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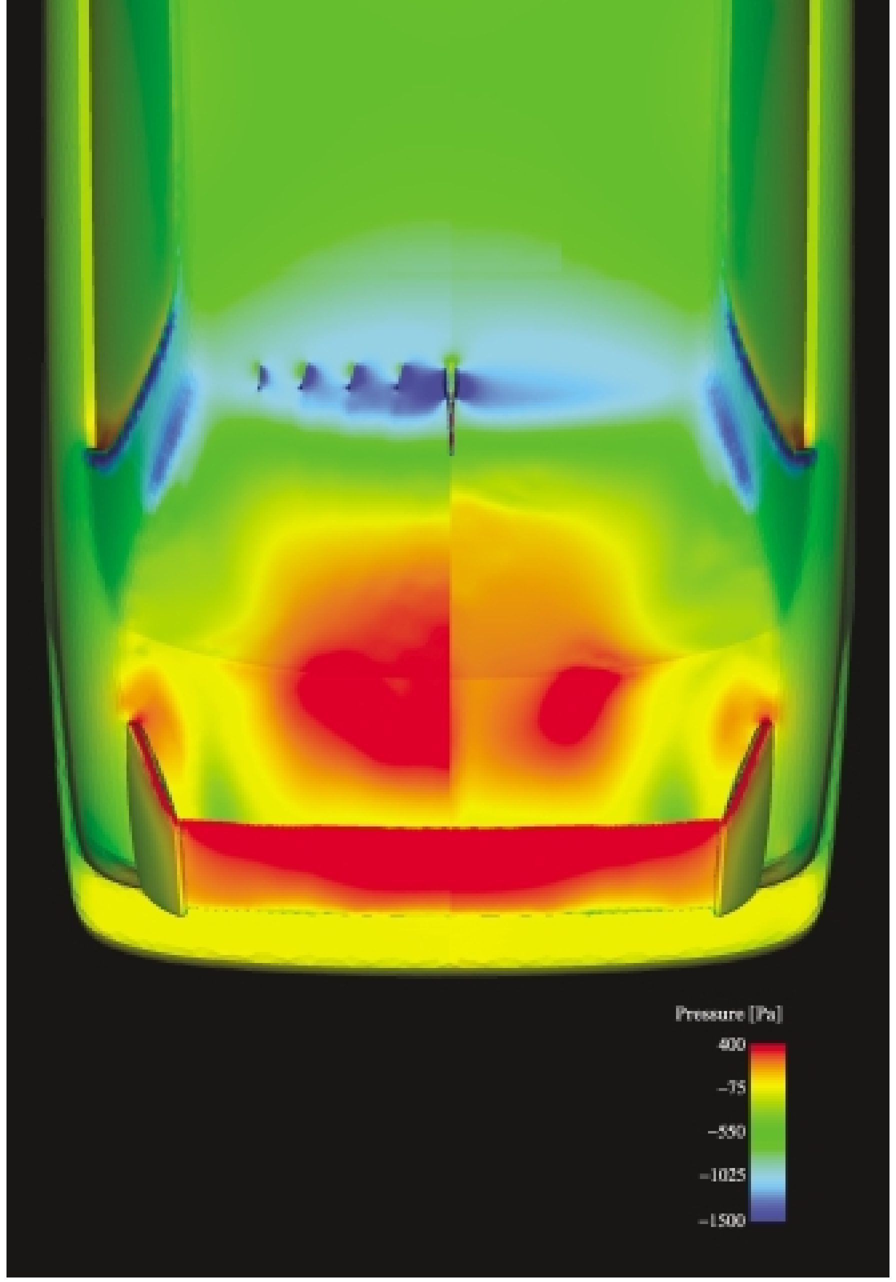


# TECHNICAL REVIEW

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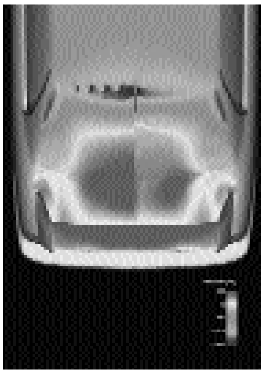

- **Cover Photograph**

The cover photo highlights the benefit of the vortex generators (VGs) mounted on the Mitsubishi LANCER EVOLUTION VIII MR, which was launched in February 2004. The left-hand side of the photo shows the pressure distribution with the VGs (which are located at the rear edge of the roof), and the right-hand side of the photo shows the pressure distribution without them. As shown, the vortexes generated by the VGs yield a pressure increase over the rear window and trunk. The result is a lower drag coefficient.

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MITSUBISHI MOTORS

# Technical Review 2004

# 16



# MITSUBISHI MOTORS TECHNICAL REVIEW

## 2004 NO.16

### Contents



Photo on first page
The Mitsubishi FCV, a fuel-cell vehicle based on the Mitsubishi GRANDIS, was used in public-relations activities for the Osaka International Women's Marathon, which took place on January 25, 2004.

## Technical Topics



## New Products

MITSUBISHI MOTORS



FUSO



On 6 January 2003, Mitsubishi Motors Corporation spun off its truck and bus operations to form a new company, Mitsubishi Fuso Truck and Bus Corporation. Beginning in 2004, the companies are publishing the *Mitsubishi Motors Technical Review* and *Mitsubishi Fuso Technical Review* independently of each other. Contact details for inquiries about the *Mitsubishi Fuso Technical Review* are shown below.

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# Further Refinement and Evolution of Core Technologies through Global Interaction

**Akira KIJIMA**
Senior Executive Officer, Corporate General Manager,
Research & Development Office

Last October, China succeeded in launching its first manned spacecraft "Shenzhou V", thus becoming the world's third major space power after Russia and the United States. The pace of human invention is accelerating, extending beyond the terrestrial world into space. We are living in a world quite different from that of a few years ago when technological development was led mainly by European countries, the United States, and Japan. Technological levels are becoming increasingly uniform around the world, as evidenced by China's rapid attainment of state-of-the-art technology, creating a common platform for sophisticated basic technologies on which countries compete fiercely for breakthroughs.

The automotive industry is no exception to this trend. Every automaker around the globe is striving to improve its technologies to ensure its survival. The key to remaining competitive is to further refine and develop the core technologies, and to act with a global vision.

Mitsubishi Motors' technological innovation is proceeding in line with its corporate vision of : "concept leadership and driving fun", "Japanese craftsmanship, engineering and design", and "environment friendly technology".

Today's major challenges for automobile engineers are to develop environmental technologies to reduce greenhouse gases and nitrogen oxides which are the worldwide demands, as well as passive and active safety technologies.

At the 2003 Tokyo Motor Show, Mitsubishi Motors presented an environment-friendly next-generation family of engines and the MITSUBISHI FCV, a fuel cell vehicle based on Mitsubishi's GRANDIS minivan body and DaimlerCrysler's latest fuel cell technology.

The next-generation family of engines includes three engine series having different displacement ranges while delivering the same performance and features such as high power, low fuel consumption, light weight, compactness, and low cost. All of them also sport an aluminum cylinder block and cutting-edge technologies such as variable valve systems. At the Motor Show, Mitsubishi also showcased its next-generation GDI engine, an improved fuel consumption version of the Mitsubishi original GDI engine, which offers a significantly extended stratified lean-burn zone.

In addition to these technological achievements in the driving components, Mitsubishi Motors exhibited weight reduction and other innovative technologies for the body, the essence of which was captured by the Mitsubishi "i", a concept car that uses an aluminum space-frame.

One of our solutions for the other major challenge, namely safety, is Mitsubishi's next-generation safety system achieved by using advanced electronics for both active and passive safety. This system was mounted in the COLT safety test car and demonstrated excellent results. The system is now under further development for commercialization.

As we learned through development of the new-generation engine series, the important point when developing innovative technologies is to consider the basis of that technology before advancing to the next step. This is especially true in today's world of technology where there are so many different fields of speciality. We should thus aim to improve the value of our products by first building a foundation of highly reliable core technologies and then adding to them Mitsubishi's original, specific technologies in order to satisfy customers' demands.

The second key to remaining competitive is to act on a global scale. This does not simply mean selling our products in international markets, but globally expanding our activities in all dimensions. The Mitsubishi FCV was developed in cooperation with our alliance partner, which is one example of corporate globalization in the field of development. Another example is the way in which Mitsubishi Motors is working closely with overseas suppliers in various areas, such as perfecting new technologies and products through technological cooperation at the early stages of development, and optimizing parts procurement on a global scale.

While we must embrace economic and technological globalization, we must also offer customers unique and distinctive products as people's lifestyles and tastes are becoming increasingly diverse. When responding to customers' needs, we must therefore do business on the global stage while keeping Mitsubishi's distinctive identity.

To create a distinctive corporate identity, a distinctive identity in technology is crucial, and this requires creating innovative and original technologies. To this end, we must consider technical development not only in the short-term but also from a long-term perspective. We will be able to create more exciting and enticing cars by combining such promising technologies as nanotechnology, information technology, and human engineering technology with automobile technology, and hence realize our potential through international, business, and academic interactions.

To do this, each employee must grasp the latest trends and technological information in their own field, and store that knowledge in a databank shared by all members. This new information must be processed into comprehensible knowledge, which must then be quickly used in the development of components and basic technologies. This will require courage, passion, and a strong sense of responsibility and mission. Some technologies require a long time and profound research before they work sufficiently; others should be implemented quickly to be really effective. Engineers must be sensitive enough to distinguish between these two types of technology and to achieve a good balance between the two. True technological innovation is possible by those engineers who understand and meet these requirements. Mitsubishi Motors also remains committed to technological innovation for minimizing impact on the environment and realizing safe, efficient, and clean driving.

This issue of MITSUBISHI MOTORS TECHNICAL REVIEW introduces many of Mitsubishi Motors' latest technologies and products. We will continue to use the MITSUBISHI MOTORS TECHNICAL REVIEW as an important means of informing our customers of Mitsubishi's current technological and production activities in the pursuit of providing all customers around the world with vehicles that bring pleasure to life.

SPECIAL CONTRIBUTION

# Methodology for Research Enabling

Hiromitsu ANDO*

## 1. Introduction

"What man of you, having a hundred sheep, if he loses one of them, does not leave the ninety-nine in the wilderness, and go after the one which is lost until he finds it?" Japanese literary critic Tsuneari Fukuda quoted these words of Jesus from Gospel Chapter 15 of according to Luke and continued by saying that politics is for the ninety-nine sheep, and literature is for the one lost sheep. Fukuda went on to comment that "bad politics mobilizes pens to serve itself and forces the scholarly to ignore the lost sheep" and "second-class literature wanders around the ninety-nine sheep in search of the one".

When we consider the form that research should take in modern industrial society, Fukuda's comments are thought-provoking and relevant. The ninety-nine sheep signify success in business, and the one lost sheep relates to the veneration of and yearning for knowledge. When the words 'development' and 'research' are compared in this context, it can be seen that 'development' calls for the mind to seek only the ninety-nine sheep but 'research calls' for the mind to seek the ninety-nine sheep and the one sheep simultaneously.

If research is understood as mentioned above, describing it as 'fundamental' or 'applied' is not particularly meaningful. Ever since the concept of engineering was created, research in engineering has been supported by minds in pursuing profit. If engineering research is conducted in focusing only on the one lost sheep, in other words, with a focus on understanding fundamental phenomena, it ought to be called 'fundamental' research at all times regardless of its stages, from research-theme establishment to applied research and ultimate development.

Research management is a concept that was introduced a few years ago, and it has since been provoking vigorous arguments on how to position research in social foundation establishment models and business models. Consequences of these arguments in Japan include the 'Frontier 21' program of the Ministry of Economy, Trade and Industry (METI) and the 'Center of Excellence' program of the Ministry of Education, Culture, Sports, Science, and Technology (MECSST). Both of these programs have the same key research management concepts: 'designation of core fields', 'shifts toward short-term programs', and 'partnership between industry, government, and academia'. Similar initiatives have been launched by private businesses. In Europe and the United States, research management arguments are taking place on most basic issues such as how to bridge the gap, the so-called 'valley of death' between fundamental research and ultimate commercialization, whether to model research as a survival-type model or as an advancement-type model, and on whether to have research organizations independent as central research laboratories or to disperse them among business divisions.

The mission of an enterprise is to offer value to customers by way of its products, and this value is perceived by customers in terms of differences from the products that they are currently using. Consequently, enterprises are forced to deny the value of the products and the technologies used in them they already have on the market and continue to offer new products and create new technologies. If repetition of this value denial and new creation cycle is defined as 'innovation', most of today's innovations are underpinned by new technological know-how in areas such as materials, processing methods, and information technology (although product planning and application of existing technologies are important processes in the creation of new value).

The role of research in enterprise lies in the building up of new technologies/knowledge and in finding ways to transfer the enterprises' accumulated technologies/knowledge into the value of products. What should not be forgotten with regard to these roles of research is that technologies and knowledge accumulated in enterprises are self-growing and enabling this self-growth is also an important role of research.

Various arguments on the roles of research can be simplified if we use the key word "techknowledge", which the author coined for this particular discussion by combining 'technology' and 'knowledge'. All these arguments should share the following premises:

(1) The sum of accumulated techknowledge within an enterprise is an important element of the value of that enterprise.
(2) Only techknowledge can create new techknowledge.
(3) Techknowledge is a uniquely human property.

The most important role of research management lies in creating a vision for the techknowledge that forms the value base of an enterprise and in creating a system that supports and maintains the process of continuous self-growth of techknowledge. Only a system based on this vision can create the value the enterprise it deserves. Since techknowledge is the result of a unique human process, making a system for techknowledge growth and self-growth is not an easy task. In an ideal system in which techknowledge is actively created and automatically develops, the vision for new techknowledge must be presented in a comprehensive man-

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ner. An environment rich in techknowledge resources must be created in accordance with that vision, and individual researchers working in the techknowledge-rich environment must have a strong sense that they are helping to raise that environment to an even higher level.

To present this ideal system in a visible way to researchers, Mitsubishi Motors Corporation (MMC) has established subsidiary systems with the names 'House of Knowledge', 'Technology Database', 'Technology Trend Analysis Book', and 'Research Partnership'. This paper describes some of the fieldwork conducted by MMC to determine the orientation of these systems.

## 2. What is the current state of Japanese industries reflected by key performance indicators?

The hollowing-out of Japanese industry is widely recognized as the 'lost decade'. Many people seem to attach little importance to this phenomenon, seeing it as temporary and believing that the hollowed-out industries will eventually be restored. However, when the situation is examined via key performance indicators (KPIs), we find it extremely serious. They indicate that the rate of successful investment in research within Japan has been in continuous decline for the past decade. More important is that this trend is seen only in Japan. To deal with this situation, industry and government have been making significant investments in research (in terms of percentage of gross domestic product, these investments are greater than those made in the United States), but the situation shows no sign of improvement. Not one of the 38 epoch-making products recently listed in *Fortune* magazine was invented in Japan. Trade statistics including those for software and other intellectual property show considerable deficits. The number of patent applications per year made by universities in Japan is mere 206[(1)] compared with 5,591 in the United States and Europe.

There is a book entitled *Chuokenkyujo-jidai-no-shuen* (literal translation: The End of the Age of the Central Research Institutes), a translation published by Nikkei BP of a book originally entitled *Engines of Innovation*. That a negative-sounding title was chosen as a Japanese translation of the positive-sounding original title is indicative of the current environment of stagnation in Japan.

The 'valley of death' model has often been used to explain the current stagnation. Here, the 'valley of death' signifies the gap that must be crossed before fundamental technologies can be translated into actual products. According to one explanation of this model, the United States has an established industry-government-academia partnership system, has venture capital, and has major corporations that are keen to break into new fields. These mechanisms work successfully enough to cross the gap. Japan has none of these mechanisms and thus cannot cross the 'valley of death'. A number of political measures have been implemented in Japan to improve the situation, but they have led only to the marketing of products with limited applicability by small enterprises; Japan has yet to produce its own Intels or Microsofts. The 'valley of death' model assumes that, if help is given to cross the gap, unique products will be created. In other words, it assumes that Japan already has necessary fundamental technologies. The author feels this perception is wrong. What is lacking is a supply of new fundamental technologies; no innovative products can grow without new techknowledge.

## 3. In concepts, the key word is 'culture'.

Another explanation given for Japan's 'lost decade' is this: Japanese people were competent enough to achieve great economic growth by striving to catch up with the industrialized West, but they lacked the ability to subsequently pioneer new technological fields.

The author supposes that the key word underlying this explanation is 'culture'. During Japan's catch-up period, a profit-driven approach based on mass production and price competition was taken for the reason of by industrial needs. However, the end of that period saw a market where consumers possessed all the basic commodities necessary for daily life; apparently, their interest had already shifted to value-added products for a richer, more relaxing, more sophisticated way of life. In the author's view, industries in Japan, unlike those in the United States and Europe, failed to take this opportunity to mature the market culture into a richer one and hence were not able to create more intrinsically valuable products.

In today's Japan, there are a growing number of people who not only enjoy the physical benefits of an affluent society but also lead their life with a rich imagination. However, the ideas of these people seem to have little influence on Japan's industries. It is surely necessary to adopt product concepts that reflect today's popular culture no matter how juvenile they might appear.

The author believes that the concept of market culture must be given much higher importance, particularly in the automobile market. This is because today's culture with regard to automobiles is outdated compared with culture in other areas of daily life. The trend of residential interiors in homes is to conceal functional elements inside walls and create a simple appearance, but functional elements are most often exposed in automobile cabins. Drive controls and other control systems of automobiles are more complicated than home appliances, and their designs are far from standard. It is difficult to exchange or upgrade elements to suit different purposes because 'open architecture' is not yet an actual trend in the specifications of automobile electrical equipment.

In Japan, the METI a few years ago designated the key promotion fields of technological development as the manufacturing technologies that yield added intellectual value, technologies that address the needs of an aging society, technologies that address aesthetic needs, and complex systems technologies. In the author's view, this move was intended to invigorate Japan's industries with a focus on people and culture. However, the METI's new Frontier 21 program seems to have shifted the development promotion fields toward fundamental technologies.

## 4. In technologies, the key phrase is 'bottom-up vision'.

The Frontier 21 project designated the following four key promotion fields of technological development:

(1) Biotechnology and life science technology field
(2) Information technology and telecommunications technology field
(3) Nanotechnology and material technology field
(4) Environment field

Among these four fields, the environment field seems incongruous. While the first three are associated with distinct technical fields and there exist corresponding industries and scholastic fields, the environment field is conceived from the objective and does not correspond to independent technical fields.

In 2003, the MECSST selected several universities in Japan as 'centers of excellence for research' according to the key promotion fields of technological development it had designated. A large number of research themes were selected for the technical fields (1) to (3), but few were selected for the environment field.

The above disparity can be explained by this: While fields (1) to (3) are selected by 'bottom-up vision' (or inductive vision), field (4) is selected by 'top-down vision' (or deductive vision). When technologies and technological fields exist and research themes are selected based on concepts that are born from them, such a selection is made by 'bottom-up vision'. When the selection of research themes is made based on the concepts created from the objectives, such a selection is made by 'top-down vision'. The author has heard that many universities, selected as centers of excellence for the environment field, were given themes that either lacked concreteness in terms of achievement methods and content of research or, conversely, were too specifically defined.

Where selection of fundamental research themes is concerned, therefore, the important vision is 'bottom-up vision' rather than 'top-down vision'. In fact, the themes selected in the environment field for the 2004 financial year in the Frontier 21 project included carbon-nano-tubes and liquid-crystal-display technologies, which should all have been classified in the nanotechnology and material technology fields. This fact also highlights the validity of the bottom-up approach for research theme selection.

Techknowledge and mathematical theories about molecules, atoms, and other objects and phenomena lies at the base of the bottom-up approach. For example, with regard to research themes in the biotechnology and life science technology field and in the nanotechnology and material technology field, the techknowledge should be about molecules and atoms; for the information technology and telecommunications technology field, it should be about voice recognition, image recognition and encryption technologies in addition to molecules and atoms. Most of the innovative inventions announced recently are supported by new material technologies derived from techknowledge about molecules and atoms and by new data processing technologies supported by mathematical theories.

Research in the product development area requires market knowledge, technological knowledge, and business knowledge[(2)]. The approach market knowledge is playing a role in research theme is a top-down approach which requires identification of latent needs and a search to realize its technology.

Technological knowledge, on the other hand, should be given for its role a bottom-up thinking approach through which new base technologies are discovered and applications for them are sought. Needless to say, top-down and bottom-up approaches are both predicated upon techknowledge that has been accumulated and enriched within the organization. It is also needless to say that it is business knowledge that enables the final evaluation of the advantages and disadvantages of launching any new product.

## 5. The significance of research by enterprises is now being re-evaluated.

Today's business managers seem to have left behind conventional straightforward thinking about the role of research in technological innovation. Some seek ways to cut investment in research as a way to cut costs, thinking ahead to keep a cost model, while others look for research to play a pivotal role in overcoming the dilemma of competition. Positions vary widely, but every manager is striving to better understand the form that research should take.

Business models in which survival is pursued through improvement of existing products and manufacturing methods in order to reduce research costs are not successful because they preclude creation of the new value demanded by customers. The 'quickly making the second from the first' model is also difficult to use successfully because the lifecycles of products acceptable to customers are becoming shorter. Also business models that focus on research do not always work effectively. They may be seriously compromised by the scarcity of research themes that have been successfully commercialized and by the existence of continued research whose link to needs has already been lost or whose feasibility of being seeds of future research is virtually zero.

The author does not think it effective to analyze model-based arguments of the above mentioned types and become involved in them for better understanding of the expectable future form of research, because most of these arguments do not seem to have direct connection to the purpose.

To have a long-term vision of research, one must do a large amount of work to process a virtual matrix focusing on the future. Many people support the short-term, intensive research as a survival strategy but they do so simply because they find it difficult to predict the future. At the same time, though, many people argue that a long-term research strategy is necessary for advancement but they often lack solid belief or vision and insist on long-term research simply to counter an ambiguous fear of competition or simply as a form of insurance.

Needless to say, the most desirable stance when thinking about research is to keep one's eyes on the future and devise strategies for advancement while accepting that creating new knowledge is accompanied by significant risk. The important question is how to minimize the risk.

## 6. Can knowledge be managed?

Not only enterprises, but universities and research institutes seem to have also come to realize that they must evaluate the processes and results of knowledge creation. Knowledge management requires politics that seek the ninety-nine sheep. In reality, however, people responsible for knowledge management depend mostly on easy-to-acquire information and concentrate only on making tools, failing to achieve the true objective of knowledge management effectively.

They may think like this: Creation of knowledge is associated with human nature, and the very concept of knowledge management and its quantification may be beyond human capability.

Recently, Professor Ikujiro Nonaka of Hitotsubashi University and co-authors presented the concept of "knowledge enabling" in a book[3]. This approach seeks the ninety-nine sheep and one sheep simultaneously and seems to be very useful when applied to the execution of research. The concept is based on the following three assumptions:

(1) Knowledge is a distinct conviction that has been justified and has an individual aspect and a social aspect as well as a tacit aspect and an explicit aspect.
(2) Knowledge depends on the perspective of individuals.
(3) Knowledge creation is a craft work, not a science.

The concept of knowledge enabling begins with the assumption that organizations cannot manage knowledge. Organizations are seen to be only capable of enabling knowledge. After defining that enabling knowledge is the key factor for enterprises to continuously achieve knowledge creation, Nonaka et al. proposed knowledge enablers, knowledge activists, and other specific methods for enabling knowledge. Knowledge creation always occurs in an environment where everyone is accepting each other. When members of the organization establish such an environment by proactively accepting the ideas of others, a source for higher creativity becomes available. The roles of the knowledge enablers and knowledge activists are to distribute information throughout the organization and remove obstacles to communication.

The concept presented by Professor Nonaka and his co-authors in the book offers its main values in the support for creation of knowledge and in the realization of the created knowledge in the form of products. The author would like to add to these values another value that lies in activity in which individuals study and then share the results of their studies as knowledge throughout the organization.

What should an organization do for systematic knowledge creation? Richard Saul Wurman answers this question with a key word 'study'[4] :

(1) If one plans to use a wonderful original idea to build a business, one must build a company culture that values study.
(2) If one hopes to be given a responsible job and advance one's career, one must continue to have a strong desire to study.
(3) The most important point is to work in an organization that continues to provide opportunities for study.

In fact, it is actually relatively easy for an organization to achieve the above. The only thing the organization needs to do is to declare a corporate culture that values study. Humans innately seek the one lost sheep; we instinctively want to solve worthwhile puzzles when we encounter them, or more generally expressed, we have awe and adoration for knowledge. Simply enabling this mindset leads naturally to a corporate culture that values study. The results of study are accumulated within individuals. Individuals in an organization instinctively want to contribute to the organization and to the organization's output. Providing just a modicum of support leads the knowledge accumulated within the individuals to be naturally spreads into the organization.

## 7. Research management can provide certain support to knowledge creation.

It seems reasonable to think that research management is able to fulfill a certain support function in order to enable study and the creation of knowledge through study. Frameworks for this support include MMC's recently introduced 'House of Knowledge', 'Technology Database', 'Technology Trend Analysis Book', and 'Research Partnership' systems.

Since knowledge creation is vulnerable, its achievement requires careful support through various organizational activities that are devised to overcome various obstacles. 'House of Knowledge' is an organizational concept that MMC has introduced as its declaration of a corporate culture that values study.

Required for next knowledge creation is a clearly presented research vision. An example of a vision presenting method is a portfolio system with a coordinate chart in which the X-axis shows the time, the Y-axis shows the value, and key words for technologies expected to emerge at different timings are plotted against the two axis. It is desirable that the technologies to which this method is applied are of the bottom-up vision nature. An inevitable characteristic of the technology of bottom-up vision nature is the branching of extremely numerous subfields and an extremely large number of key words needed to be plotted. Research vision presentation with this method should ideally be conducted by management while researchers add the results of their studies into the portfolio. This is the role of 'Technology Trend Analysis Book'.

It is also important for research management to establish a knowledge database as a knowledge creation support function. Currently most research time is spent on reaching information. If the information that individual researchers have acquired is collected in a database, the time can be shortened. This is the role of 'Technology Database'.

The greatest support that research management can provide to knowledge creation comes from the promotion of joint research. Taking material technologies (the most important technologies of the bottom-up vision nature) by way of example, we see that the latest research efforts involve materials design where researchers handle individual molecules. It is impossible for a single company to implement such high-level technology in all fields. In such a case, it is effective for the company to form tie-ups with leading researchers in different fields. In the tie-up forming, the company presents the theme selected based on top-down vision to researchers of the field concerned. This necessitates clear explanation of the value of the technologies under research, past performance and future obstacles all in the language of the technological fields of those who undertake the research of the selected theme. It is the role of research management to locate the most suitable specialists and start communication with them using the most appropriate language. This is the role of the 'Research Partnership'.

