan	Masayuki Sasanouchi	Tokyo Engineering Div.	Mar.18
Japan Society for Technology of Plastisity JSTP International Semminar on Precision Forging	Current Trends in Automotive Forging Industry	Tatsuo Iwama	Metal Forming, Welding & Heat Treatment Engineering Div.	Apr.1
Society of Automotive Engineers, Inc. (SAE) Total Life Cycle Conference and Exposition	Life Cycle Inventory Study of Automotive Fuel Tank	Masako Yamato Satoshi Asada Yoshihito Mitsuhara	Engineering Administration Div. Engineering Administration Div. Plant Engineering Div.	Apr.7 -Apr.9
	The Paint Sludge's Recycling to the Vinyl Chloride Plastisol Coating of Under-Floor	Mitsuo Nakajima Koichi Nishioka Syoichi Banno Satoshi Kodama Keiichi Yokouchi Toshihisa Ota	Plant Engineering Div. Plant Engineering Div. Plant Engineering Div. Material Engineering Div.II Material Engineering Div.II Material Engineering Div.II	
JASA JASA Embedded Technical Seminar	Software Development Environment for Automotive Control	Koji Sato	Electronics Engineering Div.III	Apr.10

Conference	Paper Title	Authors	Comp./Div./Dept.	Date
Austrian Society of Automotive Engineer 18th International Vienna Motor Symposium	A Study of Stratified Mixture Formation of Direct Injection SI Engine	Daisaku Sawada Terutoshi Tomoda Shizuo Sasaki Akinori Saito	Engine Engineering Div.III Engine Engineering Div.III Engine Engineering Div.III Toyota Central Res. & Develop. Labs., Inc.	Apr.25
Society of Automotive Engineers, Inc. (SAE) Int'l Spring Fuel & Lubricants Meeting	Reduction of Diesel Particulate Matter by Oil Consumption Improvement Utilizing Radioisotope Tracer Techniques	Takashi Inoue Masago Yamamoto Yoshihiko Masuda	Future Project Div.I Toyota Central Res. & Develop. Labs., Inc. Future Project Div.I	May.5 -May.7
AIC AIC97	The Effects of Figural Unity on the Simultaneous Contrast in Koffcaring Pattern	Shinya Takahashi Shinji Nakamura	Toyota Technological Institute Future Project Div.I	May.25
IEEE Electron Device Society ISPSP '97	A He-Irradiated IGBT with a Shallow p-Base and Shallow FLRs	Tomoyoshi Kushida Akira Mase Akira Kawahashi Kenji Ono	Electronics Engineering Div.IV Electronics Engineering Div.IV Electronics Engineering Div.IV Electronics Engineering Div.IV	May.26
Federation of Asian Die & Mould Associations (FADMA) 4th International Conference on Die & Mould Technology (ICDMT)	Machining Curved Tunnel for Coolant with Mole EDM	Shunpei Ichiyasu Akinobu Takeuchi Akihiro Goto Takuji Magara	Machinery Engineering Administration Div. Machinery Engineering Administration Div. Mitsubishi Electric Corporation Mitsubishi Electric Corporation	Jun.5 -Jun.6
Federation of Asian Die & Mould Associations (FADMA) 4th International Conference on Die & Mould Technology (ICDMT)	Development of a CAM System with Curvilinear Interpolation for High-Speed, High-Accuracy Machning of Dies	Haruhisa Higasayama Yoshiki Muta Mitsuru Kubota Masatake Higasi	Machinery Engineering Administration Div. Machinery Engineering Administration Div. Information Systems Div.I Toyota Technological Institute	
Int'l Magnesium Assin 54th Annual World Magnesium Conference	The Future Prospect of Magnesium Usage in Asian Automotive Industry	Akiyoshi Morita Toshihiro Chikada	Director Material Engineering Div.I	Jun.9
SURFACES SURCAR XVIII	Evaluation Method for Color-matching Between the Bumper and the Car-Body	Takako Nagata	Surface Finishing Engineering Div.	Jun.12