## 8. Ultimately, communication is key.

Knowledge is an attribute of individuals. It can become significant only when it is communicated. Many reports indicate, however, that this quite natural mechanism often does not work within companies. Researchers, who have the seeds (knowledge), believe that their responsibility has been fulfilled when they file and register the knowledge in the database, thinking that it is the designers' responsibility to access the knowledge. The designers, on the other hand, believe that the researcher's responsibility is to provide the knowledge in a language understandable to them.

It would be easy to say that such problems do not arise if communication is conducted properly. In reality, however, conflicts of this kind have been frequently occurring in a large number of enterprises, which allows one to infer that they are innately inevitable. Based on this inference, Professor Nonaka and his co-authors propose to add "support" to the evaluation items for researchers in addition to "trust". How much a researcher is responding to a request for support, how long a researcher is spending on listening to the desires of others and looking for a solution, how long a researcher is spending on transferring his/her knowledge to others, and how long a researcher is spending on helping to put the knowledge of others in a clearly understandable form; these would all be indicated in specific indexes.

The author believes that the most practical form of knowledge transfer system from knowledge creators to knowledge users is a system in which knowledge creators are obliged to give support to knowledge users and knowledge users indicate demand for such support on their own initiative.

## 9. Conclusion

Research managers want to contribute to their organizations through research. For this reason, they wish to recruit researchers with better capabilities than themselves. If they cannot recruit such competent researchers, they seek to empower the pride latent within their subordinates, give them incentives to do higher-level work, and nurture them to become researchers with better capabilities than themselves.

It is easy for research managers to force researchers to conduct research, but it is not possible for them to force researchers to create something. All they can do is to pray that the god of creation may smile on the researchers. But a prayer alone is not sufficient. It is necessary for them to establish an environment that attracts the god of creation. It is possible for them to create a corporate culture that attaches value to study and provide a modicum of support to maintain that environment.

Continuing research and maintaining knowledge at a cutting-edge level is a painstaking job. Researchers sometimes worry about whether they are working in fields where solutions do not exist. The way to remove this anxiety is to broaden fields of activity through study. There is also anxiety about when the next brainchild will emerge. The way for a researcher to escape from this anxiety is to have an excellent research theme for which a solution is really wanted. To this end, it is effective for them to continue studying in a knowledge-filled environment. Studies not only solve problems but also present more research themes.


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Hiromitsu ANDO

# Research on Aerodynamic Drag Reduction by Vortex Generators

Masaru KOIKE* Tsunehisa NAGAYOSHI* Naoki HAMAMOTO*


## Abstract

**One of the main causes of aerodynamic drag for sedan vehicles is the separation of flow near the vehicle's rear end. To delay flow separation, bump-shaped vortex generators are tested for application to the roof end of a sedan. Commonly used on aircraft to prevent flow separation, vortex generators themselves create drag, but they also reduce drag by preventing flow separation at downstream. The overall effect of vortex generators can be calculated by totaling the positive and negative effects. Since this effect depends on the shape and size of vortex generators, those on the vehicle roof are optimized. This paper presents the optimization result, the effect of vortex generators in the flow field and the mechanism by which these effects take place.**


**Key words:** *Body, Aerodynamics, Aerodynamic Devices, Flow Visualization, Computational Fluid Dynamics (CFD)*

## 1. Introduction

To save energy and to protect the global environment, fuel consumption reduction is primary concern of automotive development. In vehicle body development, reduction of drag is essential for improving fuel consumption and driving performance, and if an aerodynamically refined body is also aesthetically attractive, it will contribute much to increase the vehicle's appeal to potential customers.

However, as the passenger car must have enough capacity to accommodate passengers and baggage in addition to minimum necessary space for its engine and other components, it is extremely difficult to realize an aerodynamically ideal body shape. The car is, therefore, obliged to have a body shape that is rather aerodynamically bluff, not an ideal streamline shape as seen on fish and birds. Such a body shape is inevitably accompanied by flow separation at the rear end. The passenger car body's aerodynamic bluffness, when expressed by the drag coefficient ($C_D$), is generally between 0.2 and 0.5, while that of more bluff cubic objects is greater than 1.0 and that of the least bluff bullets is less than 0.1. Two elements that have major influence on the drag coefficient of a bluff object are the roundness of its front corners and the degree of taper at its rear end. The importance of the influence of the rear taper in passenger cars can be described as follows:

**Fig. 1** schematically shows the flow around a sedan. Because of the presence of a trunk at the rear, the flow separates at the roof end and then spreads downward. As a result, the flow around the car is similar to that around a streamline-shaped object with a taper at the rear. For this reason, a sedan with a trunk tends to have smaller drag coefficient value than a wagon-type car.

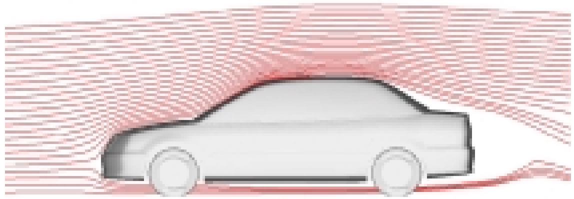

**Fig. 1 Flow around a sedan**

In other words, taper at the rear has the effect of delaying flow separation (or shifting the flow separation point downstream).

A well-known example for intensifying the flow separation delaying effect is utilizing a dimple (like the ones on golf balls)[1]. Adding dimple-shaped pieces can lower the $C_D$ to a fraction of its original value. This is because dimples cause a change in the critical Reynolds number (the Reynolds number at which a transition from laminar to turbulent flow begins in the boundary layer). There are reported examples of aircraft wings controlling the boundary layer, in which vortex generators (hereinafter referred to as VG(s)) successfully delayed flow separation even when the critical Reynolds number is exceeded[2].

Although the purpose of using VGs is to control flow separation at the roof end of a sedan, it is so similar to the purpose of using VGs on aircraft. To determine the shape of sedan VGs, the data on aircraft VGs are referred to[2].

## 2. Mechanism of flow separation and objectives of adding vortex generators

**Fig. 2** shows a schematic of flow velocity profile on the vehicle's centerline plane near the roof end. Since

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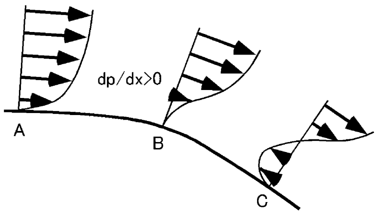


**Fig. 2 Schematics of velocity profile around rear end**

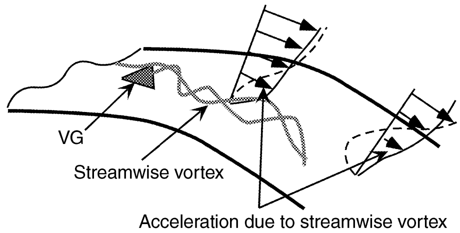


**Fig. 3 Schematics of flow around vortex generator**

the vehicle height in this section becomes progressively lower as the flow moves downstream, an expanded airflow is formed there. This causes the downstream pressure to rise, which in turn creates reverse force acting against the main flow and generates reverse flow at downstream Point C. No reverse flow occurs at Point A located further upstream of Point C because the momentum of the boundary layer is prevailing over the pressure gradient (dp/dx). Between Points A and C, there is separation Point B, where the pressure gradient and the momentum of the boundary layer are balanced. As shown in **Fig. 2**, in the lower zone close to the vehicle's surface within the boundary layer, the airflow quickly loses momentum as it moves downstream due to the viscousity of air. The purpose of adding VGs is to supply the momentum from higher region where has large momentum to lower region where has small momentum by streamwise vortices generated from VGs located just before the separation point, as shown in **Fig. 3**. This allows the separation point to shift further downstream. Shifting the separation point downstream enables the expanded airflow to persist proportionately longer, the flow velocity at the separation point to become slower, and consequently the static pressure to become higher. The static pressure at the separation point governs over all pressures in the entire flow separation region. It works to reduce drag by increasing the back pressure. Shifting the separation point downstream, therefore, provides dual advantages in drag reduction: one is to narrow the separation region in which low pressure constitutes the cause of drag; another is to raise the pressure of the flow separation region. A combination of these two effects reduces the drag acting on the vehicle.

However, the VGs that are installed for generating streamwise vortices bring drag by itself. The actual effectiveness of installing VGs is therefore deduced by subtracting the amount of drag by itself from the amount of drag reduction that is yielded by shifting the separation point downstream. Larger-sized VGs increase both the effect of delaying the flow separation and the drag by itself. The effect of delaying the flow separation point, however, saturates at a certain level, which suggests that there must be an optimum size for VGs.

## 3. Experimental methods

Evaluation of the effectiveness of VGs and optimization were conducted using MMC's full scale wind tunnel[3]. The test section was closed and the main flow velocity was set at 50 m/s. Mitsubishi LANCER EVOLUTION VIII was used as the test vehicle. To evaluate the effectiveness of VGs, six component forces of the vehicle were measured and VGs' optimum shape and size were examined. Furthermore, in order to clarify the factors contributing to the effect provided by VGs, the total pressure distribution of the wake flow was measured with pitot rake, the velocity distribution was measured by the particle image velocimetry (PIV) method, and the flow field was analyzed in detail using computational fluid dynamics (CFD).

## 4. Finding the optimum VGs

To select appropriate shape and size of the VG which generates streamwise vortex the most efficiently (with the least drag by itself) is important to achieve objectives.

In connection with the size, the thickness of the boundary layer is measured based on the assumption that the optimum height of the VG would be nearly equal to the boundary layer thickness. **Fig. 4** shows the velocity profile on the sedan's roof. From this figure, the boundary layer thickness at the roof end immediately in front of the separation point is about 30 mm. Consequently, the optimum height for the VG is estimated to be up to approximately 30 mm.

As to the shape, a bump-shaped piece with a rear slope angle of 25 to 30° is selected. This is based on the fact that a strong streamwise vortex is generated on a hatchback-type car with such rear window angle[4]. A half-span delta wing shape is also recommended for the VG. This shape is inferred from an aircraft's delta wing that generates a strong streamwise vortex at its leading edge[2].

As to the location of VGs, a point immediately upstream of the flow separation point was assumed to be optimum, and a point 100 mm in front of the roof end was selected as shown in **Fig. 5**. The effects of bump-shaped VGs mounted at this point are presented in **Fig. 6**. The front half contour of the bump-shaped VG was smoothly curved to minimize drag and its rear half was cut in a straight line to an angle of approximately 27° for maximum generation of a streamwise vortex. As shown in **Fig. 6**, three bump-shaped VGs that were similar in shape but different in height (15 mm, 20 mm, and 25 mm) are examined. The graph in **Fig. 6** shows that the drag coefficient was smallest at the height of 20 to 25 mm, so a height in this range was considered optimum for the VG. However, a taller VG might cause a

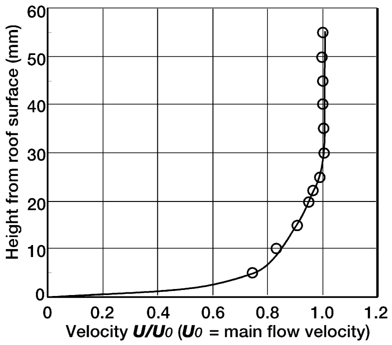


**Fig. 4 Velocity profile on roof (100 mm upstream from rear end)**

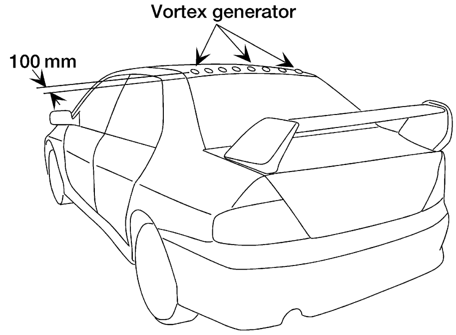


**Fig. 5 Location of vortex generators**

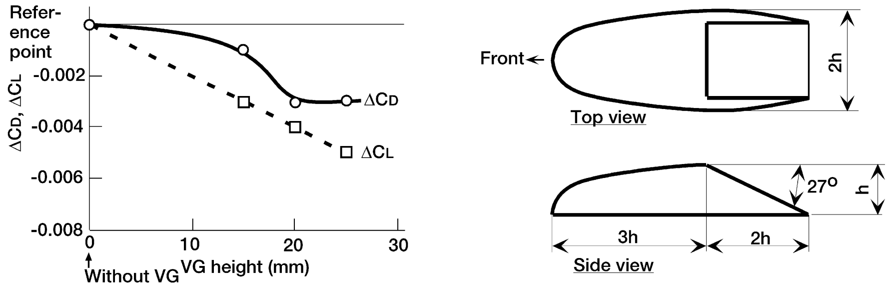


**Fig. 6 Effects of bump-shaped vortex generators**

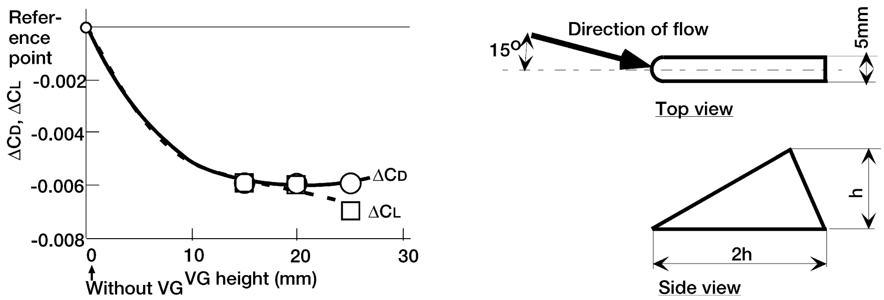


**Fig. 7 Effects of delta-wing-shaped vortex generators**

decrease in the lift. The rather small change in drag coefficient resulting from change in height can be accounted for as follows. As mentioned before, an increase in height of the VG simultaneously causes two effects: one is reduced drag resulting from delayed flow separation and the other is increased drag by the VG itself. These two effects are balanced when the VG's height is between 20 and 25 mm.

From these results, a reduction of $C_D$ is 0.003 with this bump-shaped VG when the shape and size are optimized.

The effectiveness of the delta-wing-shaped VG is also examined. The recommended shape of the delta-wing-shaped VG is defined by the following[(2)]:

Length/height = 2
Yaw angle = 15˚
Interval/height = 6

Based on this data, delta-wing-shaped VGs are created with the following specifications:

Length/height = 2
Height = 15 mm, 20 mm and 25 mm (three types)
Thickness = 5 mm

The delta-wing-shaped VGs should be installed at a yaw angle of 15˚ to the airflow direction. In order to meet this condition, the direction of airflow at the roof end was investigated by oil flow measurement. Airflow direction was found to be different between sideways positions on the roof. The airflow is aligned directly with the backward direction at center of a car, but it increasingly deviates toward the center as the measurement point shifts away from the central position. For this reason, the delta-wing-shaped VGs must be installed at an angle of 15˚ against the vehicle centerline for the central position, whereas they must be installed at an angle near 0˚ for outermost positions. The results of these tests are shown in **Fig. 7**. Delta-wing-shaped VGs were found to be less sensitive to change in height than bump-shaped VGs; the drag reduction effects for the VGs of three different heights

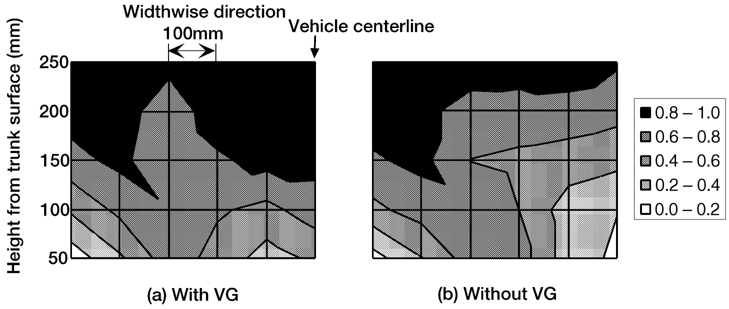


**Fig. 8 Total pressure distribution (upstream of rear spoiler)**

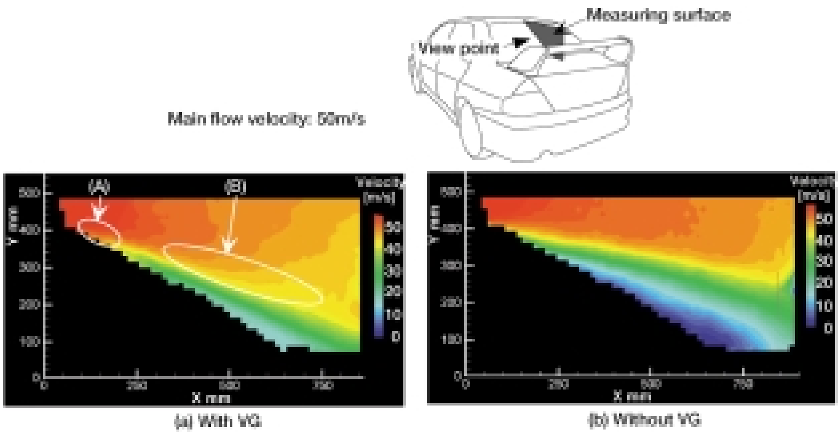


**Fig. 9 Velocity distribution by PIV measurement**

(15 mm, 20 mm and 25 mm) were all equivalent to –0.006. The effect of lift reduction increased only slightly with the height. The drag reduction also differed only slightly with changes in the number of VGs and their positions. The number and positions of the tested VGs seems to be in their optimum ranges.

From these results, delta-wing-shaped VGs were capable of reducing drag by –0.006.

The reason for why delta-wing-shaped VGs are more effective than bump-shaped VGs can be explained as follows: Delta-wing-shaped VGs have a smaller frontal projection area, which means that they themselves create smaller drag. Moreover, the vortex generated at the edge of a delta-wing-shaped VG keeps its strength in the flow downstream of the edge since it barely interferes with the VG itself because of the VG's platy form. With bump-shaped VGs, on the other hand, the vortex is generated at a point close to the downstream edge of the bump, which causes the vortex to interfere with the bump and lose its strength.

## 5. Verification of VG's mechanism

In Section 2 above, the effect of VGs is estimated that the separation point is shifted to downstream, which in turn narrows the flow separation region. The flow field was thus investigated in order to verify the correctness of this estimation.

**Fig. 8** shows total pressure distribution in the wake flow immediately upstream of the rear spoiler for both cases with and without VGs. High total pressure regions correspond to high velocity regions. As the figure shows, the high velocity region is expanded downward by addition of VGs, signifying that the flow separation region is narrowed.

**Fig. 9** shows the results of velocity distribution using the PIV method. The PIV laser light sheet was illuminated from above on the center plane of the vehicle body and the measuring surface was photographed from the side (as indicated by the viewpoint arrow in **Fig. 9**) to calculate the two-dimensional velocity distribution. **Fig. 9 (a)** shows the velocity distribution for the case with VGs, and **Fig. 9 (b)** shows the velocity distribution for the case without VGs. As evident from the figure, the case with VGs shows an increase in velocity on the surface of the body (rear window) just behind the VG (Zone A in the figure) and extension of the high velocity zone downward (Zone B in the figure). This supports our estimation in the previous section that VGs cause airflows above the rear window to attach to the surfaces of the body.

This phenomenon was examined in detail using CFD analysis. Star-CD was used as the solver and RNG k-$\varepsilon$ model as the turbulence model in this analysis. In order to detect flow separation at the rear window, a prism cell was inserted in the vicinity of the vehicle, and the "y+" value of computational grid is arranged to become an appropriate value between 20 and 50 near the separation point. **Fig. 10** shows the calculation results for the case with VGs and the case without VGs. These results show good agreement with the experimental results using the PIV method, and clearly show that the

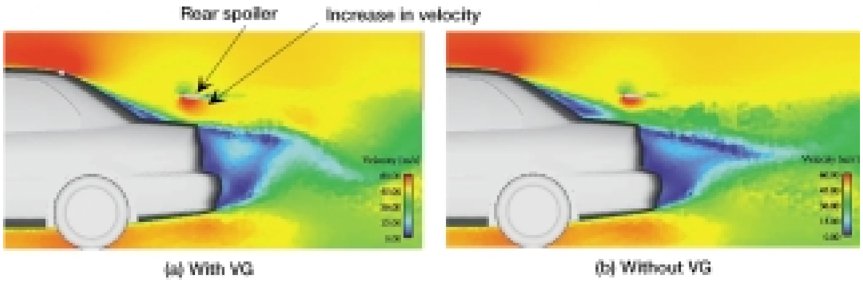


**Fig. 10 Velocity distribution by CFD**

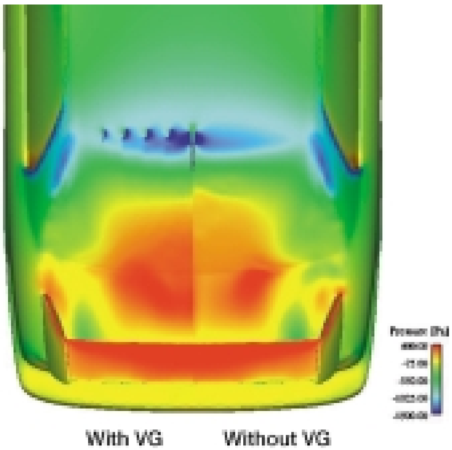


**Fig. 11 Pressure distribution of vehicle (CFD)**

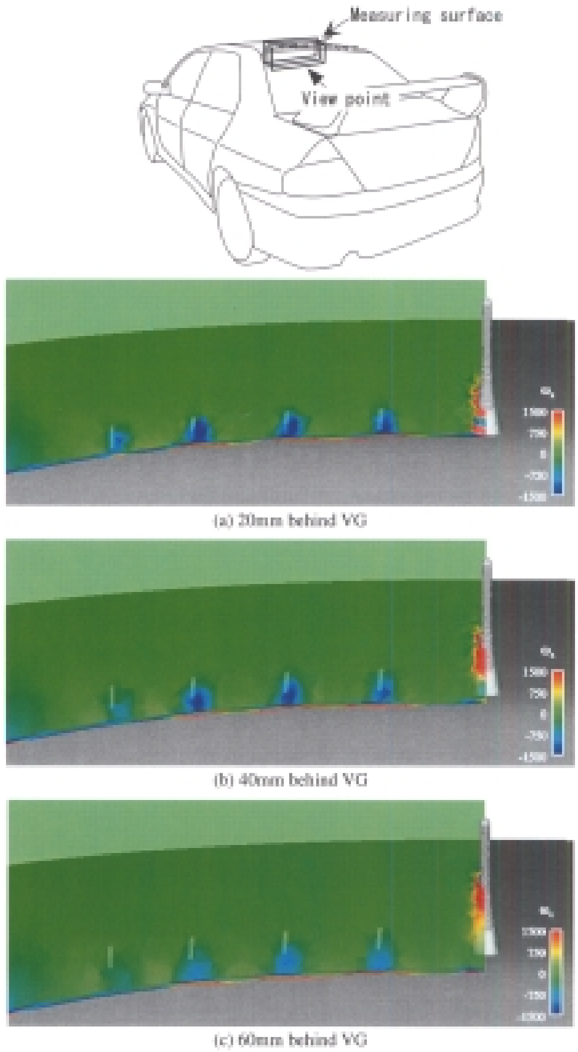


**Fig. 12 Vorticity distribution behind vortex generators (CFD)**

low velocity region is narrowed by the addition of VGs. The changes in drag and lift calculated by CFD shown below are almost agree with the experimental results (**Fig. 7**).

$\Delta C_D = -0.004$
$\Delta C_L = -0.013$

The CFD calculation, therefore, could simulate the actual phenomenon. CFD results in **Fig. 10** also show that the velocity of the airflow along the bottom surface of the rear spoiler increases by addition of VGs, which reveals that a decrease in lift (an increase in down-force) did occur. These results also show that the flow separation region (low velocity region) at the rear portion of the trunk is slightly narrowed.

**Fig. 11** shows the pressure distribution on the vehicle body surface. The addition of VGs gives the effect of increasing the surface pressure over a wide area ranging from the rear window to the trunk and this in turn reduces the drag. However, negative pressure region around the VGs indicate that VGs themselves cause drag.

Such changes in airflow can be attributed to VGs that work to suppress flow separation at the rear window. To verify this mechanism, the airflow was studied in further detail. **Fig. 12** shows vorticity distribution behind the VGs. Streamwise vortices are generated behind the VGs.

Our estimation that the streamwise vortex causes the separation point to shift downstream is confirmed by CFD results. **Fig. 13** shows close-up views of the flow field near the separation point. The case with VGs shows flow separation occuring further downstream than in the case without VGs.

## 6. Conclusions

The conclusions of this research can be summarized into the following points:

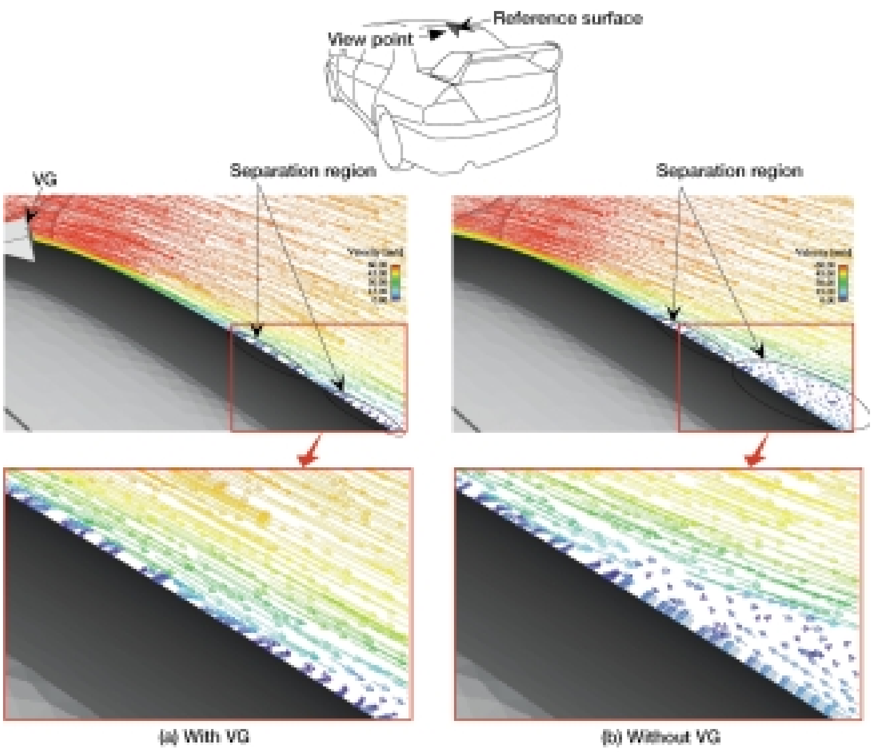


**Fig. 13 Velocity vectors around separation point (CFD)**

(1) Vortex generators (VGs) were studied to install immediately upstream of the flow separation point in order to control separation of airflow above the sedan's rear window and improve the aerodynamic characteristics. It was found that the optimum height of the VGs is almost equivalent to the thickness of the boundary layer (15 to 25 mm) and the optimum method of placement is to arrange them in a row in the lateral direction 100 mm upstream of the roof end at intervals of 100 mm. The VGs are not highly sensitive to these parameters and their optimum value ranges are wide. Better effects are obtained from delta-wing-shaped VGs than from bump-shaped VGs.

(2) Application of the VGs of the optimum shape determined through the abovementioned analyses to the Mitsubishi LANCER EVOLUTION showed a 0.006 reduction in both the drag coefficient and lift coefficient.

(3) Factors contributing to the effect of VGs were verified by conducting measurement of total pressure, velocity distribution and CFD. As a result of the verifications, it is confirmed that VGs create streamwise vortices, the vortices mix higher and lower layers of boundary layer and the mixture causes the flow separation point to shift downstream, consequently separation region is narrowed. From this, we could predict that VGs cause the pressure of the vehicle's entire rear surface to increase therefore decreasing drag, also the velocity around the rear spoiler to increase, and the lift to decrease.

The delta-wing-shaped VG, which demonstrated high effectiveness in this research, is planned for commercialization as an accessory for sedans after slight modifications to the shape with respect to design, legal conformance and practicality.

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# Study of Engine Cooling Technologies for Knock Suppression in Spark Ignition Engines

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## Abstract

**The gas temperature at the end of a compression stroke was calculated from measured cylinder pressure, and was evaluated as an index of knock suppression effect. This method enables the potential of ignition timing advance to be correctly estimated while eliminating influences such as individual differences in perception and combustion chamber shape, even if it is smaller than the setting resolution. Reducing the gas temperature at the end of a compression stroke effectively suppresses knock. Using a cooling technique which controls the transfer of heat to gas before the combustion stage, we succeeded in achieving an additional 4° CA spark advance in the engine.**


***Key words:*** *Spark Ignition Engine, Knocking, Cooling*

## 1. Introduction

Engine cooling optimization is attracting the attention of researchers as a means of making engines comply with increasingly stringent demands for lower fuel consumption and lower exhaust emissions. Whereas the conventional objectives of engine cooling optimization were to satisfy material durability requirements and prevent abnormal combustion, automotive engineers are now focusing on the additional benefits of engine cooling, such as improvement of engine output through intense cooling and improving fuel consumption by reducing losses resulting from unnecessarily intense cooling.

The improvement of engine output through intense cooling is due to the increase in charging efficiency and the spark advancing effect it yields. The amount of spark advance is usually determined by listening to knocks by the human ear. However, this method is inaccurate because there are unavoidable differences in sensitivity between evaluators and variations between individual engines. Further, improvement of cooling results in only a small amount of spark advance which is minute relative to the setting resolution in the ignition timing. To determine accurately the effects of improving engine cooling on suppressing knocks without being affected by any of the abovementioned causes of inaccuracy, we devised and tested a method that used as an evaluation index the drop in cylinder gas temperature at the end of the compression stroke, which is closely related with the occurrence of knocks. This report describes this new method of evaluating the knock suppression effect. In addition, as the reduction of cylinder gas temperature is essential for knock suppression, we tested an approach for improving engine cooling and achieved an additional 4° CA spark advance, which is also described here.

## 2. Calculating cylinder gas temperature

### 2.1 Average cylinder gas temperature

Assuming that the working gas in the cylinder is homogeneous, we calculated the average cylinder gas temperature by applying a cylinder gas pressure measurement, gas volume calculated from the cylinder's geometrical specifications, and total number of moles of the working gas to the equation of state. The cylinder gas pressure used in the calculation was the average of the measurements taken for 30 cycles for every one-degree crank angle. The cycle number of 30 is less than that which is widely considered to be suitable for this type of analysis. However, our analysis concerns only the phenomenon before ignition, and the variation in data between cycles is so small that our data are sufficient for significant results. Fresh intake air, fuel, and residual gas are considered as working gas. The amount of fresh intake air was calculated from the amount of fuel consumption and exhaust gas composition. A molecular mass of 114 was adopted for the fuel, assuming that the fuel evaporated completely before the start of the compression stroke, and the mass was converted into the number of moles. The amount of residual gas was calculated using intake manifold pressure, exhaust manifold pressure, and exhaust manifold temperature, based on the assumption that the space that is not occupied by fresh air at the bottom dead center of the intake stroke is filled with residual gas (**Fig. 1**). An increase in number of moles after the start of combustion was not taken into account in these calculations.

### 2.2 End gas temperature

Although the knock suppression effect of engine cooling was to be finally determined based on the gas temperature at the end of the compression stroke, we also calculated the end gas temperature which is direct-

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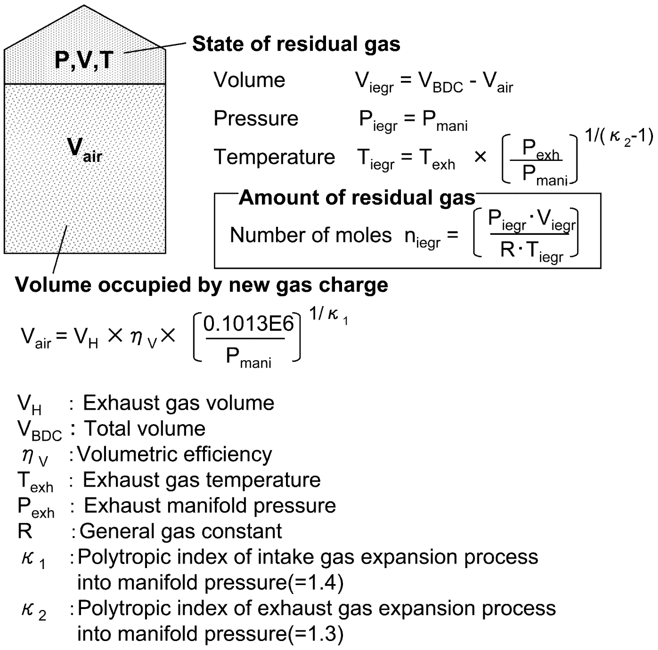



**Fig. 1 Estimation of residual gas amount**

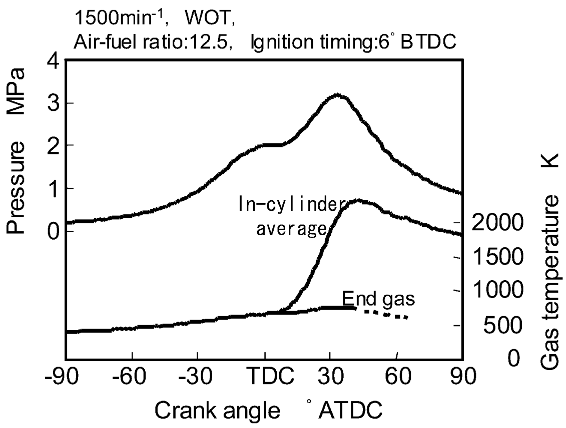



**Fig. 2 In-cylinder gas average temperature and end gas average temperature**

ly related to the occurrence of knock, using a simplified method in order to clarify the relationship between temperature and knock. Assuming that there are two regions present in the combustion chamber after the start of combustion – burned and unburned gas regions – and that the unburnt region continues to undergo polytropic compression of the same index (1.35) as that during the compression stroke due to the rise in pressure following combustion, we calculated the end gas temperature using the condition at the start of combustion as the initial condition for calculation. We defined the start-of-combustion point, i.e., the initial calculation condition, as the point at which the heat release exceeds 1 % of the total amount of heat release in a cycle. The calculated average cylinder gas temperature and end gas temperature are shown in **Fig. 2**.

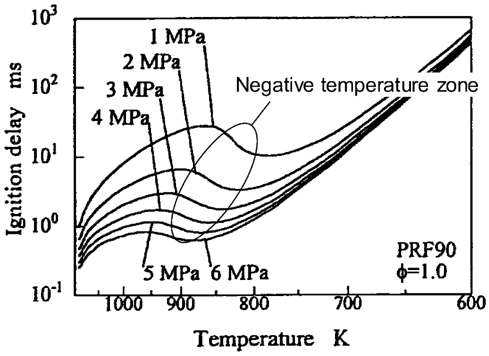



**Fig. 3 Ignition delay at low temperature oxidation reaction[2]**

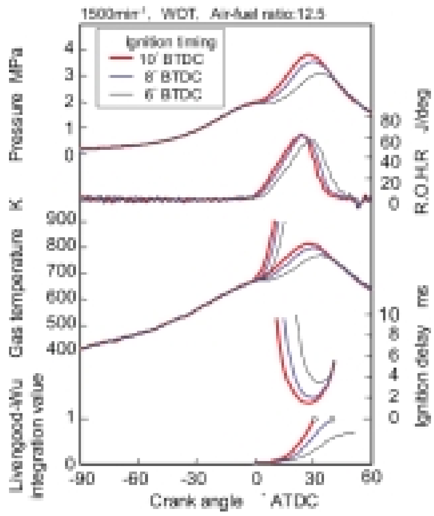



**Fig. 4 History of ignition delay and Livengood-Wu integration**

## 3. Relationship between gas temperature and knock

### 3.1 End gas temperature and knock

Knock refers to the spontaneous ignition of end gas, and its occurrence depends on the balance between the ignition delay of low-temperature oxidation reaction, which is a function of both temperature and pressure, and the time required for the flame front to reach the end gas. In general, except in a zone referred to as the negative temperature zone, the lower the end gas temperature is, the slower the autoignition reaction progresses and the smaller the chance of knock occurring. As the end gas temperature and pressure have been determined and the ignition delay time of the air-fuel mixture under these temperature and pressure conditions are known, the autoignition time can be calculated by integrating the reaction speed, which is the inverse of ignition delay time (Livengood-Wu's integration[1]). Although the ignition delay time should ideally have been calculated at the equivalence ratio and octane number of fuel used in this experiment, the ignition delay time determined by Saijo et al.[2] for an air-fuel mixture of octane number 90 and equivalence ratio 1.0 (**Fig. 3**) was used for the calculation. **Fig. 4** shows

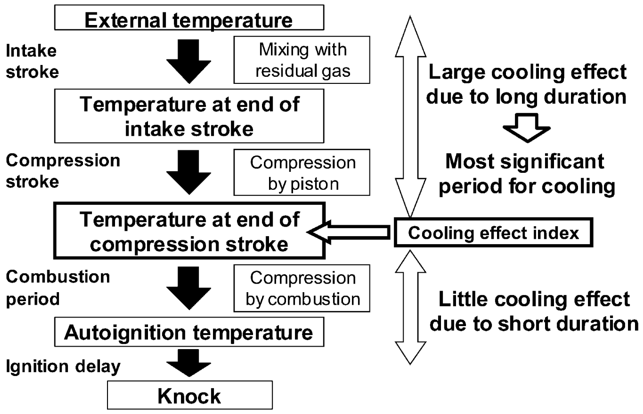



**Fig. 5** **Process of rise in gas temperature**

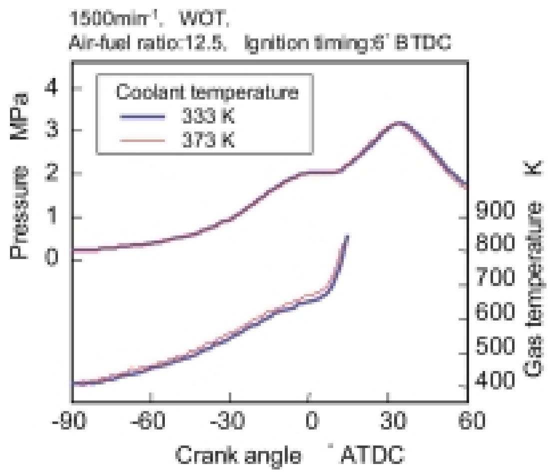



**Fig. 6** **Coolant temperature and average in-cylinder gas temperature**

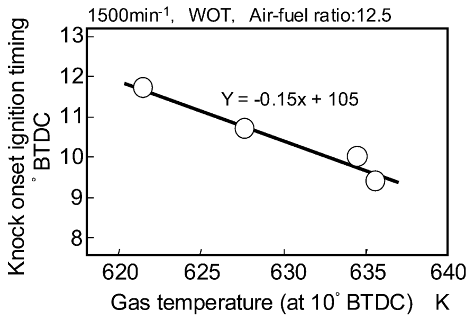



**Fig. 7** **Gas temperature at end of compression stroke vs. knock onset timing**

the end gas temperature calculated from the in-cylinder pressure, ignition delay time, and Livengood-Wu's integration value. When the ignition timing is advanced, the heat release curve shifts to the advance side by almost the same angle as the ignition timing advance angle while maintaining the same shape. However, advanced ignition timing causes a high equivalent volume combustion, which heightens the pressure and temperature, and the increased pressure and temperature shorten the ignition delay time. As a result, the estimated autoignition time, or the time when the integration value becomes 1, advances by much more than the advance angle. Since there are almost no changes in the shape of the heat release curve even when the ignition timing is advanced, it is conceivable that the speed of flame propagation remains almost the same. This means that only the ignition delay time becomes shorter without significant change in the other conditions, or that the ignition timing advances excessively. This is the knock onset process described in terms of the autoignition mechanism.

Determining the autoignition onset time by the abovementioned calculation method and comparing it with the combustion completion timing deduced from the heat release rate appears to be a valid method of predicting the occurrence of knock. However, given that the temperature derived from measured cylinder pressures is a spatially averaged, and the pressures themselves are cycle-averaged ones, the actual occurrence of knock cannot be accurately predicted by this method. Further, this method is not practical for evaluating the potential effect of ignition timing advance that can be expected from optimizing the engine cooling because of the difficulty of determining the ignition delay for each type of fuel and each equivalence ratio of air-fuel mixture used in the test and of the massive man-hours needed to adjust this method for each cycle.

### 3.2 Average cylinder gas temperature and knock

We therefore selected the average in-cylinder gas temperature as a factor that might be usable for evaluating the effects of engine cooling optimization. **Fig. 5** shows the process by which the temperature of the air-fuel mixture in a cylinder rises to the onset of knock. The temperature of the air-fuel mixture before combustion rises due to compression by the piston and the temperature of the end gas during the combustion period rises due to compression by the pressure increase following combustion. Since heat transfers take place between the gas and cylinder wall during these processes, the temperature history of the in-cylinder gas is influenced by the cylinder wall temperature. This is why optimum engine cooling helps to prevent knock. In this context, the influence of engine cooling during the period by the end of compression is considered to be dominant compared with that during combustion because of the short duration of the combustion stroke. We can therefore consider the decrease in gas temperature at the end of the compression stroke as an index which effectively represents the effect of engine cooling optimization. **Fig. 6** shows experimental measurements of the in-cylinder pressure and calculated in-cylinder gas temperatures for various coolant temperatures. It shows that the gas temperature at the end of the compression stroke decreases with a decrease in coolant temperature. **Fig. 7** shows the relationship between the gas temperature and the ignition timing of knock onset, taking the gas temperature at the end of the compression stroke with the crank angle at 10° BTDC as a typical example. The graph shows that there is a clear relation-

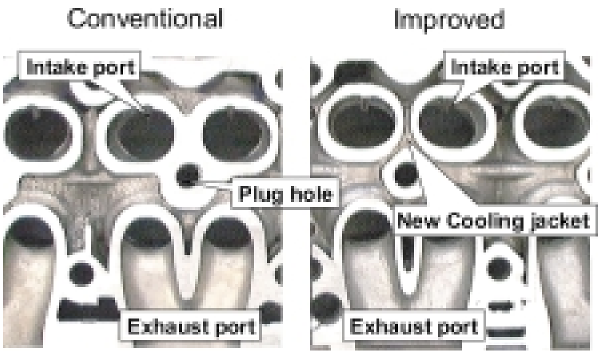



**Fig. 8 Cooling jacket structure in cylinder head**

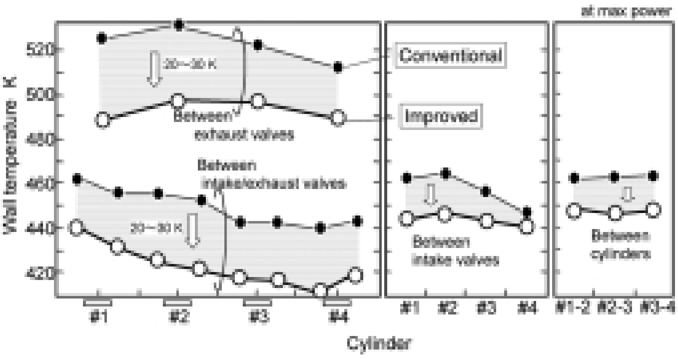
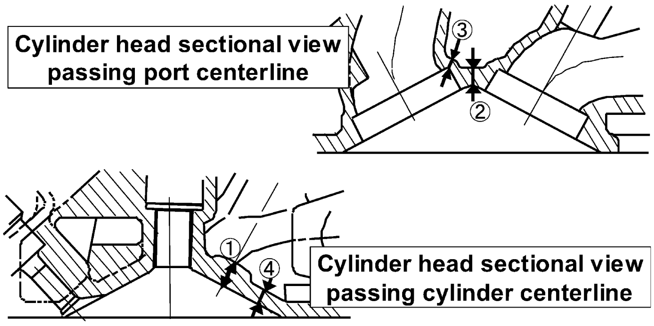



**Fig. 10 Cylinder head wall temperature**




| No. | Part | Wall thickness (mm) | |
|---|---|---|---|
| | | Conventional | Improved |
| ① | Between exhaust valves | 15.5 | 12.5 |
| ② | Between intake/exhaust valves | 11.0 | 6.0 |
| ③ | Valve sheet ring back boss | 5.0 | 3.0 |
| ④ | Base thickness (Drawing-specified) | 10.0 (8.0) | 6.0 (6.0) |

**Fig. 9 Wall thickness of cylinder head combustion chamber**

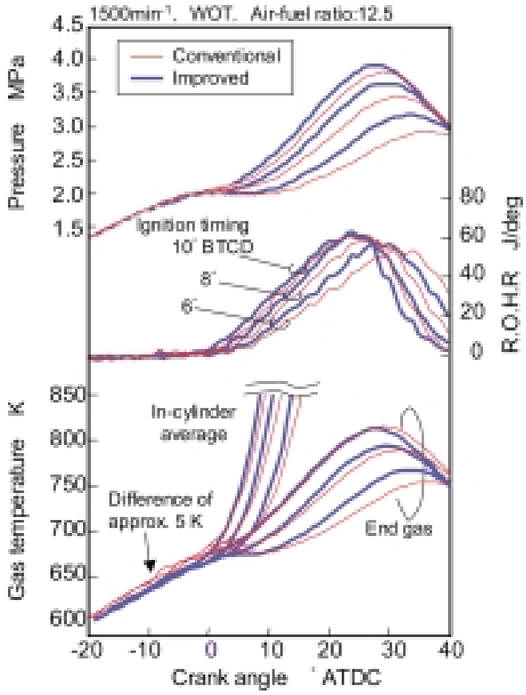



**Fig. 11 Comparison of in-cylinder pressure analysis results**

ship between the gas temperature at the end of the compression stroke and the ignition timing of knock onset, which supports the assumption that the potential of an ignition timing advance can be evaluated depending on the decrease in gas temperature at the end of the compression stroke. The relationship between these two factors was used to evaluate the potential of ignition timing advance caused by engine cooling optimization discussed in the next section.

## 4. Application of new method to evaluation of engine cooling optimization

The effects of ignition timing advance were obtained by intensified cooling of the cylinder head, cylinder block and pistons. The details of the effects are described below for the cooling of each part.

### 4.1 Intensified cooling of cylinder head

New coolant passages were added between the intake valves (**Fig. 8**) and the entire thickness of the combustion chamber walls was reduced (**Fig. 9**) in order to restrain the heat transfer to gas during intake strokes and lower the temperature of the entire cylinder head. As a result, the temperature of the combustion chamber walls decreased by more than 20 K as shown in **Fig. 10**, and the gas temperature at the end of the compression stroke decreased by approximately 5 K as shown in **Fig. 11**. When evaluated based on the relationship between in-cylinder gas temperature and knock onset described in section 3.2, an ignition advance potential of approximately 1° CA was achieved, whereas no difference was identified in ignition advance potential before and after intensification of cooling when the result was evaluated by ear. A separate investigation revealed that this contradiction was due to the change in in-cylinder gas flow due to the difference between individual engines, which is explained as follows. In the cooling intensified engine, the combustion speed quickened as shown by the heat release rates in **Fig. 11**,

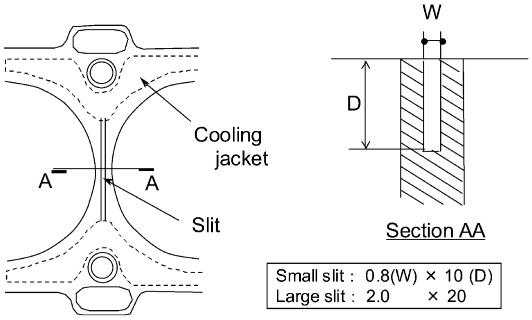



**Fig. 12 Slit cut between cylinder / s**

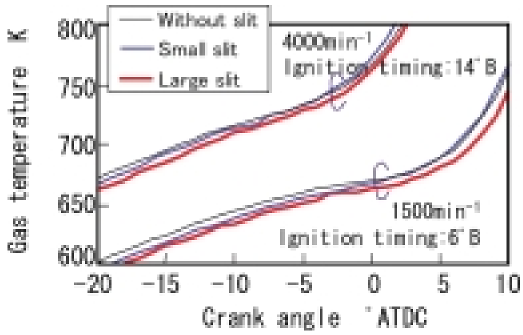



**Fig. 14 Effect of slit on gas temperature reduction**

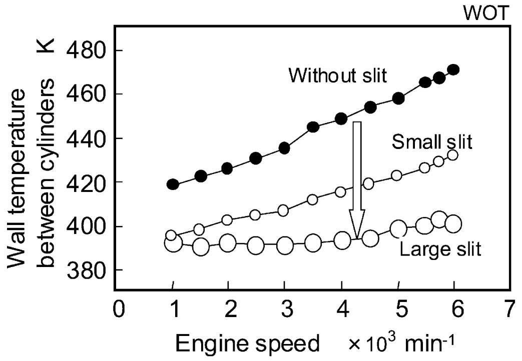



**Fig. 13 Effect of slit on wall temperature reduction**

which in turn advanced the knock onset ignition timing, but the advance in knock onset ignition timing was canceled out by the ignition timing advance potential created by the intensified cooling. This caused knock to occur at the same ignition timing for both the engines with and without intensified cooling. As this example shows, by comparing in-cylinder gas temperatures, it was possible to clearly identify the ignition timing advance potential created by intensified cooling, which can be masked by individual differences between engines and hence cannot be determined by the human ear.

### 4.2 Intensified cooling of cylinder block

The areas between two adjacent cylinders in a siamese cylinder block are subject to heat from both cylinders and sufficient cooling is very difficult as they constitute the hottest parts in the cylinder block. Sufficient cooling of these areas is necessary not only for temperature control, but also for preventing thermal deformation in the circumferential direction of cylinder liners caused by localized high temperatures. To solve the problem, we attempted to additionally cool the areas by cutting a slit in the top part of the metal between adjacent cylinders as shown in **Fig. 12** to make it function as part of the water jacket. Two different sizes of slits were prepared for evaluation to clarify the relationship between the expected temperature reduction effect and knock control effect of the slits. **Fig. 13** shows the liner wall temperatures measured at a cylinder adjoining portion. As seen from the graph, the slits significantly reduced the temperature of the areas between cylinders. **Fig. 14** compares average in-cylinder gas temperatures for the three tested cylinder blocks: the first one without slits, the second one with large slits, and the third one with small slits. The graph shows that the order of the three cylinder blocks in terms of the average in-cylinder gas temperature is the same as that in terms of the cylinder wall temperature. Evaluation by ear identified a 1° CA knock onset advance for the "large slit cylinder block" as compared with the "no slit cylinder block", but no significant difference was detected for the "small slits cylinder block", hence the effects of the small slits were not obvious. The evaluation method depending on a decrease in in-cylinder gas temperature, on the other hand, clearly showed that the small slits could cause an ignition advance potential of approximately 0.5° CA. In this example, the new method enabled the effect of intensified cooling on the knock onset timing to be determined even when the ignition advance resolution was smaller than the setting resolution. Improvement in engine cooling depends on the accumulation of incremental improvements, and this method will help guide such efforts.

### 4.3 Intensified cooling of pistons

The piston constitutes the largest and hottest part of all the combustion chamber wall surfaces. Therefore, reducing the temperature of the piston is a promising way to reduce the in-cylinder gas temperature significantly. We tested three pistons with different cooling conditions (A, B, and C) for the relationship between the temperature of the piston's top surface and the knock suppression effect yielded by the temperature. **Fig. 15** shows the piston top temperature distributions for the three pistons depending on experimental measurements. In **Fig. 16**, the area averages of these temperature distributions are plotted against the x-axis to show their relation with knock onset ignition timings determined by ear and with gas temperatures at the end of the compression stroke. The piston top temperature has good correlations with the gas temperature at the end of the compression stroke and with the knock onset ignition timing. When the top mean temperature was reduced by 6 to 7 K, the gas temperature at the end of the compression stroke was reduced by 7 to 8 K and the knock onset timing was advanced by 1° CA.

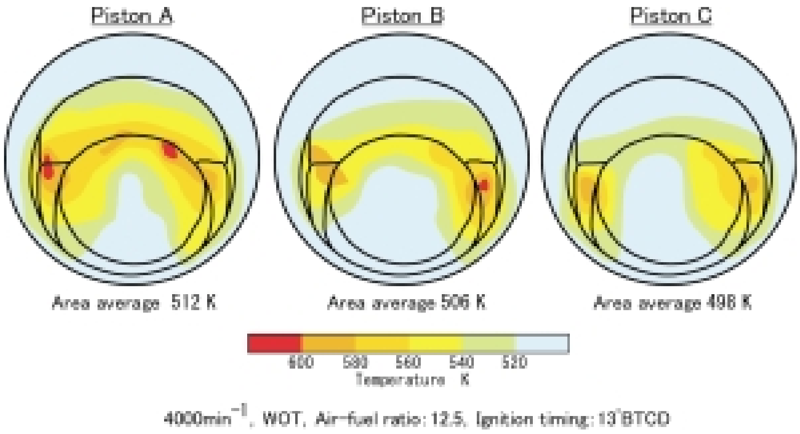



**Fig. 15 Temperature of piston top surface**

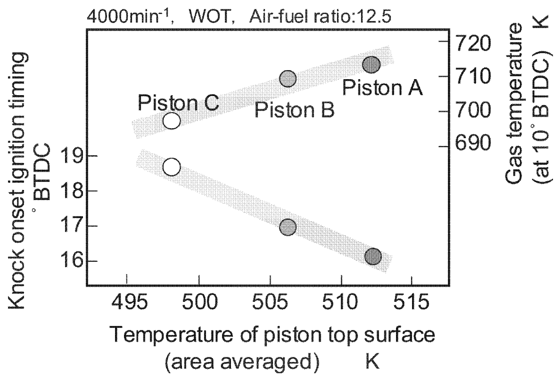



**Fig. 16 Relation between piston top surface temperature, gas temperature and knock**

## 5. Summary

(1) By using the in-cylinder gas temperature calculated from in-cylinder pressure measurements as an evaluation index, we were able to accurately evaluate knock suppression effects without ambiguity or error factors included in the aural evaluation method due to differences in individual hearing abilities and variations between individual engines.