Conference	Paper Title	Authors	Comp./Div./Dept.	Date
International Symposium on Automotive Technology and Automation (ISATA) 30th ISATA	An Absolute Steering Sensor Using Switched Capacitance Technology	Kimitoshi Tsuji Masayuki Kawamoto Junichi Nakaho	Electronics Engineering Div.IV Electronics Engineering Div.III Tokai Rika Ltd.	Jun.16 -Jun.17
	Development of the Recycling Technology for the Painted Bumper Collected from the Market	Naoyuki Takahashi Sadao Ikeda Hisayuki Iwai Naruhito Tatsuta	Production Engineering Development Div. Production Engineering Development Div. Material Engineering Div.II Toyota Central Res. & Develop. Labs., Inc.	
	Development of Traffic Simulation and An Applied Example	Ryoji Nakagawa Hiroyuki Oshika	Plant Engineering Div. Plant Engineering Div.	
	The Paint Sludge's Recycling to the Vinyl Chloride Plastisol Coating of Under-Floor	Mitsuo Nakajima Kouichi Nishioka Shoichi Banno Satoshi Kodama Keiichi Yokouchi Toshihisa Ota	Plant Engineering Div. Plant Engineering Div. Plant Engineering Div. Material Engineering Div.II Material Engineering Div.II Material Engineering Div.II	

■ Contribution to Publications in English

Conference	Paper Title	Authors	Comp./Div./Dept.	Date
Society of Automotive Engineers of Japan, Inc. (JSAE) JSAE Review Vol.18 No.1	Basic Car Concept from Production Engineers	Seiichi Hashimoto Masaki Ogawara Masayo Tsuzuki	Machines & Tools Engineering Div. Fuji Heavy Industries Ltd. Honda Engineering Co.,Ltd.	January
Perceptual and Motor Skills Perceptual and Motor Skills	Effects of Background Motion on Eye-Movement Information	Shinji Nakamura	Future Project Div.I	February
The American Society for Biochemistry and Molecular Biology, Inc. The Journal of Biological and Molecular Biology, Inc.	Conversion from Archaeal Geranylgeranyl Diphosphate Synthase to Farnesyl Diphosphate Synthase	Chikara Oto Kazutake Hirooka Shinichi Onuma Tokuzo NiShino	Future Project Div.I Future Project Div.I Electronics Engineering Div.III Electronics Engineering Div.III	

Conference	Paper Title	Authors	Comp./Div./Dept.	Date
Society of Automotive Engineers of Japan, Inc. (JSAE) JSAE Review Vol.18 No.2	The New Supercharged Engine, 2TZ-FZE, for Mini-van	Tetsushi Suzuki Eiji Ito Nobuhiko Kakeno	Power Train Engineering Div.III Power Train Engineering Div.III Engine Engineering Div.I	April
	Quick Sampling GC System for Analyzing Specific Hydrocarbons in Exhaust Gas	Hiroshi Ito Kenichi Uchida Takeshi Watanabe Kazuhiisa Kunitake	Toyota Central Res. & Develop. Labs., Inc. Engine Engineering Div.II Engine Engineering Div.II Engine Engineering Div.II	
	Optimum Tooth Profile Design for Hypoid Gear	Yoshikatsu Shibata Norihiko Kondou Toshinari Ito	Drive Train Engineering Div. Drive Train Engineering Div. Drive Train Engineering Div.	
	Control Methods for Induction Machine Directly Coupled to Engine	Yasushi Kusaka Yoshihide Nii	Electronics Engineering Div.III Electronics Engineering Div.III	
IEEE/ASME IEEE/ASME Transactions on Mediatronicson Human Friendly Mechatronics	Human/Robot Contact in the Safeguarding Space	Kazutsugu Suita Yoji Yamada Yoji Umetani Yasuhiro Hirasawa S.Y.Hung	Body Assembly Engineering Div. Toyota Technological Institute Toyota Technological Institute Toyota Technological Institute Toyota Technological Institute	June



In Commemoration of Recipients of 1997 Distinguished Environmental Service Award (Global Warming Category) by Environment Agency - June 5, 1997
(Mr. Matsubara, Director of Toyota Motor Corporation: Fifth from the right in the front row [See the next page.])