(2) As the effect of reducing the cylinder temperature at the end of the compression cycle is considered to be significant for suppressing knock, we tested engine cooling measures for restraining the heat transfer to gas. These measures intensified the cooling of the cylinder head, cylinder block, and pistons, and led to an ignition timing advance of approximately 4° CA.

(3) The in-cylinder gas mean temperature has perhaps the greatest influence on knock. Since the knock phenomenon is caused by a complex combination of many factors, this method should be used for evaluating in relative terms, not absolute terms, the occurrence of knock in engines.

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Tomoki NISHINO    Hiromichi SENBA    Nobuaki MURAKAMI

# Gear Whine Analysis with Virtual Power Train

Tadashi TAKEUCHI* Kazuhide TOGAI*

**Abstract**

**Meshing transmission error (TE) is well known as a contributing factor of gear whine, but system-level prediction of transmission error and quantitative analysis of dynamic meshing vibromotive force have not been analyzed adequately until now. This paper describes the use of a computer-aided-engineering (CAE) model for the analysis of the dynamic gear meshing behavior and for the prediction of dynamic transmission error from the input torque of the system. This paper also describes the analysis of a dynamic vibromotive force at a bearing location where vibration is transmitted to the vehicle body. The gear whine critical frequency can be predicted with the proposed method at an early stage of passenger-car development when no prototype is available.**

***Key words:*** *Gear Whine, Meshing Transmission Error, Noise, Vibration, and Harshness CAE, Bearing Dynamic Load, Gear Stress Analysis*

## 1. Introduction

Gear whine is an automotive quality problem that can be perceived by any driver regardless of his/her level of driving experience, but it tends to manifest itself in the final stages of vehicle development when, in most cases, effective design measures that can be taken against it are extremely limited. Consequently, power-train designers have a great need for CAE technologies that enable them to predict gear whine using a virtual power train before the power train is physically constructed.

Inputs to the transmission and other power-train elements in the vehicle include the engine torque and accompanying fluctuations, which are regarded as combustion-originated dynamic-excitation factors. These inputs, however, initiate only vibration within the growling-sound frequency range, not vibration at whine frequencies, which are much higher. If gear-tooth shapes were optimum and tooth meshing were perfect, the gears would transmit the input torque in a manner precluding the generation of frequency components other than those related to engine-torque fluctuations. In actual gear-tooth meshing, however, forced displacements resulting from meshing error causes meshing vibromotive forces to be generated during torque transmission. These vibromotive forces then constitute a source of vibration. Further, the complete power-train system includes shafts and cases whose stiffness has an influence on gear-tooth meshing in such a way that the meshing vibromotive forces have peaks at certain frequencies.

In addition, if the vibration transmission process that begins with tooth-meshing vibration and results in cabin noise has resonance in the frequency band in which the meshing vibromotive forces have their peaks, there is a significant likelihood that annoying whine will occur in the cabin during actual vehicle operation. There is a good chance of being able to prevent such whine from occurring in the cabin if the frequency band in which the dynamic meshing vibromotive forces have their peaks is known, the frequency band can be compared with the resonance frequencies of the body vibration transmission system, and the peak vibromotive frequency band can be shifted away from the resonance frequencies.

## 2. Creation of power-train model

At Mitsubishi Motors Corporation, in-house-developed software was originally used for predictive simulation of the transmission error of gears. However, the cost of modifying this software to accommodate graphical user interfaces (GUIs) and sizeable databases (both necessitated by changes in the analysis requirements) recently prompted the introduction and test-employment of commercially available Romax Designer software for this purpose. This paper describes gear whine analysis performed by means of models created with this software.

When the transmission is regarded as a vibration transmission system with a multibody spring-mass structure, the gears and shafts are compared to the masses and the stiffness of the gears, shafts, and bearings is compared to the springs. The frequency of peak vibromotive force in gear-tooth meshing in this analogy corresponds to the eigen value of the transfer function matrix.

The gears and shafts were modeled using GUIs, and the bearing models were, as much as possible, retrieved from the database. When bearing models were not available from the database, characteristic values such as preloads and rigidities were input to create them. All these inputs allowed the software to automatically create simulation models consisting of springs and masses (**Fig. 1**). Each created model has six

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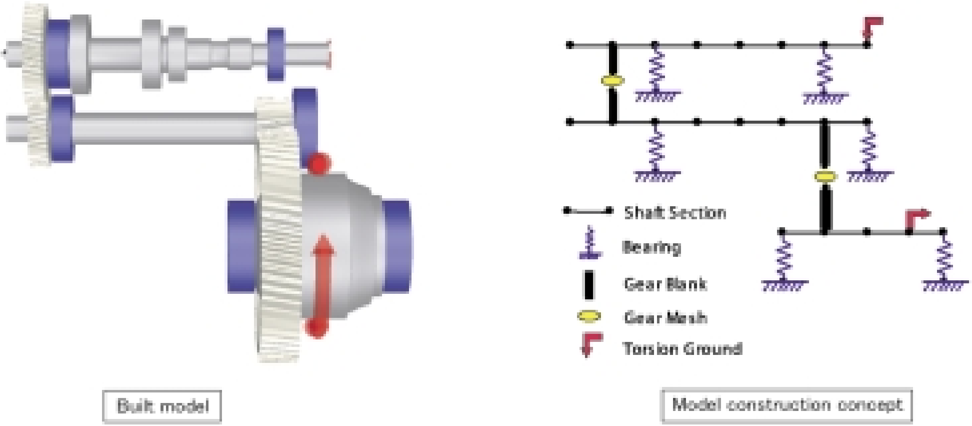


**Fig. 1 Modeling outline**

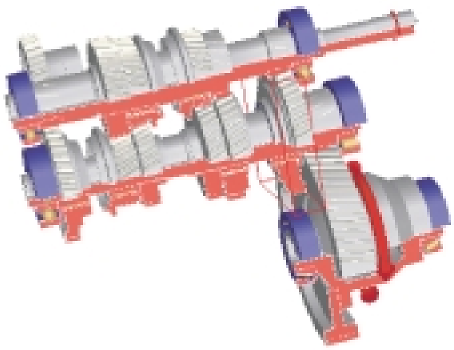

**Fig. 2 Model of manual transmission**

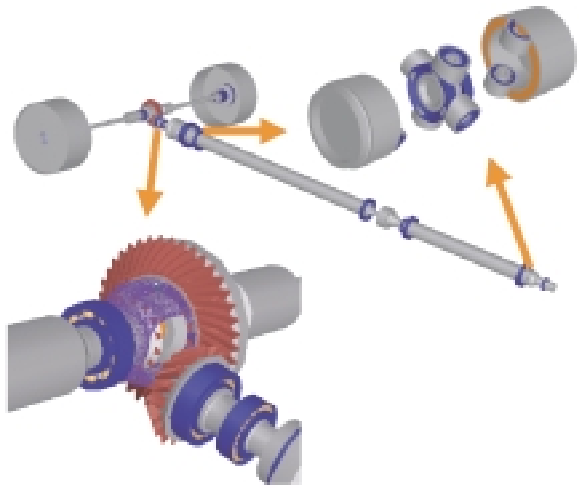

**Fig. 3 Model of rear-wheel-drive drive-train**

degrees of freedom at each analysis point. In a transmission model, the stiffness of the clutch can be modeled as the input shaft's torsion-spring characteristic. The overall model's accuracy can be raised by the addition of finite-element models of the transmission case and differential case.

## 3. Analysis of NVH using virtual power-train model

Stress and fatigue-life are the most common subjects of gear analyses, and the basic functions of the Romax software used in the effort described in this paper support predictive calculation of them. The software also allows the dynamic gear-meshing vibromotive force to be predicted through calculation of the load-based meshing transmission error and dynamic vibration mode. The following parts of this paper describe the method employed for simulation of a five-speed manual transmission used in front-engine, front-wheel-drive vehicles and of a rear-wheel-drive drive-train (**Figs. 2** and **3**).

### 3.1 Vibromotive force source and vibration transmission system

(1) Transmission error as a source of vibromotive force

Fluctuations in the force transmitted by two meshing gears do not occur as long as the teeth are continuously and smoothly meshing while transmitting torque. In other words, for fluctuation-free force transmission the gears must be geometrically in an involute relationship (such that there is no interruption in tooth contact between one tooth pair and the next) and both gears must be stiff enough to resist deformation such that their relative positions never change (**Fig. 4**). In reality, however, unvarying tooth contact cannot be assured owing to factors such as non-ideal tooth-shape design, tooth-shape errors that occur during gear production, deflection and deformation that occur in gears and shafts during operation under load, and resonance in the system. These factors yield transmission error (TE). Actual TE measurements (shown in **Fig. 5**) indicate that the TE constitutes forced displacement (a source of vibromotive force) that causes gear whine. Since deflection and deformation occurring in shafts, cases, and bearings during system operation contribute to the TE, an appropriate model of the whole system is essential for prediction of the vibromotive force.

(2) Vibration transmission system

Gear whine as initially generated by gear-tooth meshing is shielded by the case (carrier). Thus, the

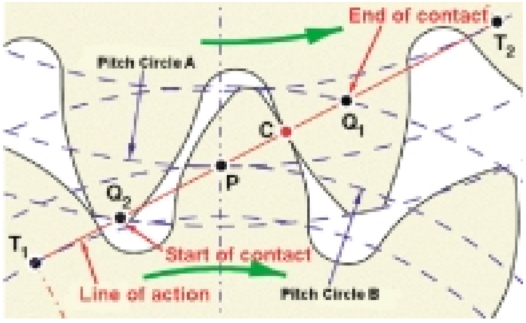


**Fig. 4 Tooth meshing (J. Derek Smith)**

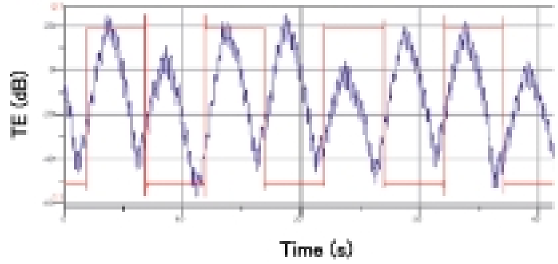


**Fig. 5 TE measurement example**

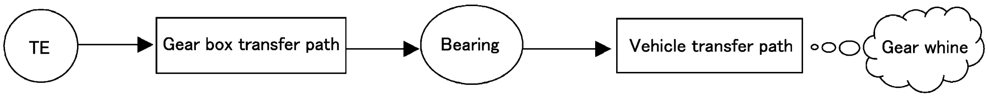


**Fig. 6 Vibration transmission concept**

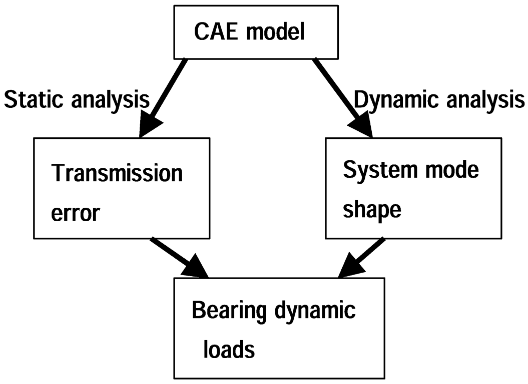


**Fig. 7 Analysis process**

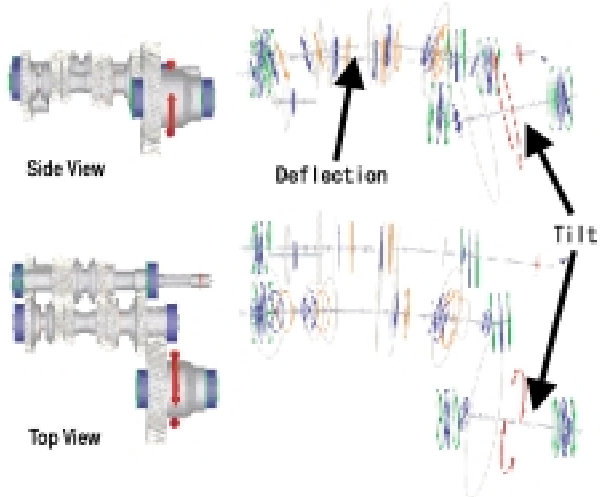


**Fig. 8 Static analysis example**

whine heard in the cabin is usually the result of vibration that has originated from gear-tooth meshing, reached bearings by way of the resonance system formed in the transmission, and propagated from there to the vehicle body through the transmission mountings. Key vehicle-design objectives for gear whine minimization are thus as follows: minimizing the TE that occurs under actual operating conditions and optimally reducing the transfer paths vibration sensitivity to the cabin. For the first of these objectives, estimation of the vibromotive forces acting on the bearings is essential (**Fig. 6**).

### 3.2 Gear whine analysis process

In the employed gear whine analysis process, a transmission model including the torque input and output ends is created then the deflections of shafts and tilts of bearings are calculated through a static analysis. Using the calculation results, the TE is predicted. Next, the system's vibration modes are calculated through a dynamic analysis to determine the dynamic load inputs applied to the bearings. This process is illustrated in **Fig. 7**.

### 3.3 Static analysis

In the static analysis, the deflection and tilt of each shaft and the static misalignment and TE involved in gear-tooth meshing are calculated.

In a manual-transmission model, deformation and displacement usually occur in each shaft due to input torque from the engine. With the transmission model on which analysis was conducted, deflection was evident in the output shaft due to low stiffness and the differential case showed a significant tilt although its deflections were very small in amount (**Fig. 8**).

The predictive calculation conducted on the model also revealed that the amount of misalignment involved in gear-tooth meshing in the front differential was far greater than the amounts occurring between speed gears and that the load-supporting stiffness of the transmission case made a large contribution to the misalignment (**Fig. 9**).

The analysis results described above suggest that the model in question has the characteristic of generat-

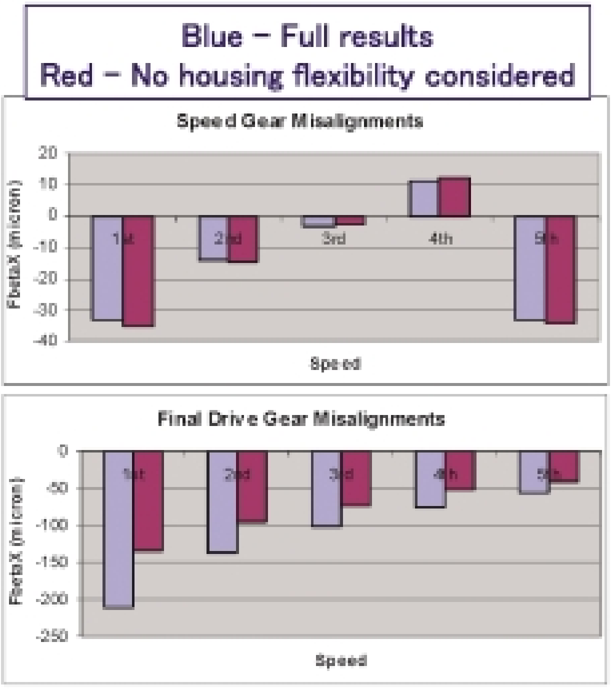


**Fig. 9** **Misalignment calculation results**

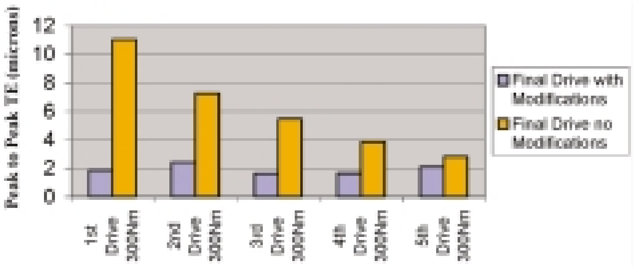


**Fig. 11** **Calculated tooth-meshing TE values for front differential**

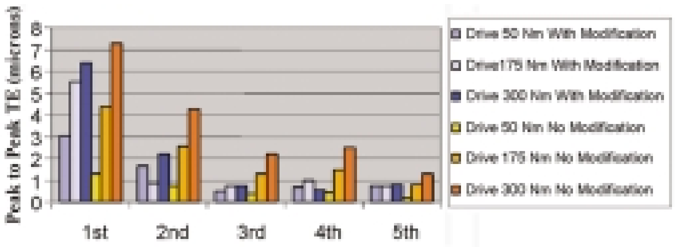


**Fig. 12** **Calculated tooth-meshing TE values for individual speed gears**

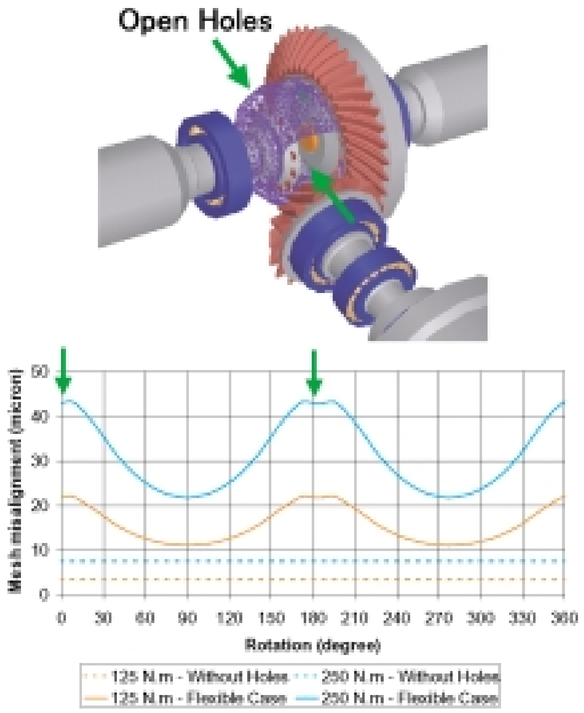


**Fig. 10** **Effect of differential-case stiffness manifested in calculated tooth-meshing misalignment**

ing relatively large vibromotive forces in gear-tooth meshing at the front differential, rendering the front differential prone to whine generation.

Next, a rear-wheel-drive drive-train model was subjected to a simulation in which fluctuations in the amount of tooth-meshing misalignment in the rear differential were analyzed with regard to the stiffness of the differential case (**Fig. 10**). The results show that the stiffness of the differential case influences tooth-meshing misalignment in the rear differential.

Using the data derived from the abovementioned analyses, calculation for prediction of the TE in final-drive gear-tooth meshing was performed and a predictive TE reduction attempt was made by modification of gear-tooth shapes. The results are shown in **Figs. 11** and **12**, respectively.

The abovementioned studies began with analyses of the TE and tooth-contact loads. Next, the amount of tooth-meshing misalignment during rotation of gears was calculated. Based on the calculation results, the lead, crowning, and tooth tip of gears were modified on the desktop to optimize the TE and tooth-contact load. The results indicated that modifying the tooth shape based on the calculation results enabled tooth-meshing TE values to be made significantly smaller than the original ones in the front differential and between speed gears.

### 3.4 Dynamic analysis

This section of the paper describes analysis of vibration modes during gear rotation under loading.

Both the manual-transmission model and the rear-wheel-drive drive-train model include non-linear models to simulate bearing stiffness, which causes the vibration mode to vary according to load conditions. With the manual-transmission model, the shafts, bearings, and gears were treated as a fully coupled internal system of the transmission for calculation of the vibration mode (**Fig. 13**). From **Fig. 13**, it can be ascertained that when the gear is set at 4th and a 50 Nm torque is applied to the input end in this mode the bend of each shaft and the tilt of the 4th speed gear make a signifi-

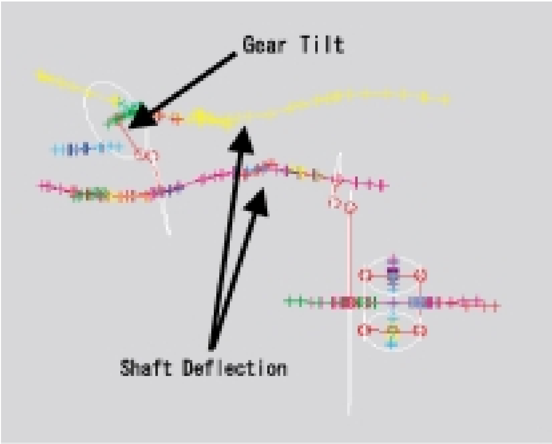


**Fig.13 Modal shape analysis of manual-transmission model (3 kHz)**

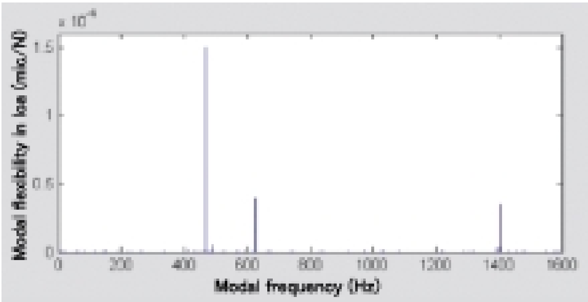


**Fig. 14 Analysis of modal flexibility of vibration resulting from excitation by rear differential gear meshing**

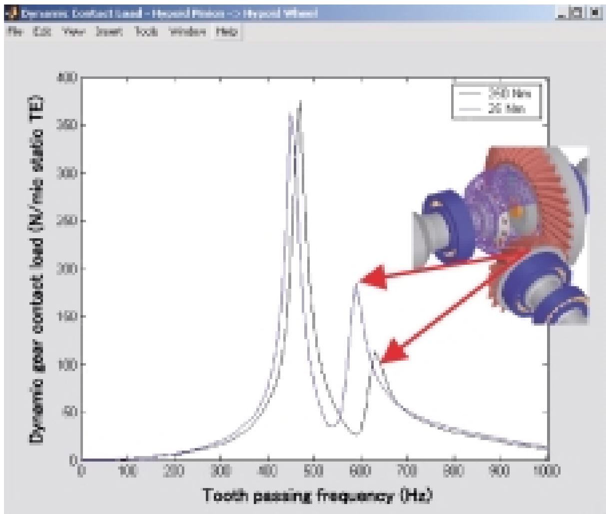


**Fig.15 Variation in model resonance frequency with loading torque**

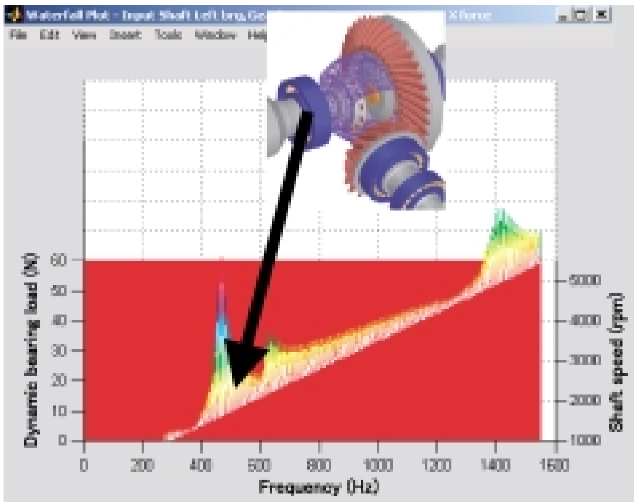


**Fig. 16 Calculated dynamic loading on bearing**

cant contribution to vibration at approximately 3 kHz. Analysis of the rear-wheel-drive drive-train model was conducted on the assumption that the elements formed a fully coupled system (as with the manual-transmission model) and by simulation of the case where excitation forces were generated during tooth meshing in the rear differential (**Fig. 14**). Through this analysis, it was seen that, under a torque of 250 Nm applied to the drive side end of the propeller shaft, there was a mode in which the drive power train was sensitive to vibrations at 468 Hz and 627 Hz frequencies that originated from excitation by the rear differential meshing.

**Fig. 15** shows how the dynamic tooth-surface contact stress for a given TE value varies in the drive power train model in accordance with changes in the loading torque. From this graph, it can be seen that the system's modal resonance frequency varies with the loading torque.

### 3.5 Prediction of dynamic loading on bearings

Using the aforementioned TE calculation results and modal analysis results, it is possible to calculate the dynamic loading on each bearing.

**Fig. 16** shows the calculated dynamic loading on a bearing in the rear-wheel-drive power-train model. In this graph, meshing frequencies are plotted against the x-axis, rotation speeds against the y-axis, and bearing dynamic loads against the z-axis. The waveform indicated on the line rising diagonally in the graph corresponds to the basic frequencies and their harmonics. Each peak vibromotive force corresponds to resonance in the drive power-train system, which in turn corresponds to the frequency of the gear's potential vibromotive force that is applied to the vehicle body.

## 4. Comparison of experimental and simulated results

The dynamic loading on a bearing predicted using the rear-wheel-drive power-train model was compared with an experimental measurement on the actual bearing to evaluate the validity of the simulation (**Fig. 17**).

The data used in the predictive calculation were the relevant design values, not values taken from an actual power train through measurement. As shown by the graphs, the predicted and experimentally measured

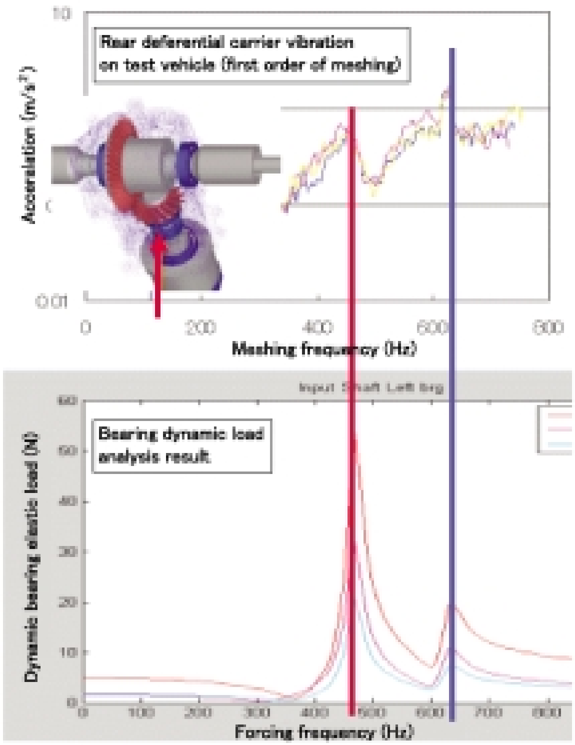


**Fig. 17 Simulated and experimentally measured dynamic loading on bearing**

peak frequencies of the bearing under a dynamic load condition agreed well. In this prediction, no influence of differential carrier resonance on differential carrier vibration was assumed because of the differential carrier's great stiffness.

## 5. Conclusion

Dynamic gear-tooth meshing behavior was simulated using virtual models. The simulation enabled clarification of the following items: increases in gear-meshing TE caused by deflection of the elastic system under the torque loaded condition; dynamic vibration modes present in shafts and gears; and the process of generation of dynamic loading at the bearing locations from which vibration is transmitted to the vehicle body. Simulation using the virtual models presented here will likely provide an effective means for dealing with gear whine problems from the earliest stages of vehicle development as it can be used as a tool for design optimization.

## 6. Future challenges

Once the dynamic loads on bearings are known, it is possible to predict vibration response through the transfer paths by means of finite-element models. If only the peak frequencies of vibration to which the paths will respond are to be identified, detailed analysis of the vibration-damping characteristics of the vibration transmission system is not very important. In situations where prediction of the amplitude of vibration is necessary, however, adequate data on the system's damping characteristics are indispensable. For accurate prediction, a technique that enables the amount of the system's vibration damping to be determined accurately is required. Research aimed at realizing such a technique is under way.

Finding a method for accurately determining the system's response to vibration is a further issue to which research efforts are to be directed. With accurate vibration-response data available, it will likely be possible to predict the noise radiation.

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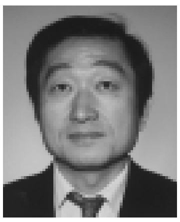
Tadashi TAKEUCHI



Kazuhide TOGAI

# Development of "i" Concept Test Car for 2003 IAA and 2003 Tokyo Motor Show

Yoshinaka KAWAKAMI* Takanori YOSHII*


## Abstract

**The "i" is a concept test car developed by Mitsubishi Motors Corporation (MMC) in line with a 'small and surprising' theme. Built on a midship-engine/rear-wheel-drive (MR) platform, it combines a small body with class-topping comfort and crashworthiness. Further, the "i" is the first vehicle in its class to earn five stars (the highest score) for both fuel economy and emissions performance in the Federation International de l'Automobile (FIA) EcoTest (as administered by the Allgemeiner Deutscher Automobil Club (ADAC)). Factors enabling this outstanding performance include an environment-friendly powertrain (this incorporates a 1.0-liter MIVEC engine and a Mitsubishi Smart Idling System), minimal weight (achieved through extensive use of plastics and aluminum in the body and chassis), and maximized aerodynamic performance.**


***Key words:*** *Motor Show, Light Weight, Low Fuel Consumption, Concept Car*

## 1. Introduction

MMC has for many years been expanding and refining its base of development technologies for minicars and other small cars. Against this background, MMC has identified a need for new proposals on vehicle configurations, which are becoming increasingly uniform. At the same time, the Japan Automobile Manufacturers Association has voluntarily adopted a target of 140 g/km or less for average carbon-dioxide ($CO_2$) emissions among passenger vehicles made for the European Union, thus increasing the need for automakers to develop small cars with extremely low fuel consumption. As a response to these needs, MMC refocused on the challenge of finding ways to achieve a spacious interior environment and extensive design freedom within the limited dimensions of a small car while also giving form to the three main MMC brand attributes of passion, performance, and perfection. At the 2003 Frankfurt International Motor Show, MMC unveiled the result of its study: the "i" concept test car (**Figs. 1** and **2**), which combines ultra-low fuel consumption with class-eclipsing comfort and safety and a stylish design. An overview of the "i" is given in this paper.

**Fig. 1 Exterior**

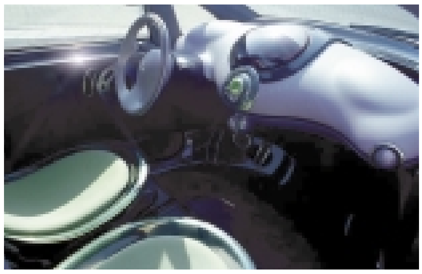


**Fig. 2 Interior**

## 2. Features

Key features of the "i" include

(1) a newly developed MR platform that permits a simple and unique one-motion form together with superior comfort and crashworthiness;
(2) ultra-low weight, outstanding aerodynamics, and a newly developed engine that together realize ultra-low fuel consumption; and
(3) future-oriented applications of information technology (IT).

## 3. Newly developed MR platform

The MR platform, which locates the engine behind the passenger space but within the wheelbase, was newly developed for the "i" (**Fig. 3**). Notwithstanding the vehicle's modest external dimensions, this platform permits a long wheelbase, which in turn permits a spacious cabin (big enough to accommodate four people in comfort), superior ride comfort, outstanding crash-

* Advanced Vehicle Development Department, Research & Development Office

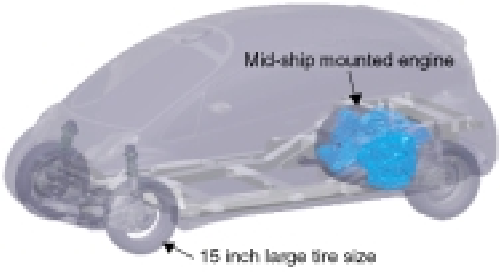



**Fig. 3 MR platform**

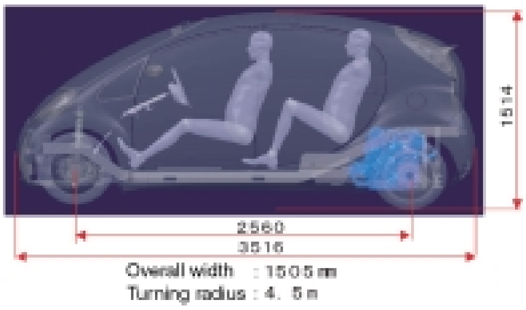



**Fig. 4 Packaging**

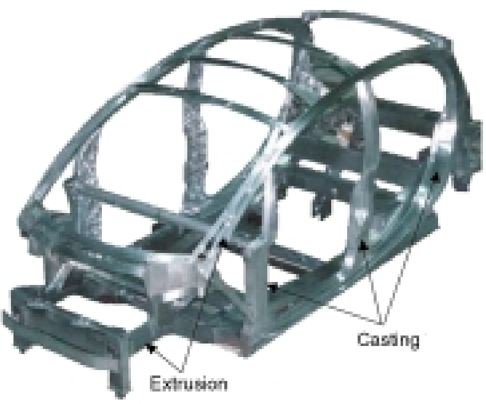



**Fig. 5 Aluminum space frame**

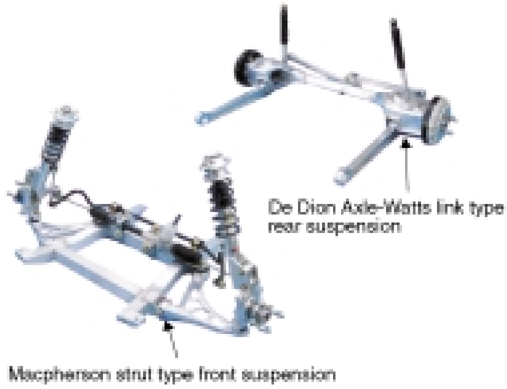



**Fig. 6 Lightweight suspension system**

**Fig. 7 Testing of full-size vehicle in wind tunnel**

**Fig. 8 Airflow over roof spoiler**

worthiness, and ample pedestrian-protection performance (**Fig. 4**).

## 4. Fuel-saving technologies

(1) Body

The body is based on an aluminum space frame, and the hood, doors, front fenders, tailgate, and other panels are formed from ultra-light plastics. In the space frame, the latest hybrid laser welding technology was used to realize high-strength, high-precision welds between aluminum extrusions and aluminum die-castings, resulting in a 35 % weight saving over a steel space frame (**Fig. 5**).

(2) Chassis

In the suspension system, MacPherson struts are used at the front and a De Dion axle with Watts linkage is used at the rear (**Fig. 6**). Weight is minimized by extensive use of aluminum for the suspension members, lower control arms, struts, steering knuckles, brake rotors, brake calipers, shock absorbers, and other chassis components, by adoption of hollow suspension stabilizers, and by adoption of coil springs made of high-tensile steel. Also, low-friction ceramic wheel bearings and measures to minimize brake drag keep running resistance to a minimum.

(3) Aerodynamic performance

By adopting a rounded one-motion form (rather than the boxy styling that automakers typically use to maximize space efficiency) and by shape-optimizing the rear spoiler, the door mirrors, the fenders, and the bottom surface of the body, MMC gave the “i” outstanding aerodynamic performance that’s reflected in a drag coefficient of only 0.24 (**Figs. 7** and **8**).

(4) Powertrain

For ultra-low fuel consumption and easy driving, the

**Fig. 9 Newly developed engine**


**Fig. 11 Functions of information key**

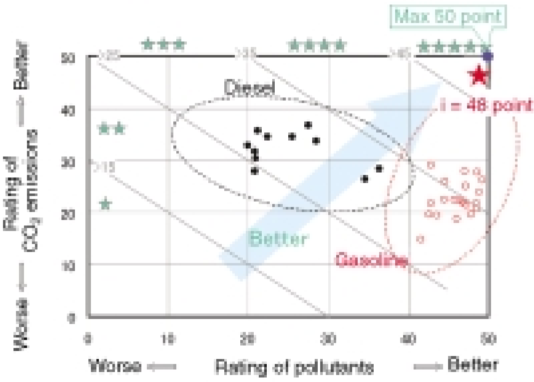



**Fig. 10 Results of FIA EcoTest administered by ADAC**

powertrain of the “i” combines a newly developed high-efficiency gasoline engine with a continuously variable transmission and incorporates a Mitsubishi Smart Idling System, which stops the engine when the vehicle is stationary.

① Newly developed engine

The “i” is powered by a newly developed 1.0-liter, three-cylinder, DOHC, 12-valve engine (**Fig. 9**). Lightness and compactness are realized by features including an aluminum cylinder block, a valvetrain in which the valves are actuated directly by the camshafts, and a silent camchain. Combustion efficiency is maximized by a Mitsubishi Innovative Valve timing and Electronic Control (MIVEC) system, which optimally varies the intake- and exhaust-valve timing. And losses are minimized by features including low-tension piston rings and exhaust-gas recirculation. The overall result is a combination of high performance (maximum output is 50 kW at 6,000 rpm; maximum torque is 92 Nm at 3,500 rpm) and low fuel consumption.

② Mitsubishi Smart Idling System

The Mitsubishi Smart Idling System stops the engine when the vehicle is stationary and restarts it when the driver prepares to pull away. It has a 14 V belt-drive starter/generator unit that enables it to restart the engine rapidly and without noticeable vibration.

(5) Exhaust emissions and fuel economy

In the FIA EcoTest (as administered by the ADAC), the “i” satisfied the Euro 4 exhaust-emissions standards and achieved $CO_2$ emissions of 89 g/km (with fuel consumption of 3.8 L/100 km) – lower than the 90 g/km limit defined for so-called three-liter cars. The “i” is the first vehicle in its class to earn five stars (the highest score) for both fuel economy and emissions performance in the FIA EcoTest (**Fig. 10**).

(6) Environment-oriented construction

In addition to the fuel-efficiency advantages yielded by its lightness, the “i” reflects the benefits of an environment-oriented structure. Recyclability is promoted by component joints that facilitate dismantling and by minimal use of urethane in the seat cushions and other parts of the vehicle.

Emissions of $CO_2$ are minimized not only by the vehicle’s lightness but also by the use of a plant-based plastic for the cargo space floor board. Use of lead (a substance that creates an environmental burden) is also minimized.

Further, the lightweight body was subjected to a life-cycle assessment and found to offer superior environmental characteristics throughout its lifecycle.

## 5. Future-oriented IT applications – Information key

(1) Overview

The “i” provides the driver with an ‘information key’ that fits into a bay in the center of the instrument panel. This unit has a number of vehicle-control functions (including verification of the user’s identity) and can be used as a display- and memory-equipped portable audio player and for electronic financial transactions (**Fig. 11**).

(2) Functions

① Automatic keyless entry

When the driver carrying the information key approaches the vehicle, the key, which incorporates a transponder with an antenna, communicates with a vehicle-mounted unit, confirms the user’s identity, and causes the doors to be unlocked. When the driver carrying the key moves a certain distance away from the vehicle, the doors are automatically locked. When the driver fits the key into its bay in the center of the instrument panel, the key begins communicating with the vehicle-mounted unit by means of Bluetooth wireless technology. By verifying the driver’s identity, the key then disengages an immobilizer, allowing the driver to

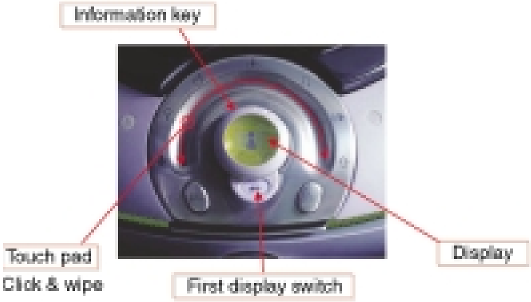



**Fig. 12 Operating method for information key**

start the engine by pushing a start button.

② Entertainment

The key provides control over FM/AM radio reception. Also, it incorporates a slot into which a memory card containing digital music or photo data can be inserted for playback inside or outside the vehicle as desired.

③ Navigation

The key can give the driver directional instructions in the form of arrows on its display based on data from a vehicle-mounted navigation-system head unit. Also, the key enables the driver to set the vehicle's destination and download it to the vehicle-mounted unit by means of a memory card.

④ Indication of vehicle status

The key shows vehicle-status information including fuel consumption, the outside temperature, and the distance driven.

⑤ Recording of vehicle-maintenance data

The key records vehicle-maintenance information on an embedded memory card. Dealers can use this information for diagnosis purposes when they service the vehicle.

⑥ Electronic financial transactions

The key can be used as a wireless terminal for credit-based financial transactions such as payment of highway tolls and payment for shopping.

(3) Operating method

The driver selects functions by drawing a fingertip over an arc-shape touch pad and then double-clicking (**Fig. 12**).

By enabling the driver to access functions using this simple method, which resembles the operating method used with notebook computers, the information key represents a totally new means of display and control – one whose modest space requirements make it ideally suited to compact cars and whose functionality suggests new lifestyle possibilities.

## 6. Summary

By employing a newly developed MR platform, MMC's development team successfully realized a concept test car with unique styling and superior comfort and crashworthiness. And by comprehensively addressing the challenge of finding ways to minimize fuel consumption without using unduly complex systems, the team achieved outstanding fuel economy (as evidenced by the vehicle's performance in a test administered by the ADAC). MMC will now work on refining the technologies it adopted in the concept test car with a view to using them in production vehicles.

In closing, the development team wishes to express sincere appreciation to everyone inside and outside MMC who co-operated in the development of the concept test car.

Yoshinaka KAWAKAMI

Takanori YOSHII

NEW TECHNOLOGIES

# Development of Mitsubishi “i” Body

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## Abstract

**Recently, the technology to develop a vehicle body with high strength, high rigidity and light weight has become increasingly necessary for the automotive industry to improve crashworthiness and reduce $CO_2$ emissions. This paper presents one of the solutions from Mitsubishi Motors Corporation (MMC) to meet the above demands. MMC developed a lightweight aluminum space-frame body with a view toward mass production at relatively low cost, and applied it on the Mitsubishi “i”. In addition, the aerodynamic characteristics of the body shape were fine tuned for reduced driving resistance, which successfully achieved very low drag ($C_D$).**

***Key words:*** *Body, Aluminum, Space Frame, Weight Reduction, Aerodynamics, Life Cycle Assessment*

## 1. Introduction

Improvements in crashworthiness and quietness, and installation of more interior equipment (for example, navigation and entertainment systems) have resulted in increasingly heavy passenger cars. However, growing demand for further reduced fuel consumption as a means of combating global warming, oil-resource depletion, and other environmental problems has created a critical need for automotive manufacturers to produce lighter vehicles.

An all-aluminum vehicle body is one means of achieving the necessary weight savings. Research and development on all-aluminum bodies have been conducted and some all-aluminum body models have already been marketed, but their application is thus far limited to a small number of production models mainly because of high material costs.

MMC developed and applied on the “i” an aluminum space-frame body that is highly strong and rigid but relatively inexpensive to produce, aiming primarily at achievement of ultra-low fuel consumption and with a view to mass-producing aluminum space-frame bodies in the future.

Recognizing improved aerodynamics as essential for realizing low fuel consumption, MMC also made exhaustive research and improvements for low $C_D$ value of the “i” body. An overview of this body is given in this paper.

## 2. Aluminum space-frame body

An all-aluminum body can be constructed using either a space-frame structure or monocoque structure. For the “i”, MMC opted for an aluminum body with space-frame construction (**Fig. 1**), which serves to keep production costs relatively low and hence is advantageous in view of future mass production. Mitsubishi Aluminum Co., Ltd. collaborated with MMC in developing the aluminum space-frame body.

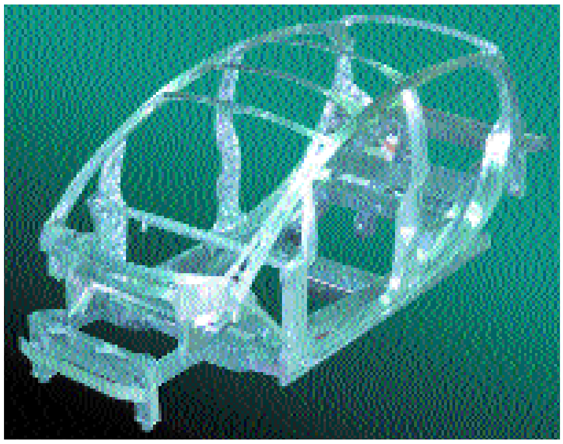

**Fig. 1 Space-frame of “i”**

The body’s basic framework is formed from aluminum extrusions and aluminum die-castings, which are laid out and combined for optimal effectiveness. The floor and roof panels are formed from aluminum pressings.

The merits of extrusions include low die costs and a good yield factor, so detailed structural studies were performed to enable maximal use of extrusions

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**** Environment & Technical Affairs Department, Group Corporate Strategy Office
***** Automotive Development Department, Mitsubishi Aluminum Co., Ltd.
****** Machinery & Environment Plant Department, Kobe Shipyard & Machinery Works, Mitsubishi Heavy Industries, Ltd.

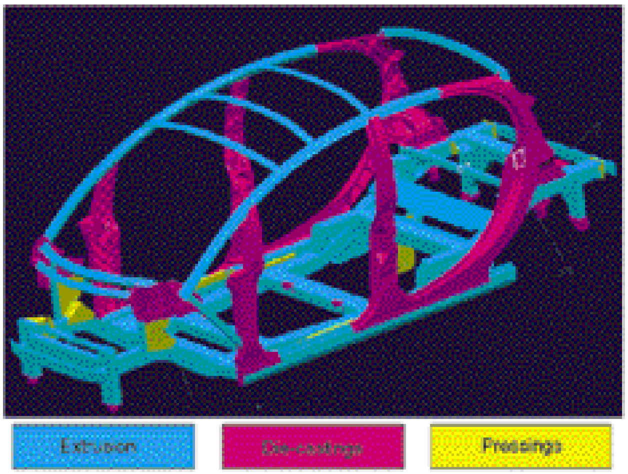



**Fig. 2 Types of space-frame members**

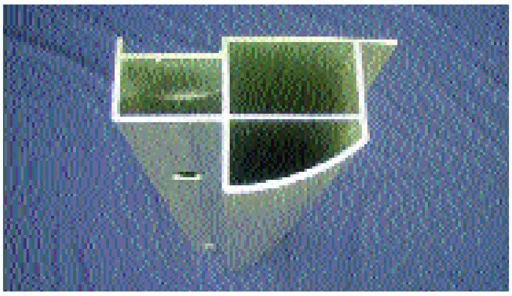


**Fig. 3 Cross-sectional view of extrusion forming dash cross member lower**

**Fig. 4 One-piece side member**

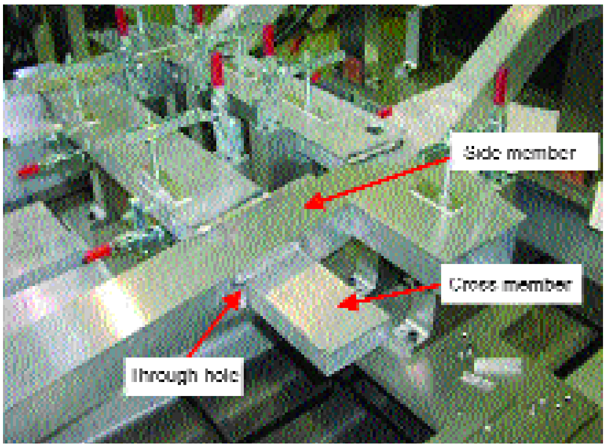



**Fig. 5 Through-hole structure**

throughout the body. As a result, extrusions account for approximately 60 % of the weight of the body-in-white (**Fig. 2**).

### 2.1 Plastic working techniques for aluminum material

(1) Extrusions

An extrusion is formed as a continuous closed-section member. The thickness of each wall constituting the cross section can be established as desired (**Fig. 3**). Compared with a monocoque structure, which consists of spot-welded pressings, a space-frame structure based mainly on extrusions allows high strength and rigidity to be achieved more efficiently. Many extrusions were applied for the “i” body including side members and cross members of the underbody and the roof side rails and roof bows of the upper body.

A6N01 was selected for the material from the 6000-series alloys that offer low cost and good extrudability, considering corrosion resistance and weldability. The tensile strength of the side members, side roof rails, and other bent members was increased by means of artificial ageing applied after the bending processes.

The side members (the main frame members of the underbody) are made of one-piece bending-formed aluminum extrusions, extending from the front of the vehicle to the rear (**Fig. 4**). This helps to minimize the number of parts and joints, thereby saving weight while helping to maximize rigidity. For the joints between the side members and cross members, a through-holes structure (**Fig. 5)** was adopted, which eliminated nodes*1. This joint structure reduces distortion of the welds and improves the strength of the joints.

*1: Node refers to die-cast pieces used for joints between frame members.

(2) Die-castings

Die-castings were applied for portions like the front pillars and center pillars because extrusions were not suitable for satisfying styling requirements as well as structural requirements including strength and trim-part retention. A specific advantage of die-castings is that they permit the consolidation of multiple parts (including those for attachment of trim parts) into single parts and thus enable minimization of material and tooling costs (**Fig. 6**).

The high-vacuum die-casting method was employed, by which the amount of gas mixing with the molten aluminum could be reduced and thus high welding stability was ensured. In addition, this method enabled the material thickness to be minimized for further lightness (**Fig. 7**).

(3) Pressings

Pressings made of a 6000-series alloy (the same series as that used for extrusions) were adopted for the floor, dash panel, roof, and quarter panels (**Fig. 8**). Specifically, the material is MX699, which is produced by Mitsubishi Aluminum Co., Ltd. A coating of lubricant on MX699 yields improved press formability, so this material can be employed for parts that are relatively difficult to press-form.

### 2.2 Joining technology

(1) Hybrid laser welding

Extrusions and die-castings are typically joined by

**Fig. 6 Front pillar**

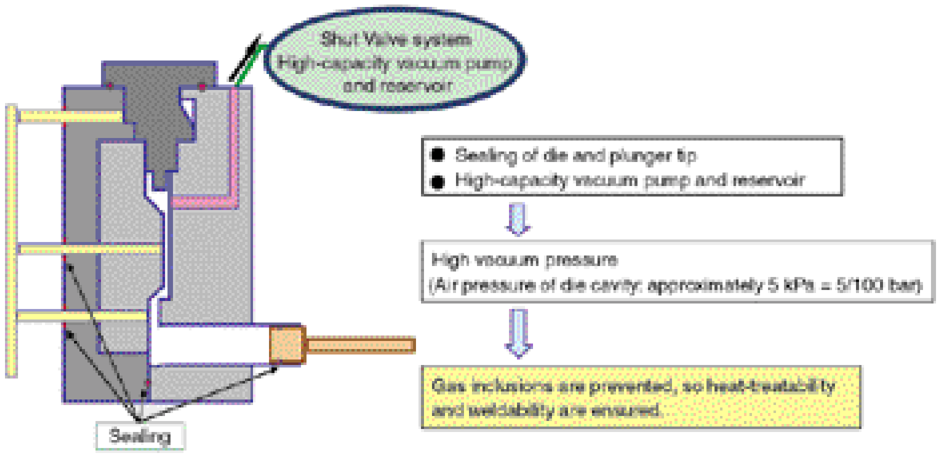



**Fig. 7 Schematic diagram of high-vacuum die-casting molds**

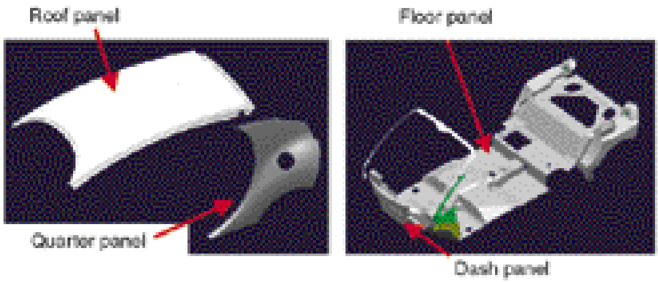



**Fig. 8 Pressings**

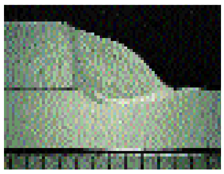
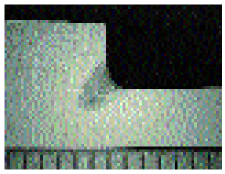
| | MIG-YAG<br>4 kW + 280 A | YAG alone<br>4 kW |
|---|---|---|
| 3 m/min<br>t 4 mm<br>AC4C<br>+ 5000<br>series |  |  |

**Fig. 9 An example of welds on aluminum alloy**

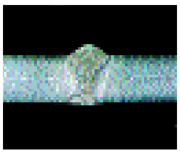
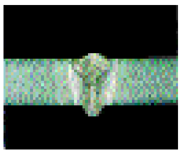
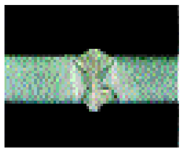
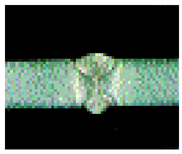
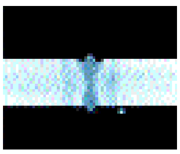
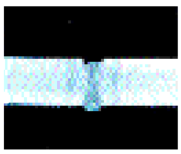
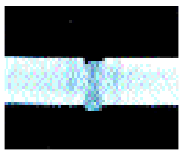
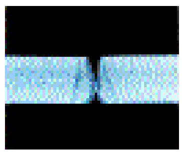
| Gap (mm) | 0 | 0.5 | 1.0 | 1.5 |
|---|---|---|---|---|
| MIG-YAG<br>5 kW, 125 A, 18 V<br>0.8 m/min |  |  |  |  |
| YAG alone<br>5 kW<br>0.8 m/min |  |  |  |  |

**Fig. 10 Gap allowance**

means of MIG welding or TIG welding. The “i” body, however, employed hybrid laser welding (a type of welding that combines laser welding and arc welding) in order to ensure superior joint strength and body dimensional precision. Among the MIG, TIG and plasma methods for arc welding, the MIG method was selected and combined with the YAG method that was selected as laser welding technique. MIG-YAG hybrid laser welding was selected because it is suitable for aluminum welding and allows gap tolerance.