Awards (January – June, 1997)

Awards	Achievement	Recipients	Comp./Div./Dept.	Date	Ref.
New Energy Foundation					
Vanguard 21 Award by the Minister of International Trade and Industry	RAV4 LEV, A High Performance Electric Vehicle	TOYOTA MOTOR CORPORATION		January	–
Japan Powder Metallurgy Association					
1997 JPSA AWARD DEVELOPMENT PRIZE <NEW DESIGN>	Development of Sintered Helical Gears for VVT Unit	Itsuki Nakamuura Hideo Aihara Chiaki Kikyo Kazuteru Nimi Toshiya Yamaguchi Toshihiro Nakashima	Surface Finishing Engineering Div.V Surface Finishing Engineering Div.V Surface Finishing Engineering Div.V Surface Finishing Engineering Div.V Production Engineering Development Div. TMMNA ^{*1}	January	Vol.46 No.1 P.166
The Japan Society of Mechanical Engineers					
JSME Medal	Development of Vehicle Stability Control System (VSC)	Hiroshi Kawaguchi Akio Okada Shouji Inagaki Yoshiki Fukada Toshirou Kurusu	Vehicle Engineering Div.I Vehicle Engineering Div.I BRVC Dept., Research & Development Group BRVC Dept., Research & Development Group Somic Ishikawa	April	P.125
JSME Distinguished Engineer's Award	Research and Development for Reliability Improvement of Exhaust Emission Controlled Engine	Masahiko Nakada	Material Engineering Div.I	April	–
The Society of Automotive Engineers of Japan, Inc.					
The JSAE Technological Development Prize	Development of Direct Injection Gasoline Engine (TOYOTA D-4)	Souichi Matsushita Michikatsu Sato Takeshi Gouno Daisaku Sawada Akinori Saito	Engine Engineering Div.I Engine Engineering Div.I Engine Engineering Div.I Engine Engineering Div.III Toyota Central Res & Develop. Labs., Inc.	April	P.126
The Society of Rubber Industry, Japan					
52th Rubber Technology Improvement Award	Development of Injection Molded Thermoplastic Polyester Elastomer Boots for C.V. Joints	Hirokazu Shimizu	Vehicle Engineering Div.	May	Vol.45 No.2 P.98
Japan Foundry Engineering Society					
Toyoda Award	The Development of Casting Technology for Aluminum Suspension Cross-Member	Yoshiro Hayashi Yasuaki Hadatsuki Sadamu Sakamoto	Foundry Div., Myochi Plant Administration Div., Honsha Plant Production Engineering Planning Div.	May	P.127
Japanese Society of Die and Mould Technology					
JSDMT AWARD FOR TECHNOLOGICAL CONTRIBUTION	Development of a CAM System with Curvilinear Interpolation for High-Speed, High-Accuracy Machining of Dies	Yoshiki Muta Mitsuru Kubota Haruhisa Higasayama Masatake Higashi	Machinery Engineering Administration Div. Machinery Engineering Administration Div. Machinery Engineering Administration Div. TOYOTA Technological Institute	June	Vol.46 No.2 P.108
The Society of Automotive Engineers of Japan, Inc.					
The JSAE Thesis Prize by The Society of Automotive Engineers of Japan	An Experimental Study of Premixed-Charge Compression Ignition Gasoline Engine	Yasuo Sato Taro Aoyama Yoshiaki Hattori Junichi Mizuta	Engine Engineering Div.III Toyota Central Res & Develop. Labs., Inc. Toyota Central Res & Develop. Labs., Inc. Toyota Central Res & Develop. Labs., Inc.	June	P.128
Environment Agency					
Recipients of Distinguished Environmental Service Award (Global Warming Category)		TOYOTA MOTOR CORPORATION Research & Development Group		June	P.134

^{*1} TOYOTA MOTOR CORPORATE SERVICES OF NORTH AMERICA, INC.