MIG-YAG hybrid laser welding provides the MIG-based benefit of gap tolerance resulting from weld overlay, and provides the YAG-based benefit of deep penetration (**Fig. 9**). As a result, it gives consistent weld strength even when slight gaps exist between welded parts. **Fig. 10** illustrates the superior gap tolerance of MIG-YAG hybrid laser welding; with YAG laser welding alone, a gap of 1 mm or more causes the laser to pass through the material, resulting in a failed weld, but with the hybrid arrangement, stable welding is possible with a gap up to 1.5 mm. Furthermore, MIG-YAG hybrid laser welding can be performed approximately three times as quickly as MIG welding alone. Since heat input into the workpieces is smaller, welds are distorted relatively little and resulting body dimensions are highly precise. **Fig. 11**, **Fig. 12**, and **Table 1** give an overview of the coaxial MIG-YAG hybrid laser head (made by Mitsubishi Heavy Industries, Ltd.) used for welding the

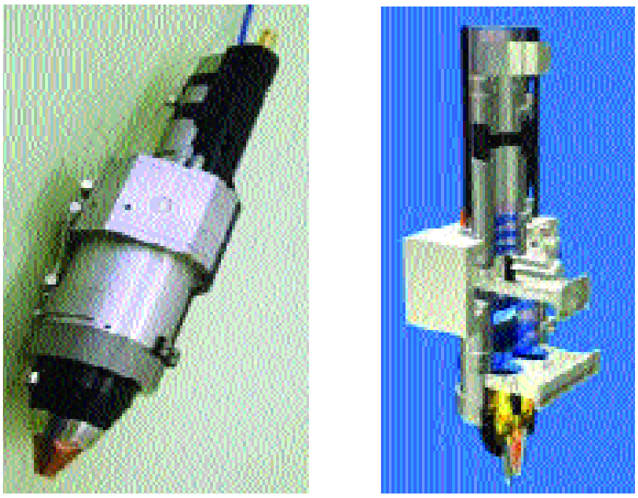


**Fig. 11　Appearance and cut model of coaxial MIG-YAG hybrid laser head**

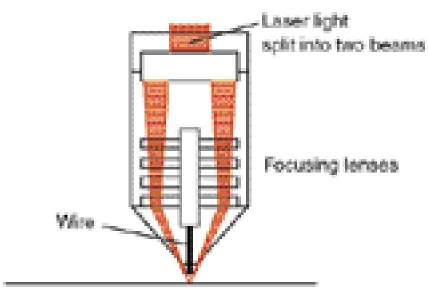



**Fig. 12　Schematic of coaxial MIG-YAG hybrid laser head**

“i” body. Inside the head, laser light is split into two beams by an optical mirror arrangement and the arc electrode and wire feed passage are positioned coaxially between the two laser beams. This structure realizes compact dimensions and permits good robot maneuverability (**Fig. 13**).

(2) Self-piercing rivets (SPRs)

SPRs, which are comparable with conventional spot welds in terms of shear strength and separation strength, were adopted for such lap joints as those between pressings and extrusions where relatively high joint strength is required. This method uses rivets that are coated to prevent electric corrosion for joining parts positioned on top of another by driving the rivets into the parts. In addition to offering high joint strength, this method also enables the joining of different materials (**Fig. 14**).

## 3. Plastic outer panels

Plastics that combine lightness with superior damage resistance were adopted for the body’s outer panels.

In addition to the bumpers that usually have been made of plastics, the fenders, hood and tail gate were also made of plastics, which not only reduced the weight of these parts but also provided them with good restorability after low-speed collision.

A newly conceived plastic module construction was adopted for the doors. With each door, a plastic outer molding is fitted over a plastic inner molding that serves both as an interior trim part and as a structural member of the door. The window regulator, window motor, and other functional parts are mounted on the outer side of the inner molding.

A high-strength polycarbonate material was adopted for the door and tailgate windows. This material has a coating that resists scratching and helps to prevent fogging.

**Table 1　Specifications of coaxial MIG-YAG hybrid laser head**

| Item | Specification |
|---|---|
| Dimensions | 400 x 100 x 100 mm |
| Weight | 5 kg |
| Laser power | < 5 kW |
| Arc current | < 300 A |
| Focal length | 145 mm |
| Focusing ratio | 1 : 1 |
| Optical fiber | 0.6 mm |

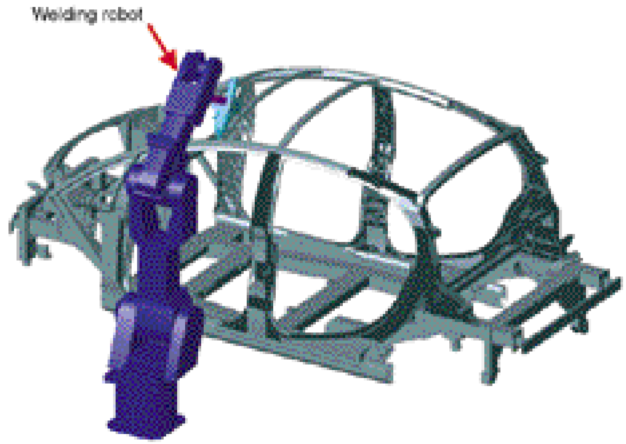



**Fig. 13　Welding process simulation**

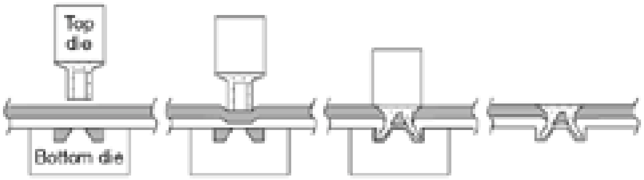



**Fig. 14　SPR joining process**

## 4. Basic properties of body framework

### 4.1 Rigidity, strength, and weight

The cross-sectional profile of the extrusions was designed to realize static flexural and static torsional rigidity comparable with that of a steel monocoque body (**Fig. 15**).

Since the underbody was, as stated, constructed using extrusions (each of which has a continuous cross section) and thus has a significantly higher level of rigidity than that of a steel monocoque structure, it facilitated further weight savings in the upper body.

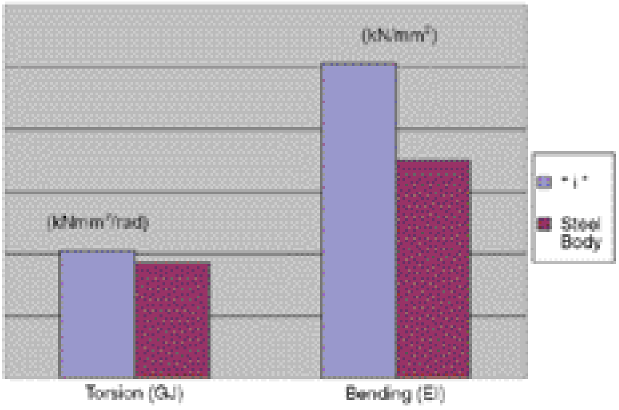



**Fig. 15 Static rigidity: “i” body vs. steel body**

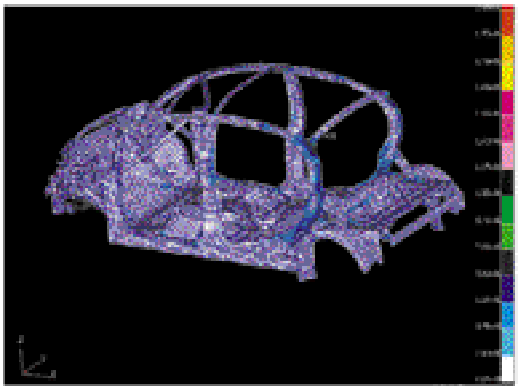


**Fig. 16 CAE analysis of static rigidity**

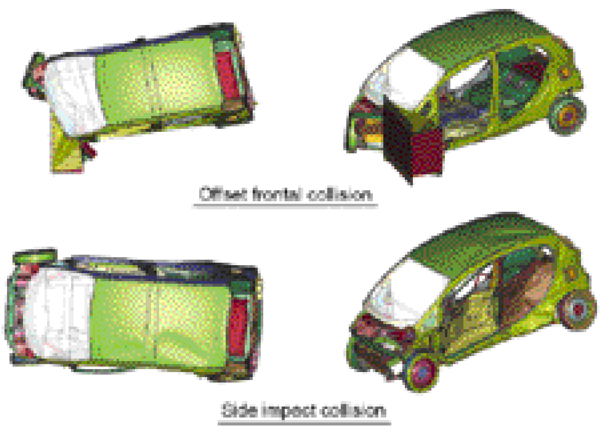



**Fig. 17 CAE analysis of crashworthiness**

Regarding the strength, joint structure and reinforcement layout throughout the body was decided with a view to minimizing the possibility of stress concentrations in welded areas (**Fig. 16**).

By adopting an aluminum space frame, it was possible to make the “i” body-in-white approximately 110 kg lighter than a steel monocoque body with the same levels of strength and rigidity.

### 4.2 Crashworthiness

One of the most significant attributes of the “i” is that it offers high crashworthiness and pedestrian-protection performance despite its compact body dimensions. Indeed, the “i” leads its class by meeting the requirements for the European New Car Assessment Programme ratings of four stars for crashworthiness and three stars for pedestrian protection (**Fig. 17**).

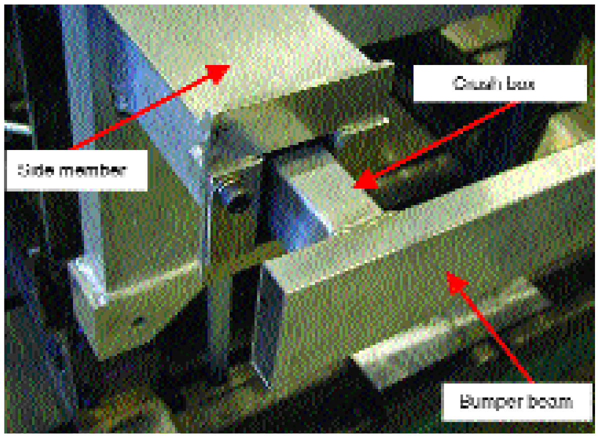



**Fig. 18 Crush box**

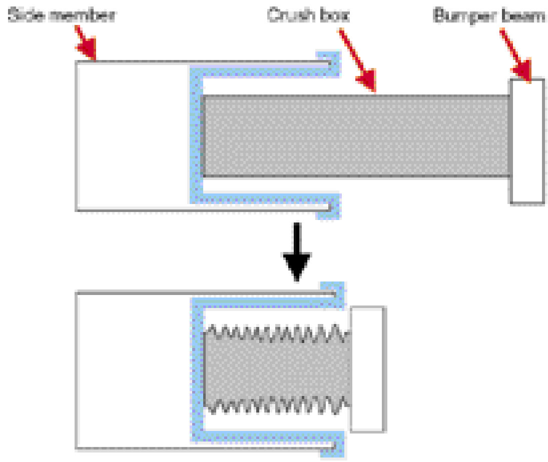



**Fig. 19 Image of crush box behavior in crash**

The “i” has a midship engine, so it was possible to achieve a long crush length at the front of the body and significant energy absorption in the hood. Energy absorption in a frontal collision and protection for pedestrians are both greatly enhanced.

Optimized cross-sectional profile in the straight, extruded side members and beads that can buckle at the front end of each side member yield ideal compression-load characteristics in the event of a crash, ensuring that collision energy is efficiently absorbed. The amount of collision energy reaching cabin occupants is thus minimized.

Furthermore, crush boxes that take advantage of the properties of aluminum extrusions were adopted to minimize damage to the body in the event of a low-speed, low-intensity collision (**Fig. 18**). A crush box is fitted inside each side member, and adequate crush length is provided for effectively attenuating shocks as it can accommodate a crushed box without causing it to protrude from the front end of the side member (**Fig. 19**). This arrangement helps to permit a short overhang both at the front and rear, which is one of the main

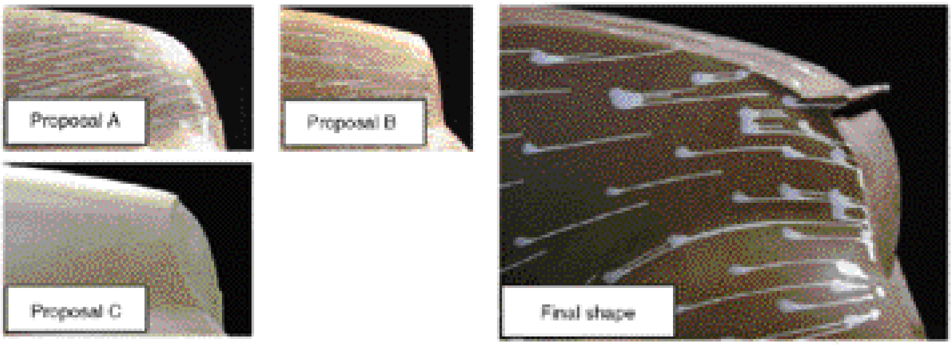



**Fig. 20 Study of roof rear-edge shape using 1/4-scale model**

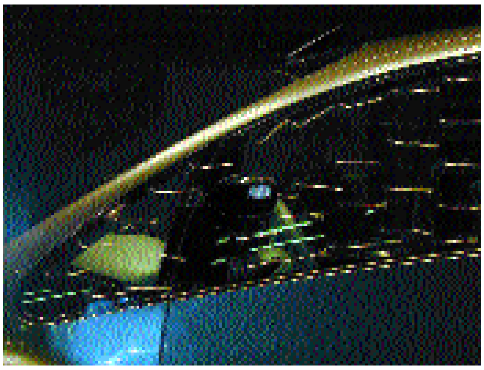


**Fig. 21 Visualization of airflow around A-pillar**

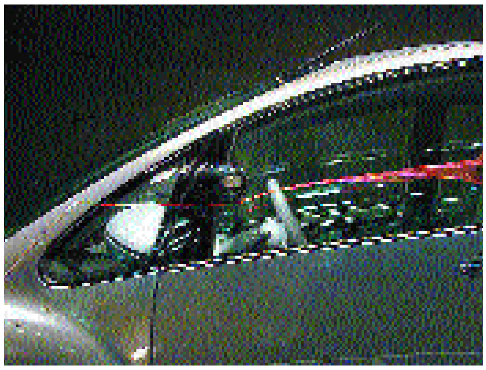


**Fig. 22 Visualization of airflow around side mirror**

styling and packaging features of the “i”.

### 4.3 Aerodynamic performance

Measures to minimize aerodynamic drag are vital for fuel economy. Indeed, aerodynamic drag at high speeds causes most of a vehicle’s running resistance.

In the development of the “i”, a 1/4-scale model and a full-size model were used in more than 500 wind-tunnel tests, and the results enabled an exceptionally low $C_D$ of 0.24 to be achieved. Although the body reflects comprehensive measures to minimize aerodynamic drag, it also has attractive styling and permits efficient packaging. The combination of superior aerodynamic efficiency, styling, and packaging is one of the most significant attributes of the “i”.

(1) Styling and aerodynamic performance

To give the body the required functionality while remaining faithful to the intentions of the stylists, who envisaged a body shape with entirely rounded contours, the aerodynamicists worked closely with the stylists and performed numerous wind-tunnel tests in pursuit of the final body shape.

The success with which the functional and aesthetic requirements were simultaneously satisfied is exemplified by the rear edge of the roof. The distinctive rounded shape of the roof initially inhibited smooth and consistent airflow separation at the rear edge and thus compromised the vehicle’s drag coefficient and rear lift coefficient. Numerous wind-tunnel tests conducted on various rear-edge shapes (**Fig. 20**) led to the best possible solution.

Furthermore, although the rear spoiler is relatively small it is positioned at the optimal height, meaning that it yields a reduction of more than 10 % in the vehicle’s overall aerodynamic drag.

Significant effort was devoted also to the A-pillar contour between the windshield and each side window and to the shape of each side mirror. Consequently, vortexes of the type formed near the A-pillars of a conventional vehicle by air flowing over the side windows are almost entirely prevented (**Fig. 21**) and the separation zone downstream of each door mirror is extremely small (**Fig. 22**).

(2) Packaging and aerodynamic performance

The “i” has a relatively short length and tall height, and it has short front and rear overhangs because its wheelbase is long relative to the overall length. These proportions are inherently disadvantageous for aerodynamic efficiency.

Although numerous wind-tunnel tests were conducted for optimization of the body shape, a great deal of additional effort was devoted to optimization of the front and rear fenders. Consequently, the flow field around each fender is almost entirely free of flow separation (**Figs. 23** and **24**).

A widely recognized means of achieving a low $C_D$ value is to slant the roof downward at the rear edge. The roof of the “i” is smoothly curved downward toward the rear for this purpose, but it does not prevent the cabin from providing ample space for four adults. Exterior aerodynamic efficiency and interior practicality are thus both realized.

**Fig. 23 Visualization of airflow around front fender**

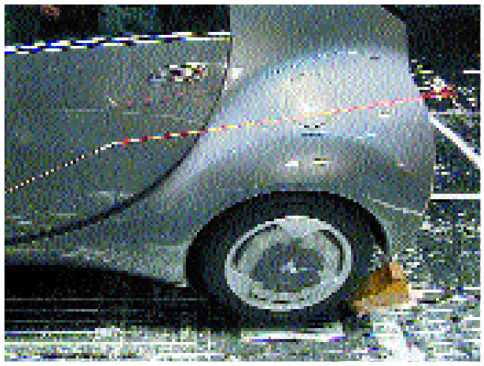


**Fig. 24 Visualization of airflow around rear fender**

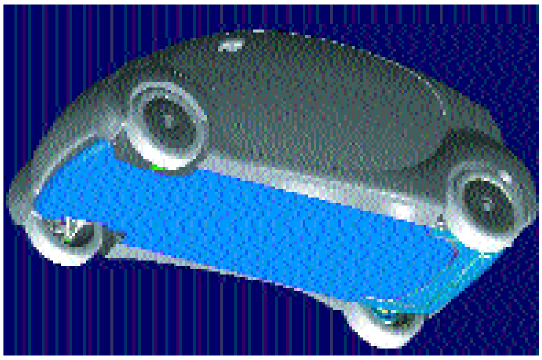


**Fig. 25 Undercovers**

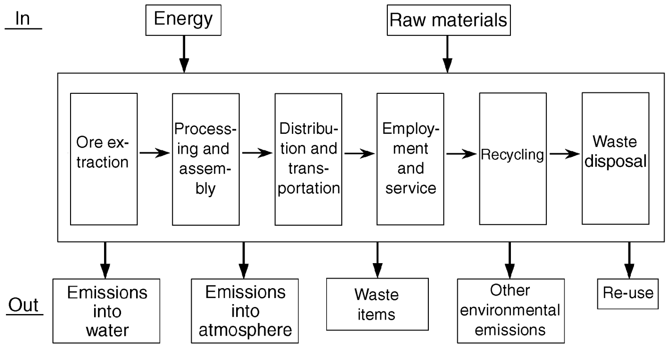



**Fig. 26 Inventory analysis for lifecycle assessment**

(3) Underfloor airflow

Most of the body’s bottom surface is provided with undercovers (**Fig. 25**) that form an ideally smooth surface for consistent airflow along with a low $C_D$ value. The undercover’s $C_D$-reducing effect is greater than 20 % of the total drag reduction amount achieved in the “i”.

Furthermore, air dams were adopted to control the airflow that is drawn into the wheel houses, thus suppressing the $C_D$ value and helping to optimize the front/rear lift balance.

(4) Cooling system

With the engine’s cooling system, cooling air that has passed through the front of the body is fed through the condenser and radiator via ducts. Some of the air is then expelled into the wheel houses. The rest is fed through the clearance between the main floor and undercover to lower the temperature in the engine compartment and is expelled through an opening in the rear bumper. This arrangement raises the back pressure, i.e., reduces the vacuum pressure, at the rear surface of the body and thus helps to minimize aerodynamic drag.

## 5. Life Cycle Assessment (LCA)

The environmental impact ($CO_2$ emissions) created by the aluminum materials and production technologies used for the “i” body were assessed.

An inventory analysis for the lifecycle was performed as shown in **Fig. 26**, and the amount of $CO_2$ emissions was thereby verified. The object of comparison was a conventional steel body. A simulation was performed to investigate the extent to which the aluminum space-frame body of the “i” reduced $CO_2$ emissions.

From the pre-extraction stage through the body-production stage, the amount of $CO_2$ emissions for the “i” body was found to be greater than that for a steel body. Virgin (non-recycled) material was used for the aluminum pressings and extrusions; therefore, the larger amount of $CO_2$ emissions was caused by electric smelting and other processes performed in production of the aluminum raw material.

At the usage stage, however, the “i” body’s lightness (approximately 110 kg lighter than a steel body) contributes to superior fuel economy. As the distance driven increased, the higher $CO_2$ emissions that occurred at the production stage were gradually offset. After approximately 20,000 km, the “i” body became superior to the all-steel body in terms of $CO_2$ emissions (**Fig. 27**). This finding proves that the “i” body can provide a real advantage over the total-service-life distances driven in any country.

Next, case studies were performed for two assumed cases of future advances in recycling infrastructure (**Table 2**). With Case ①, the higher $CO_2$ emissions caused during production were offset after approximately 13,000 km. With Case ②, where a higher rate of recyclability was assumed, the higher $CO_2$ emissions caused during production were offset after approxi-

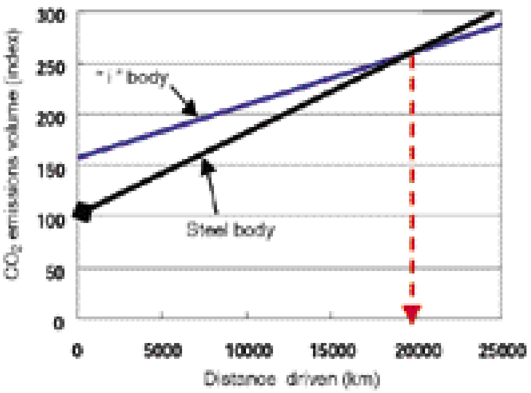



**Fig. 27 Lifecycle $CO_2$ emissions comparison (case study)**

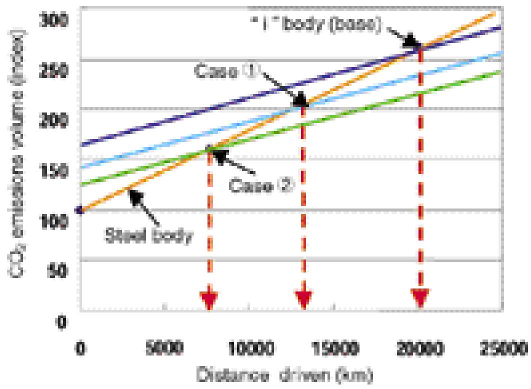



**Fig. 28 Lifecycle $CO_2$ emissions comparison**

**Table 2 Aluminum recycling case study**

| | Rate of recyclability (%) | | |
|---|---|---|---|
| | Die-castings | Pressings | Extrusions |
| Base | 90 | 0 | 0 |
| Case ① | 90 | 50 | 50 |
| Case ② | 90 | 90 | 90 |

mately 8,000 km. Beyond these points, the relative lightness of the “i” body made it superior to the all-steel body in terms of total $CO_2$ emissions (**Fig. 28**).

As advances in recycling infrastructure are achieved, it will likely be possible to use recycled aluminum, meaning that the increase in $CO_2$ emissions at the production stage will be suppressed and that $CO_2$ emissions over the entire lifecycle will be further reduced.

It was also verified that the hybrid laser welding employed with the “i” body has no significant influence on the environmental burden created during body assembly.

The benefits of the aluminum body of the “i” with respect to lifecycle $CO_2$ emissions were thus confirmed. The potential for further reductions in lifecycle $CO_2$ emissions by means of improved material selection was also confirmed.

## 6. Conclusions

Significant weight savings in the body-in-white were realized by effective use of aluminum construction through the “i” project. In the near future, the demand for lighter bodies is expected to intensify as the need to save energy becomes more acute, and aluminum space-frame bodies are a means of meeting this demand. This project provided MMC with technologies and know-how for mass production of such bodies at relatively low cost. MMC will now work on ways to rationalize the aluminum space-frame structure so that it is even easier to produce and even more commercially viable.

## 7. Acknowledgment

In developing the “i”, high targets could be achieved thanks to extensive assistance from materials and production specialists. MMC wishes to express particular appreciation to the staff of the Automotive Development Department of Mitsubishi Aluminum Co., Ltd., who assisted with development tasks ranging from basic testing to CAE analysis and actual construction of “i”.



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# Development of Mitsubishi “i” Chassis

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**Abstract**

**The main aims in developing the chassis for Mitsubishi “i” were to achieve the lightest weight and the lowest running resistance. The “i” development team also sought to satisfy the performances generally required of passenger car chassis and to make the design structurally consistent with the vehicle’s peculiarities. To reduce weight, the team mainly replaced conventional steel parts with aluminum parts and some with plastic parts. To reduce rolling resistance, the team concentrated on minimizing wheel bearing friction and brake drag torque. Together with the low rolling resistance design, a combination of McPherson struts for the front suspension and a De Dion axle with Watts linkage arrangement for the rear suspension was employed to maximize handling stability. The use of light extruded aluminum shapes for the front suspension frame and rear axle beam also yielded a functionally efficient structure.**

***Key words:*** *Chassis, Suspension, Aluminum, Plastics, Brakes, Tires, Weight Reduction, Running Resistance Reduction*

## 1. Introduction

As automakers respond to the growing need for efforts to protect the environment, they are working hard to develop technologies that minimize carbon-dioxide ($CO_2$) emissions and maximize fuel economy.

With chassis components, it is possible to gain environmental benefits by minimizing weight and running resistance. Steps to minimize weight and running resistance were thus taken with the chassis of the Mitsubishi “i”. At the same time, steps were taken to make the “i” chassis quickly adaptable for use in production vehicles. Specifically, steps were taken to achieve

- production-vehicle chassis performance (measured in terms of attributes such as handling stability, strength, rigidity, and durability); and
- a maximally rationalized chassis structure.

An overview of chassis components used on the “i” is given in this paper.

## 2. Suspension

### 2.1 Suspension overview

The suspension system is the most significant part of a vehicle’s chassis in terms of both weight and performance. A gradual increase in employment of aluminum for suspension components has led to weight reductions in recent years.

With the “i” suspension system, MacPherson struts are used at the front and a De Dion axle with Watts linkage arrangement is used at the rear. The rear arrangement reflects the importance attached to straight-line stability in Europe; this arrangement suppresses yaw-angle-speed variations in scuff characteristics when the vehicle baunces, and it offers high lateral rigidity.

The front suspension frame, rear axle beam, and other components are shaped to allow the cost benefits of fabrication as aluminum extrusions.

### 2.2 Front suspension and steering system

(1) Lightness

Lightweight parts of the front suspension and steering system are shown in **Fig. 1**.

The front suspension frame has a square configuration. Since the “i” has a midship engine, it was possible to form the front suspension frame from near-straight members and thus possible to use aluminum extrusions. A further weight saving was achieved by not offsetting the cross members relative to the lower arm mounting brackets.

For the steering system, a manual (not power-assisted) arrangement was adopted since it can reduce the load on the front axle.

For the wheel bearings, unit bearings (wherein the bearing inner races and wheel hubs are integrated) were adopted.

Further weight savings are yielded by the use of a hollow stabilizer and by the use of aluminum for the lower arms, struts, and steering knuckles.

(2) Rolling resistance

With regard to the structure of the wheel bearing seals, the lip shape, the core ring shape, and the fit

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tightness were optimized to minimize rotating torque.

(3) Suspension performance

Since the engine is not located at the front of the vehicle, it was possible to incline the suspension struts inward at a greater angle than with a front-engine/front-wheel-drive vehicle. It was thus possible to achieve ideal positioning whereby the reaction forces of the springs counteract forces that tend to bend the struts. Concomitantly low suspension-strut friction permits good ride comfort.

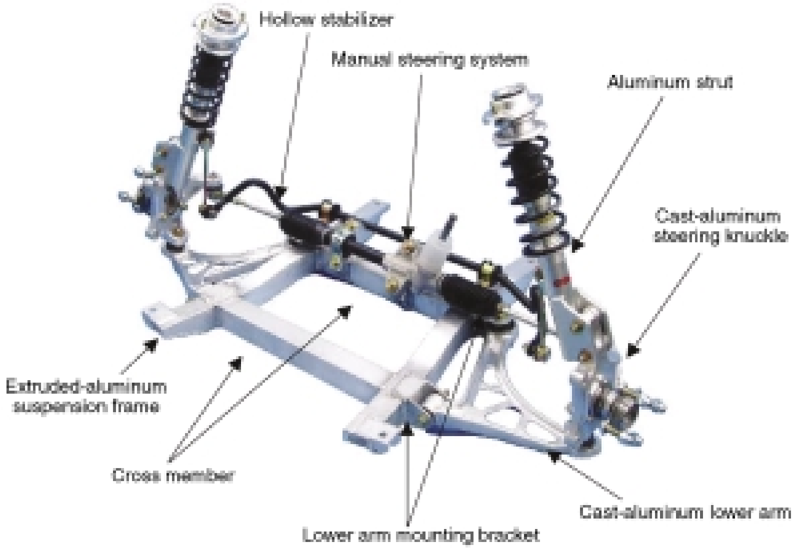


**Fig. 1 Lightweight parts of front suspension**

### 2.3 Rear suspension

(1) Lightness

Lightweight parts of the rear suspension are shown in **Fig. 2**.

As with the front suspension, the main means of weight minimization was employment of aluminum. To rationalize the structure, extrusions were used for the Watts linkage and axle beam.

(2) Rolling resistance

As with the front suspension, the seal structure of the wheel bearings was optimized to minimize rotating torque.

(3) Suspension performance

Suspension performance with the Watts linkage and suspension performance without it were compared. Inclusion of the Watts linkage almost entirely eliminated changes in scuff characteristics (**Fig. 3**) and, as a result, minimized yaw-angle-speed variations occurring with in-phase left and right inputs (**Fig. 4**). A further advantage was found to be an improvement of approximately 30 % in the lateral rigidity of the tire contact patches.

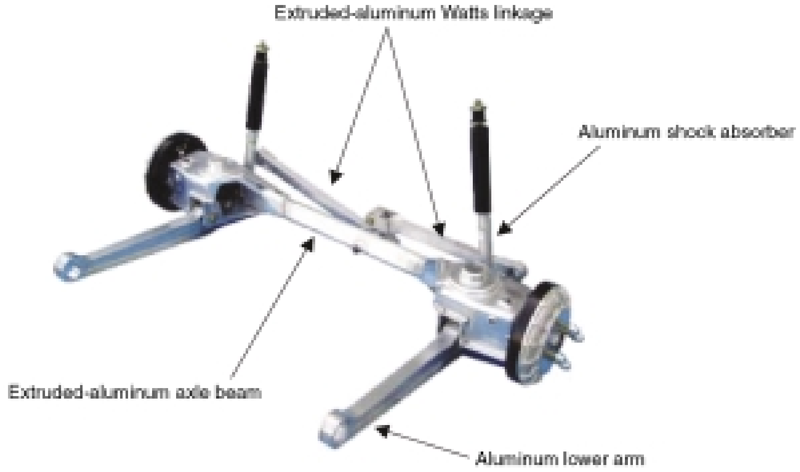


**Fig. 2 Lightweight parts of rear suspension**

## 3. Engine mounts

A pendulum-type three-point engine-mount arrangement was adopted. The powerplant is supported by the left and right main insulators. Roll is suppressed by an antiroll rod that links the body cross member and the bottom of the transmission. The antiroll rod is made of plastic for lightness (**Fig. 5**).

In the design of the plastic antiroll rod, care was taken to (a) prevent water absorption that would compromise the rod’s tensile strength, (b) prevent buckling resulting from warpage during the moulding process, and (c) ensure a tolerable operating-temperature environment. With regard to factors (a) and (b), shape optimization was performed by means of computer-aided-engineering (CAE) analysis (**Fig. 6**). With regard to factor (c), adequate distance from exhaust-system components was ensured.

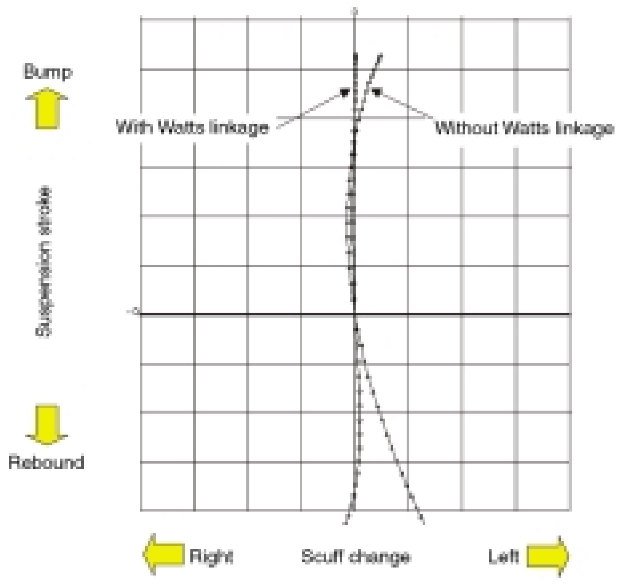


**Fig. 3 Changes in scuff characteristics of rear suspension**

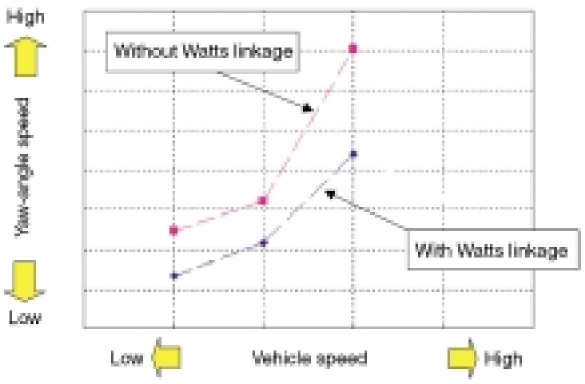


**Fig. 4 Variation in yaw-angle speed when left and right inputs are in phase**

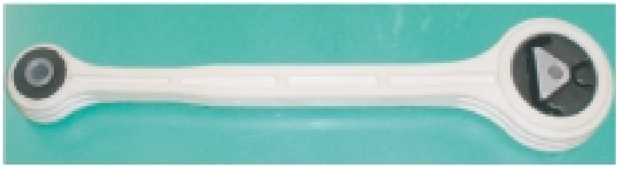

**Fig. 5 Plastic antiroll rod**

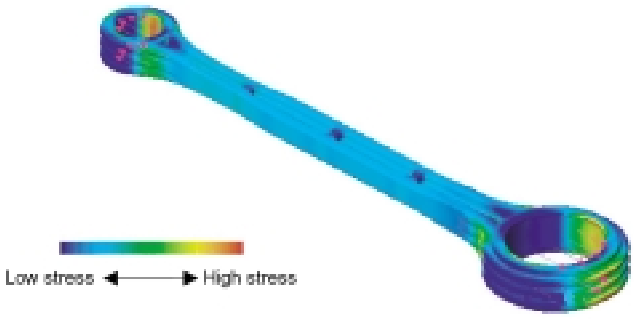


**Fig. 6 Stress distribution under tension (CAE image)**


**Fig. 7 Front brake caliper**

**Fig. 8 Front brake disc rotor**

**Fig. 9 Rear brake drum**

## 4. Brakes

### 4.1 Front brake calipers

Each caliper body was made from aluminum for lightness (**Fig. 7**), and the piston return stroke was made longer than usual to make drag torque approximately 60 % lower than that of standard brakes. Caliper rigidity is comparable with that of a steel caliper. Combined with the lightness of the vehicle, the high caliper rigidity enables a satisfyingly firm pedal feel.

### 4.2 Front brake disc rotors

Each front brake disc rotor (including the surface that makes contact with the brake pads) is made entirely of aluminum (**Fig. 8**). Specifically, the material is a ceramic-reinforced aluminum compound that resists high temperatures and thus prevents heat-induced reductions in friction coefficient. The brake pads are made from a friction material specially specified for use with the aluminum rotors.

### 4.3 Rear brake drums

Like the front brake disc rotors, the rear brake drums (including the surface that makes contact with the brake lining) are made entirely of aluminum (**Fig. 9**). A friction material specially formulated to work with the drum material was adopted for the linings.

### 4.4 On-road braking performance

The required pedal pressure during brake fade was compared between the "i" and a vehicle with conven-

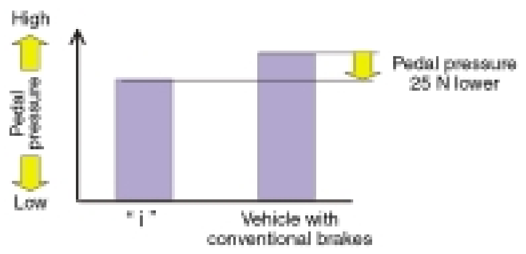


**Fig. 10 Maximum required pedal pressure during brake fade**

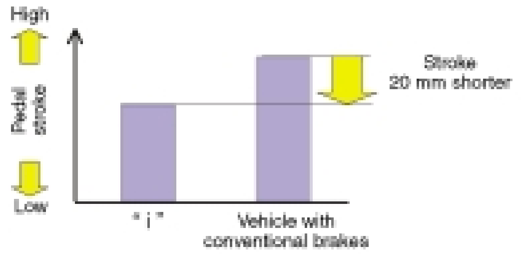


**Fig. 11 Pedal stroke (with 0.8 G braking)**

tional brakes. It was found that the brakes of the “i” had superior fade resistance and required concomitantly less pedal pressure (**Fig. 10**). The superior performance can be attributed partly to the overall lightness of the “i” and partly to the ceramic-reinforced-aluminum rotors’ superior resistance to friction-coefficient reductions at high temperatures.

Further, the brakes of the “i” were found to yield a relatively high rate of deceleration with a short pedal stroke (and a concomitantly firm pedal feel) (**Fig. 11**).

## 5. Tires

For the front wheels, 145/65R15 tires were selected with consideration given to rolling resistance and aerodynamic resistance. For the rear wheels, high-grip 175/55R15 tires were selected to ensure handling stability.

The tread compound, belt angles, and number of belts were optimized to keep rolling resistance as low as possible.

## 6. Strength

To satisfy production-vehicle-level strength requirements, suspension components were shape-optimized by means of CAE analysis (**Figs. 12** and **13**).

## 7. Summary

The development team’s focus on chassis lightness and low running resistance realized a weight saving of approximately 40 kg and a significant reduction in running resistance.

Lightness promotes the basic performance attributes of running, turning, and stopping. With the “i” chassis, the combination of low weight and high rigidity thus realizes outstanding dynamic-performance potential in addition to superior fuel economy.

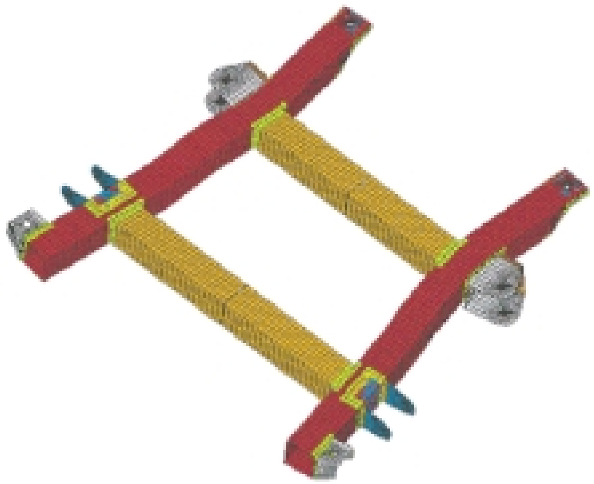

**Fig. 12 CAE model of front suspension frame**

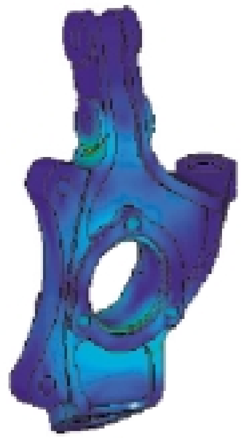

**Fig. 13 CAE model of front steering knuckle**

The development team plans to pursue further weight reductions in the chassis and other parts of the “i” platform and to take steps to facilitate adoption of the “i” platform in vehicles based on various concepts.

In closing, the development team wishes to thank the many people who co-operated in the development of the “i” chassis.

Hiromichi KAWAI

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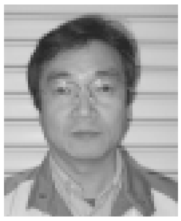

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# Development of Mitsubishi "i" Powertrain

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## Abstract

**The powertrain of the "i" uses a 1.0-liter, three-cylinder, 12-valve DOHC gasoline engine that was newly developed with the aim of achieving ultra-low fuel consumption and comfortable ride quality. The lightweight technologies and high-efficiency technologies, such as the Mitsubishi Innovative Valve Timing & Lift Electronic Control System (MIVEC) and exhaust gas recirculation system, incorporated in this new engine deliver a high power performance of a 50 kW/6,000 rpm maximum output and 92 Nm/3,500 rpm maximum torque in addition to extremely low fuel consumption. The Mitsubishi Smart Idling System that automatically turns off the engine during short stops instead of letting it idle and allows the engine to restart very quickly is another eco-friendly feature of the powertrain. In conjunction with the ultra-lightweight body and chassis and advanced aerodynamics of the body design, this idling-stop system helped the Mitsubishi "i" to gain the world's first five-star rating in both the fuel consumption and emissions categories of the FIA EcoTest, an environmental performance test carried out by the Allgemeiner Deutscher Automobil-Club (ADAC).**

***Key word:*** *Engine, Low Fuel Consumption, Weight Reduction, Idling Stop*

## 1. Introduction

The "i" concept test car developed by Mitsubishi Motors Corporation (MMC) represents a proposal for a next-generation small car whose capabilities include compliance with European standards on carbon-dioxide ($CO_2$) emissions. Next-generation small cars will be expected to deliver the environmental benefits of low fuel consumption and low exhaust emissions together with levels of running performance and value for money surpassing those of earlier models. The "i" addresses these needs in the high degree level.

Key targets for the fuel economy and emissions performance of the "i" were (a) $CO_2$ emissions lower than the 90 g/km limit defined for so-called three-liter cars and (b) compliance with the Euro 4 exhaust-emissions standards. To achieve these targets, a powertrain combining a gasoline engine with a continuously variable transmission (CVT) was adopted. Although diesel engines are typically used in three-liter cars, a diesel engine was not used in the "i" because diesel engines, notwithstanding their good fuel economy, have relatively large amounts of nitrogen oxides ($NO_x$) and particulate matter (PM) in their exhaust emissions, making compliance with future, tougher emissions regulations potentially difficult to achieve. By contrast, it is relatively easy to limit the exhaust emissions of a gasoline engine. In addition, the latest technologies for fuel efficiency can be employed with a gasoline engine to achieve further reductions in fuel consumption.

Another key attribute of the "i" powertrain is that it has an economy-oriented Mitsubishi Smart Idling system (this system stops the engine instead of letting it idle when the vehicle is stationary) rather than a costly hybrid system of the type used in three-liter cars.

**Table 1 Engine specifications**

| | NEW ENGINE IL3-1.0L | 4A31 IL4-1.1L | 3G83 IL3-0.66L |
|---|---|---|---|
| Displacement (cc) | 999 | 1,095 | 657 |
| Bore x Stroke (mm) | 72 x 81.8 | 66 x 80 | 65 x 66 |
| S/B ratio | 1.14 | 1.21 | 1.02 |
| Cylinder block height (mm) | 191 | 187 | 161 |
| Cylinder block length (mm) | 286 | 312 | 244 |
| Engine weight (kg) | 67 | 85 | 72 |

## 2. Newly developed IL3 engine

The engine was newly developed for the "i". Its specifications are shown in **Table 1**. This engine, with its displacement of 999 cc and its bore and stroke of 72 mm and 81.8 mm, respectively, is inherently compact, and it has a chain-type camshaft-drive arrangement that permits a further space saving. Overall, the new engine is significantly shorter than a four-cylinder engine with the same displacement.

(1) Lightness

Lightweight parts including an aluminum cylinder block, a compact, direct-actuation valvetrain, a magnesium rocker cover, and a modular chain case realize a

* Advanced Powertrain Development Department, Research & Development Office

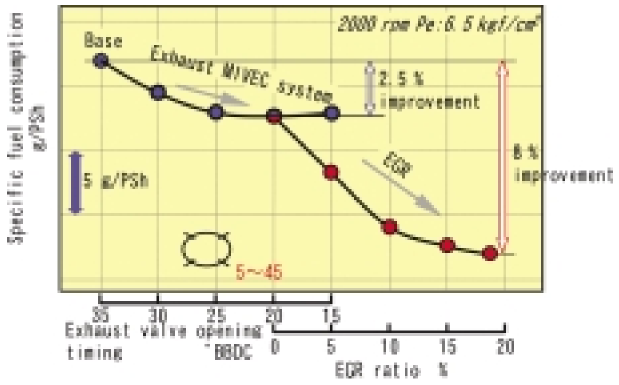



**Fig. 1 Effects of exhaust MIVEC and EGR systems on fuel consumption**

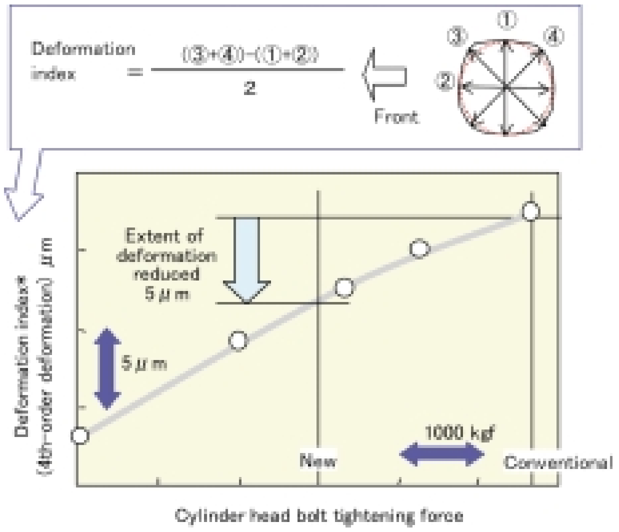



**Fig. 2 Cylinder head bolt tightening force versus bore deformation**

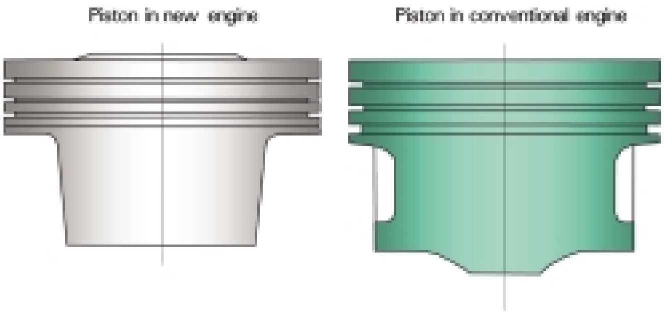



**Fig. 3 Piston shape**

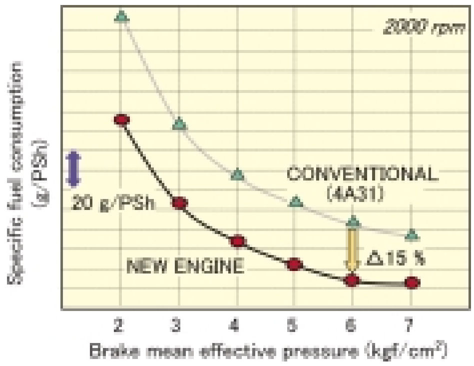



**Fig. 4 Fuel-economy effects of new technologies**

weight saving of 7 % relative to a 660 cc minicar engine.

(2) Fuel economy

Techniques for minimizing fuel consumption can be broadly divided into three groups. The first is reduction of pumping losses. This technique is beneficial when the engine is operating under light or moderate loading. The second is reduction of friction. This technique is beneficial under all operating conditions. The third is improvement of combustion.

To reduce pumping losses, an exhaust gas recirculation (EGR) system was adopted. Unlike lean combustion, the EGR system has the merit of making $NO_x$ reductions relatively easy to achieve. In addition, the latest Mitsubishi Innovative Valve timing and Electronic Control (MIVEC) system, which optimally varies the intake- and exhaust-valve timing, was adopted. Compared with MMC’s original MIVEC system, which optimizes only the intake-valve timing, the newly adopted MIVEC system permits a higher expansion ratio and thus yields a 2.5 % reduction in fuel consumption at low engine speed. The overall benefit of the MIVEC and EGR systems is up to 8 % improvement in fuel economy compared to an engine not equipped with these systems (**Fig. 1**).

To reduce friction, the tension of the piston rings was made 60 % lower than that of conventional piston rings. To permit the low-tension piston rings to be used, steps including minimization of the cylinder-head bolts’ tightening force (**Fig. 2**) and deep location of the bolt threads were taken to minimize bore deformation. Reduction of the contact surface area of the piston skirts was also implemented to cut friction. Each piston has a 30 % smaller contact surface area and is 25 % lighter than a conventional piston with the same bore diameter (**Fig. 3**).

Since the valvetrain is a direct-actuation type, it contains sliding elements. To achieve friction as low as that of roller rocker arms, physical vapor deposition was employed on the tappets and the spring load was reduced by employment of beehive springs and reductions in weight of valve-related parts.

For combustion enhancement, cooling of the cylinder head was optimized to permit a high compression ratio.

Midship positioning of the engine makes a further, significant contribution to fuel economy since it makes power-assisted steering unnecessary.

The overall benefit of the steps taken to optimize fuel efficiency is 15 % improvement in fuel consumption compared to a conventional engine (**Fig. 4**).

(3) Output

Four valves per cylinder, dual overhead camshafts, and the MIVEC system together realize output characteristics that are characterized by plenty of torque

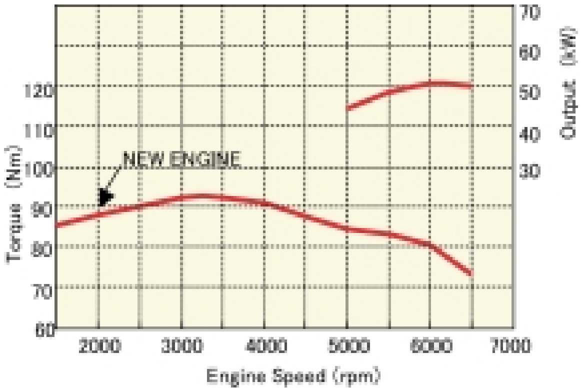



**Fig. 5  Engine performance**

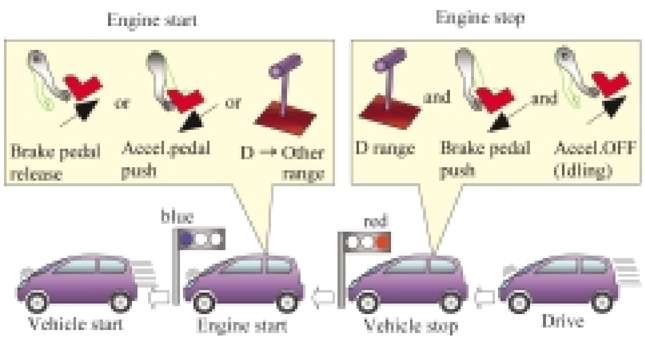



**Fig. 6  Operating logic of MSI system**

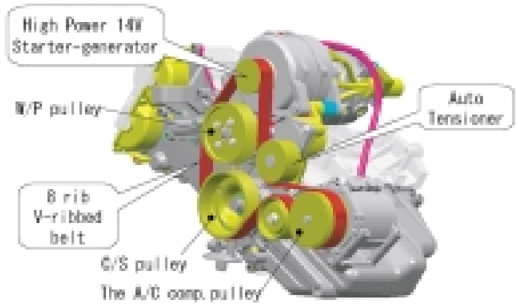



**Fig. 7  External view of engine**

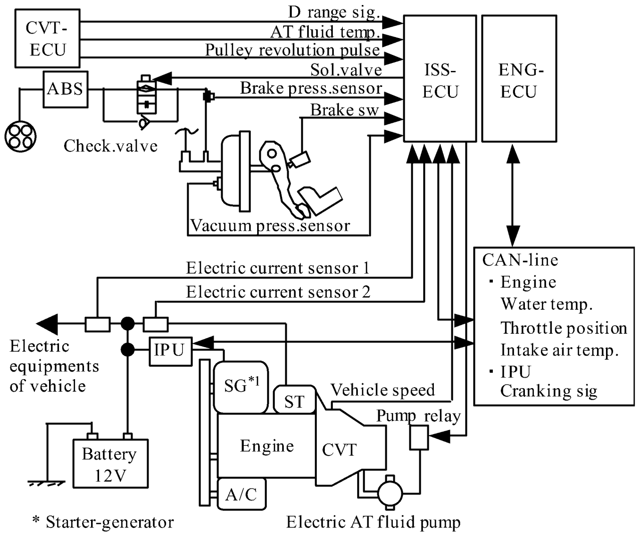



**Fig. 8  System configuration**

throughout the rev range.  Maximum output is 50 kW at 6,000 rpm, and maximum torque is 92 Nm at 3,500 rpm (**Fig. 5**).