This No.2 issue of TOYOTA Technical Review Vol.47 is being published in the winter when the evening breeze blows very cold.

Many of our readers may wonder what the TOYOTA ECO PROJECT which has been positively promoted at Toyota since early 1998 is all about.

We would be happy if you would include "Prevention of Global Warming -CO₂ Reduction-" featured in this TTR issue as a part of the TOYOTA ECO PROJECT.

Technological advancement has been accelerated year by year, and vehicles which were once dreams are now a reality. In our daily jobs, desk-top personal computers have been used since the late autumn of 1996. Electronic mail has become the communication means for exchanging meeting agendas with people outside the company using the e-mail addresses written on name cards so often that they are felt to be more closer than people in the company. It will not be long before the TTR is published electronically without any copyright or duplication problems. (Akutsu)

Six months have passed since I was unexpectedly assigned to the Eco project as a member for technological development. Through this issue, I have renewed my awareness of the quick progress in technological development that is taking place in many diverse fields concerning environmental protection and conservation.

I have been very stimulated by the activities of rival engineers, causing me to renew my enthusiasm in order to display my full potential. (Kanamori)

Environmental issues are being discussed almost every day in the press as we approach the end of the 20th century. Although we have been making efforts to ensure more efficient use of precious global resources, various kinds of waste result from their consumption. Coming up with ways to restore nature is the goal of almost every industrial field. Great advancements are expected in this regard through the application of human wisdom.

In the automotive field, these same efforts are being made every day and the image of vehicles for the 21st century is about to be formed. (Fujita)

1998

Editorial Staff

Eisaku Akutsu	Future Project Div. I
Yoshiharu Kanamori	Vehicle Engineering Div.
Norihiro Suzuki	Engine Engineering Div.
Hiroaki Tanaka	Chassis System Development Div.
Tetsuo Morita	Vehicle Evaluation & Engineering Div. III
Hikaru Aoyagi	Material Engineering Div. I
Masayuki Kotani	Electronics Engineering Div. I
Nobuo Fujita	Electric and Hybrid Vehicle Div.
Takasi Nagase	Production Engineering Development Div.
Siro Miyazaki	Plant Engineering Div.
Mikio Sato	Machinery Engineering Administration Div.
Masaharu Yuasa	Information Systems Div. I

Secretariat

*Chisato Niki	Technical Administration Div.
Norie Kishimoto	Technical Administration Div.
Kumiko Tsuji	Technical Administration Div.

*Chairman of the Editorial Committee

TOYOTA Technical Review Vol. 47 No. 2

© 1998 TOYOTA MOTOR CORPORATION, Printed in Japan

Copyrights of all articles published in the TOYOTA Technical Review are the property of TOYOTA MOTOR CORPORATION.

For permission to reproduce articles in quality or for use in other printed material, contact the chairman of the Editorial Committee.

Publisher's Office	Technical Administration Div. TOYOTA MOTOR CORPORATION 1 Toyota-cyo, Toyota, Aichi, 471-8572 Japan Tel. (565) 28-2121 Fax. (565) 23-5744
Publisher	Eishi Ohno
Editor	Chisato Niki
Printer	CMC Co., Ltd. 1-1-19 Heiwa, Nakaku, Nagoya, Aichi, 460-0021 Japan
Printed	Apr. 1998

For People, for Society, for the Earth



TOYOTA MOTOR CORPORATION