## 3.  Mitsubishi Smart Idling system

The greatest problems to be overcome with any idling-stop system are the delay that occurs before the vehicle can pull away from a standstill (when the engine must be restarted to enable movement) and the engine vibration and noise that occur when the engine is started and stopped.  The technological challenges are particularly great with an automatic-transmission vehicle; a typical driver takes 0.2 s to start depressing the accelerator pedal after releasing the brake pedal, so the engine must be started within this period.  A number of automatic-transmission vehicles with idling-stop systems have been launched by other manufacturers, but none of them fully overcomes the aforementioned problems; drivers are forced to endure less-than-satisfactory operation.  With the “i”, the problems were overcome by adoption of a Mitsubishi Smart Idling (MSI) system employing a newly developed 14 V Belt-driven Starter Generator (BSG).  An overview of the MSI system is given hereafter.

(1)  MSI system operating logic

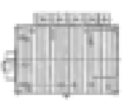
The MSI system’s operating logic is shown in a simplified form in **Fig. 6**.  The engine is stopped when all of certain conditions (vehicle stationary; shift lever in ‘D’ position; brake pedal depressed; accelerator pedal released (engine idling)) are satisfied, and the engine is started when at least one of certain conditions (brake pedal released; shift lever moved to position other than ‘D’; accelerator pedal depressed) is satisfied.

When there is a risk of excessive battery drainage or a risk of compromised safety or reliability (for example, when the master vac’s vacuum pressure is insufficient, the engine is warming up, or the vehicle is not stationary), the idling-stop function is canceled regardless of inputs made by the driver.  If the engine is not running at this time, it is force-started regardless of inputs made by the driver.

(2)  Overview of MSI system

An external view of the engine is shown in **Fig. 7**. The configuration of the MSI system is shown in **Fig. 8**. And the specifications of the BSG are shown in **Table 2**.

**Table 2  Specifications of BSG**

| Item | Specification | | |
|---|---|---|---|
| Type | Wound rotor induction |  |  |
| Max. torque | At least 30 Nm | | |
| Inverter type | Force air cooled | Starter-generator | IPU (inverter) |

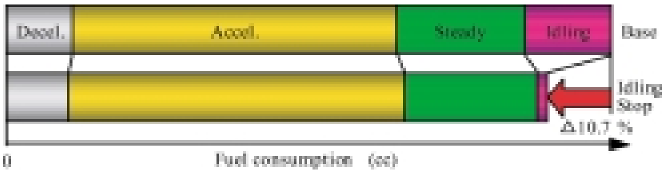



**Fig. 9 Fuel-economy benefits proved in 10·15-mode test**

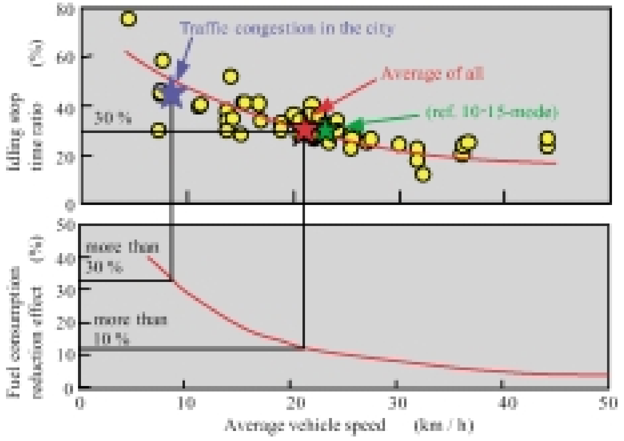



**Fig. 10 Fuel consumption during open-road driving**

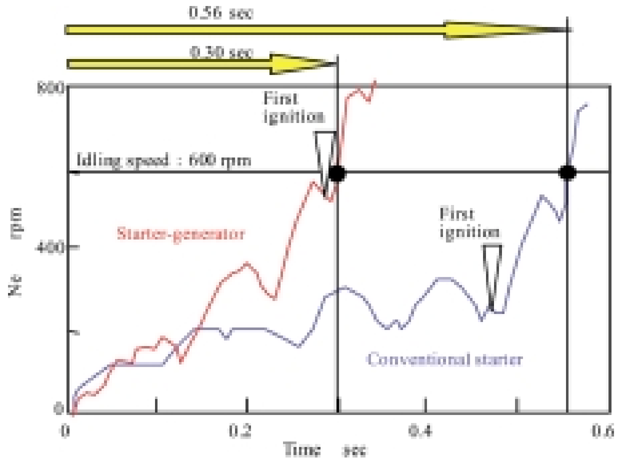



**Fig. 11 Engine startability**

The BSG is an alternator-based wound-rotor induction motor/generator. Although it has the same external appearance as an alternator, it is capable not only of generating electricity but also of rapidly starting the engine. It is driven by an Integrated intelligent Power drive Unit (IPU) (an air-cooled inverter that is located separately from the Starter-Generator) and can produce maximum torque in excess of 30 Nm. Its output is transmitted to the crankshaft pulley by an eight-rib V-belt, so the gear noise that accompanies conventional starters is absent. Operation is concomitantly quiet.

For engine restart, the output of the brake pressure sensor and the output of the brake switch are used to determine when the brake pedal has been released.

To enable a standing start immediately after engine startup, the CVT is held in its ‘D’ range while the engine is not running. The CVT has its own electric pump for this purpose.

Since no transmission creep occurs while the engine is not running, a brake pressure holding circuit is used to keep the brakes applied from the moment when the brake pedal is released until the engine has started completely and started causing transmission creep. The vehicle is thus prevented from rolling backward on slopes.

The battery’s state of charge is monitored by means of a current sensor, and the idling-stop function is canceled when necessary.

The aforementioned idling-stop control is effected by a dedicated Idling Stop System Electronic Control Unit (ISS-ECU), which exchanges information with the IPU and Engine ECU via a Controller Area Network bus.

(3) Fuel-economy benefits of MSI system

In a 10·15-mode test, the MSI system was found to yield a 10.7 % fuel saving (**Fig. 9**).

The frequency of idling-stop operation and the corresponding fuel-consumption reduction recorded during vehicle operation in a major Japanese city and in the suburbs thereof are shown in **Fig. 10**. As shown, correlation was observed between the average vehicle speed and the idling-stop frequency. With congested roads and a low average vehicle speed, the idling-stop frequency was high. A fuel-consumption reduction of at least 30 % was confirmed under such conditions, highlighting the system’s effectiveness for users who drive mainly in urban areas. The average idling-stop frequency observed during urban and suburban operation was almost the same as that observed in the 10·15-mode test, indicating that the system can be expected to realize a fuel-consumption reduction of at least 10 % in real-world conditions.

(4) Vehicle startability

With a port-injection engine, the first explosion becomes possible after in-port fuel injection, air intake, compression, and ignition (in other words, the third compression stroke in the sequence from starting the engine). For rapid engine startup, therefore, it is necessary to make the engine speed as high as possible and as soon as possible such that the engine reaches the compression stroke as soon as possible.

The time taken by a conventional starter to start the engine and the time taken by the BSG to start the engine are compared in **Fig. 11**. With the conventional starter, a high reduction ratio and a concomitantly low speed of rotation meant that 0.56 s elapsed from the start of cold startup until the engine reached its idling speed. With the BSG, the corresponding period was only 0.30 s. The difference in startup speed was found to clearly manifest itself in the time taken by the vehicle to start moving following depression of the accelerator pedal (**Fig. 12**). The BSG gave vehicle startability similar to that of a conventional automatic-transmission vehicle; the idling-stop operation did not cause the driver to feel any incongruity while pulling away from a standstill.

**Fig. 13** shows engine startability when a standing start is to performed immediately after engine shut-

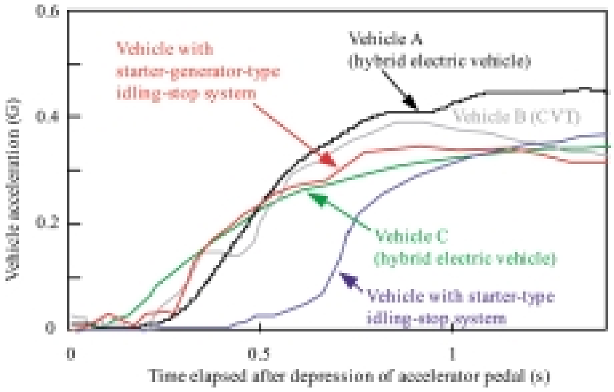



**Fig. 12 Vehicle startability**

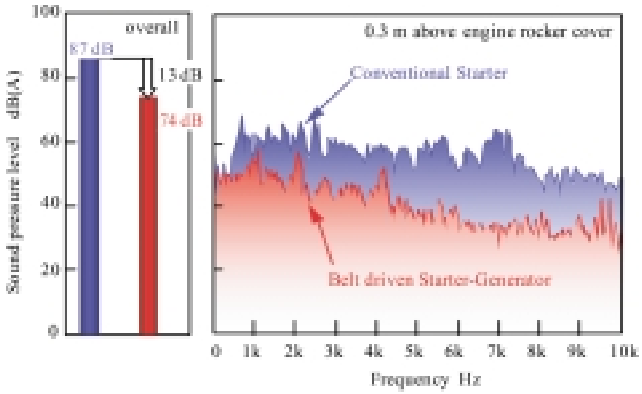



**Fig. 14 Noise level during engine startup**

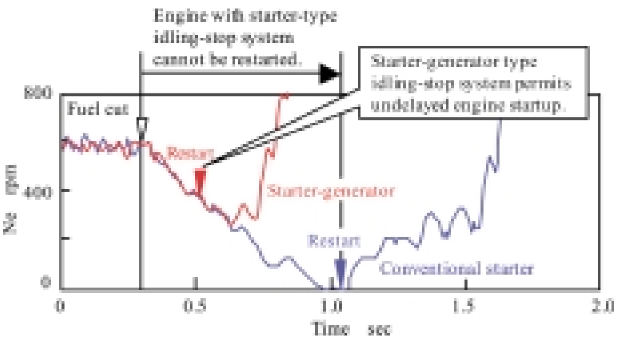



**Fig. 13 Engine startability just after stopping of vehicle**

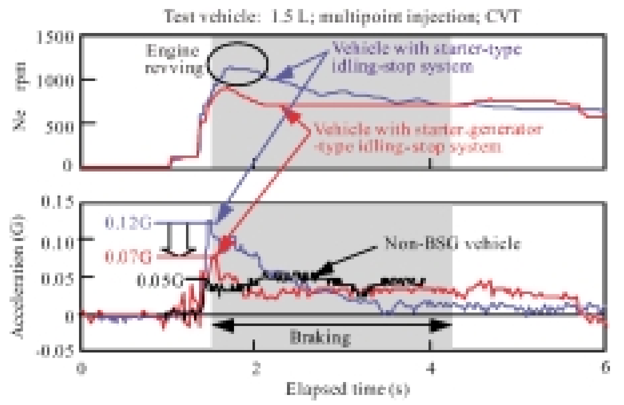



**Fig. 15 Shock just after engine startup**

down. A situation requiring a standing start immediately after engine shutdown can easily occur during urban operation, which involves frequent starts and stops. This type of situation was one of the most difficult challenges addressed in the MSI system’s development. With a conventional meshing-gear-type starter, it is not possible to restart the engine immediately after the fuel supply has been cut. This is because meshing the pinion gear with the crankshaft gear while the crankshaft is still turning due to inertia could result in gear damage. The duration of inertial rotation varies from one engine model to another, but it is generally necessary to allow 0.6 s for inertial rotation to finish. Engine restart is impossible during this period. By contrast, the BSG permits an engine restart immediately after engine shutdown (the delay is negligible) since it is belt-driven.

(5) Reduced noise during engine startup

**Fig. 14** shows noise levels recorded during engine startup. Since the BSG is belt-driven and does not contain a mechanical speed-reduction mechanism, its noise levels were found to be lower than those of a conventional meshing-gear-type starter at all frequencies. Its overall noise level was found to be 13 dB lower.

(6) Reduced shock during creep-induced starts

When an engine is started, it briefly revs before settling down to its idling speed. The initial brief revving occurs because the pressure in the intake manifold when the engine is not running is the atmospheric pressure, i.e., the pressure that exists in the intake manifold during engine operation with a wide-open throttle. The engine settles down to its idling speed as idling vacuum pressure is created in the intake manifold.

With an automatic-transmission vehicle, it is common for forward movement to occur as a result of creep when the brake pedal has been released following a stop (on a congested road, for example). When this type of creep-induced start occurs after idling-stop operation, the initial brief rise in engine speed can cause the vehicle to move forward with a jerk, creating an unpleasant sensation for the driver.

With the BSG, abrupt forward movement is prevented by means of braking (**Fig. 15**). Energy is consumed in the IPU, so constant braking force can be applied regardless of external electrical loading. This function was found to cut forward-movement shock from 0.12 G to 0.07 G. The greatly reduced shock is close to the level that occurs with a conventional vehicle.

(7) Reduced vibration during engine shutdown

A vehicle’s body typically resonates when the engine is running at a speed of 300 – 400 rpm. When the engine is stopped, therefore, the body starts to vibrate as the engine speed approaches this level. Using the braking function of the BSG, the engine speed is caused to pass through this level as quickly as possible such that vibration is minimized in terms of magnitude and duration (**Fig. 16**).

(8) Evaluation of driving feel

The extent to which adoption of the BSG improved driving feel with respect to vehicle startability and start-stop vibration and noise was evaluated by means of test

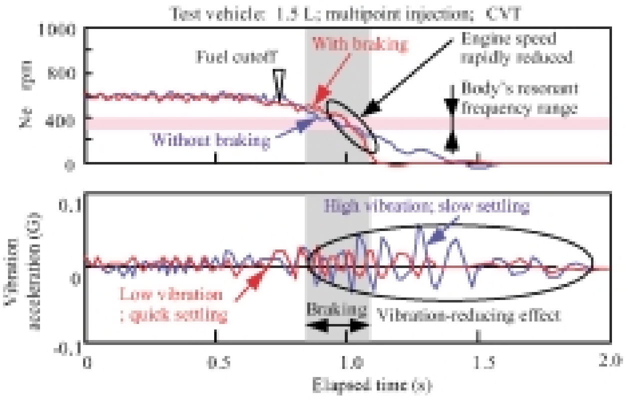



**Fig. 16  Vehicle vibration during engine shutdown**

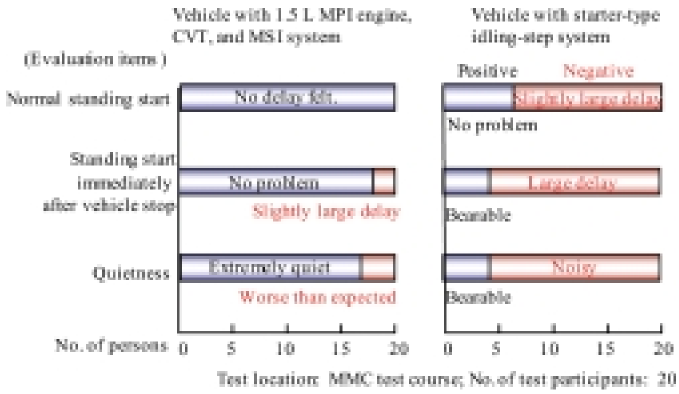



**Fig. 17  Evaluations of test drives**

drives (**Fig. 17**). The new system was fitted in a 1.3 – 1.5-litre-class test vehicle (not in the “i”), and driving-feel comparisons were made against a similar vehicle equipped with an idling-stop system employing a conventional starter. Many superior evaluations of the new system were made. The new system thus behaved as expected.

## 4. Summary

MMC’s technological concept for the “i” was to give a preview of near-future advances. At the same time, it was essential for the “i”, as a test car, to combine a high level of environmental performance with real-world driveability. Rather than seeking to meet these requirements using glamorous technologies such as a hybrid-electric drive system or a fuel-cell drive system, MMC sought to meet them in a more straightforward way using powertrain technologies that minimize friction, optimize combustion, and an idling-stop system. By refining these technologies, MMC enabled the “i” to become the first gasoline vehicle to earn five stars (the highest score) in the Federation International de l’Automobile EcoTest.

MMC aims to further refine the technologies used in the “i” to enable them to be widely commercialized and accepted with high reputation.



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# Fuel Cell Vehicle Technology Trends and MMC Initiatives

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**Abstract**

**Using the Mitsubishi GRANDIS as the base vehicle, Mitsubishi Motors Corporation (MMC) developed a fuel cell vehicle named MFCV (short for Mitsubishi Fuel Cell Vehicle). The MFCV is powered by DaimlerChrysler's newest hydrogen fuel cell system, which employs Ballard fuel cell stacks. MMC plans to conduct trials with a view to gathering data on the MFCV's driving characteristics on public roads and on its usability with hydrogen filling stations. Selected portions of the test information will be made accessible to the public in real time via an MMC website by means of telematics technology.**

***Key words:*** *Fuel Cell Vehicle, FCV, Hydrogen Fuel Cell, JHFC, Telematics, Vehicle Homepage, Maintenance Garage*

## 1. Introduction

In 1994, DaimlerChrysler (referred to as 'DC' hereafter) unveiled the NECAR 1, the world's first fuel cell vehicle (FCV). Early fuel cells were so large that they took up the entire interior space of a van, but size reductions achieved in the latter half of the 1990s enabled installation under a vehicle's floor. This progress triggered FCV development around the world, and trials were subsequently conducted in California and nine European cities under government leadership.

In 2002, Japan's Ministry of Economy, Trade, and Industry initiated the Japan Hydrogen & Fuel Cell Demonstration (JHFC) Project (http://www.jhfc.jp/) with the initial participation of five automakers and eight companies specializing in hydrogen filling stations.

Against this backdrop, MMC started developing the MFCV using DC's newest fuel cell system. The MFCV was completed in the summer of 2003, and at the time of writing it is undergoing trials on public roads and playing a role in JHFC Project activities. This paper describes MMC's FCV development efforts.

(Further in formation appears on the MMC website at http://www.mitsubishi-motors.com/corporate/about_us/technology/environment/j/fcv.html)

## 2. FCV development at MMC

MMC started research on FCVs in 1998. Of the various hydrogen-supply methods that were being developed, MMC chose the then-promising methanol reformation method (a method whereby methanol, a liquid fuel, is reformed to produce hydrogen, which is supplied to the fuel cell) and developed an FCV in collaboration with Mitsubishi Heavy Industries, which was a leader in related technologies. This joint development helped to clarify the many FCV-related technical issues that needed to be addressed.

Due to the technical difficulty of equipping a vehicle with a methanol reformer, the global trend of FCV development subsequently shifted to employment of compressed hydrogen in high-pressure tanks carried in the vehicle. Hydrogen filling stations were set up for trials on public roads in a number of places around the world.

DC, MMC's alliance partner, has a wealth of experience in development of compressed hydrogen FCVs (The NECAR 1, NECAR 2, and F-Cell FCVs, etc. developed by DC all use compressed hydrogen). MMC adopted the technologies employed in the F-Cell (DC's newest FCV) in the MFCV. It is difficult to predict what method of hydrogen supply will prevail when FCVs reach full commercialization as it will depend greatly on future technological innovations and infrastructure policies. Various hydrogen producing methods including gasoline reformation and city-gas reformation are being examined (**Fig. 1**).

Various types of power system are compared hereafter in terms of power density (the generated power per unit mass) and effective energy density (the generated effective energy per unit mass) (**Fig. 2**).

The effective energy density of fuel cells has reached gasoline engine levels, enabling FCVs to have adequate per-fill distances for good mobility. However, the power density of fuel cells is still far that of gasoline engines. FCVs lack driveability owing to their concomitantly great weight.

Rechargeable batteries used as a power system for electric vehicles offer power density as high as that of gasoline engines thanks to recent improvements in the

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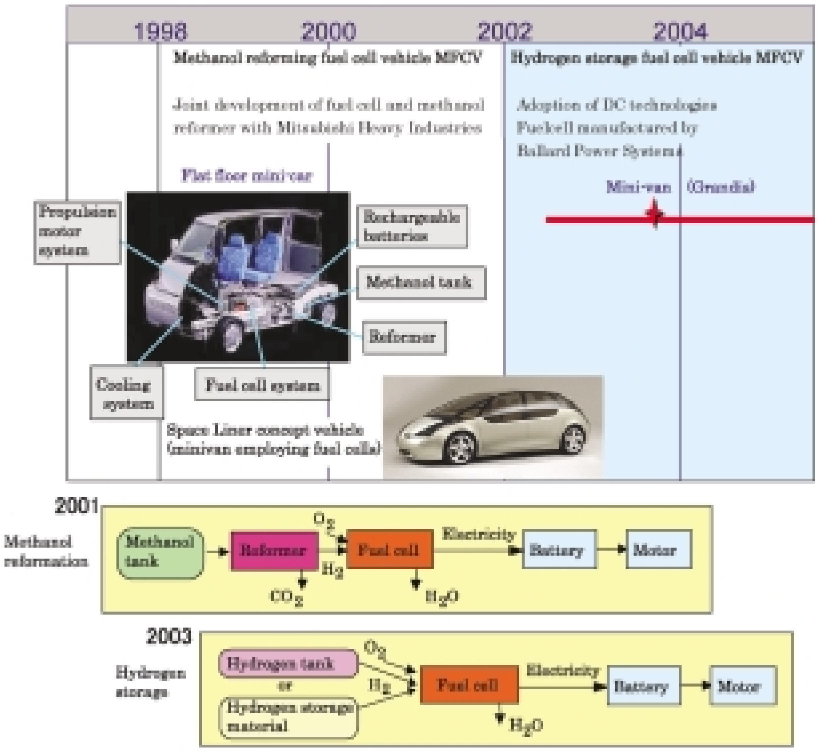


**Fig. 1 History of MMC's FCV research**

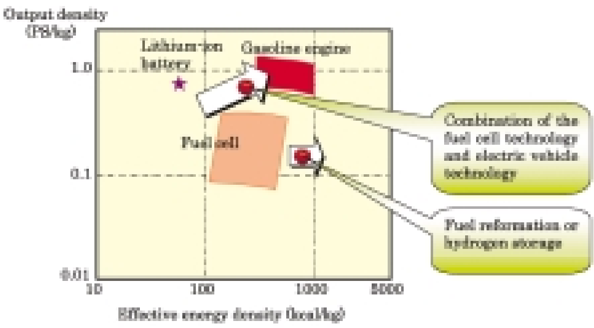


**Fig. 2 Output density and effective energy density of each power system**

performance of lithium-ion batteries. However, they are still inferior to gasoline engines in terms of effective energy density.

From these facts, it can be deduced that a hybrid electric vehicle using both fuel cells and high-performance rechargeable batteries such as lithium-ion batteries can provide mobility and driveability comparable with those of a gasoline-engine vehicle. This factor must be considered in any attempt to predict trends in FCV development.

Many automakers employ the compressed hydrogen supply method for their passenger FCVs and use a combination of polymer electrolyte fuel cells (PEFCs) and high-output rechargeable batteries (nickel metal hydride batteries or lithium-ion batteries) as their power system. Although the output of the fuel cell in an FCV of this kind is set to match the maximum output of the propulsion motor, the discussion above suggests that more efficient power system design will be possible if rechargeable batteries can in future be used to cover operating ranges requiring high power.

## 3. Alliance with DC in fuel cell development

Since 1991, DC has for environmental reasons been working on development of FCVs that use non-fossil-oil-based alternative fuels such as hydrogen and liquid hydrocarbon fuels like methanol. DC's development program has advanced to such a stage that commercialization in the near future is a realistic goal.

MMC started exchanging information concerning FCVs with DC in 2000 and began a detailed discussion with DC on the development of FCVs in 2002. To maximize the benefits of the DC-MMC alliance, the companies reached an agreement whereby MMC would use DC's F-Cell technologies in development of the MFCV and conduct fleet tests in Japan in collaboration with DC. Final assembly of the MFCV was performed in May 2003 at the DC facility in Nabern, Germany, and the MFCV's basic performance was then verified there. Test driving of the MFCV was started in August 2003 at MMC's test course in Okazaki, Japan. While this work was under way, numerous Japanese and German development personnel traveled back and forth between Nabern and Okazaki; the number of Nabern-Okazaki television conferences (these were held every week in the evening (Japan time)) reached 31 times; and the volume of data exchanged between the two companies reached 360 MB. The joint operation benefited from effective use of telecommunication technologies, but its success was ultimately attributable to the

**Fig. 3 F-Cell and members of MMC's MFCV development group (Nabern, Germany)**

**Table 1 MFCV major specifications**

| | | |
|---|---|---|
| Vehicle weight | | 2,000 kg |
| Seating capacity | | 5 people |
| Maximum vehicle speed | | 140 km/h |
| Per-fill distance | | 150 km |
| Fuel cell system | Type | PEFC (Ballard Power Systems) |
| | Output | 68 kW |
| Hydrogen tank | Storage method | Compressed hydrogen |
| | Filling pressure | 35 MPa |
| | Capacity | 117 L |
| Rechargeable battery | | Nickel metal hydride |
| Motor | Type | AC induction motor |
| | Maximum output | 65 kW |
| | Maximum torque | 210 Nm |

mutual understanding that developed between the development staff of the two companies (**Fig. 3**).

## 4. Overview of MFCV

### 4.1 Characteristics

The MFCV is based on the Mitsubishi Grandis, which underwent a complete model change in May 2003. The GRANDIS is a three-row-seating minivan (a type of vehicle that is growing in popularity around the world). By incorporating the characteristics of an FCV into a vehicle that can carry a large number of passengers, MMC is offering a new means of environment-friendly mobility.

The layout of the MFCV is presented in **Figs. 4** and **5**. The MFCV has front-wheel drive. A propulsion system in which an AC induction motor, a non-variable-ratio planetary reduction gear set, and a planetary gear differential mechanism are integrated into a single unit is located in the engine compartment. A power system including fuel cell stacks is compactly packaged under the floor, and hydrogen tanks are space-efficiently positioned under and inside the luggage area at the rear of the vehicle, enabling the FCV to have enough interior space for use as a three-row-seating minivan.

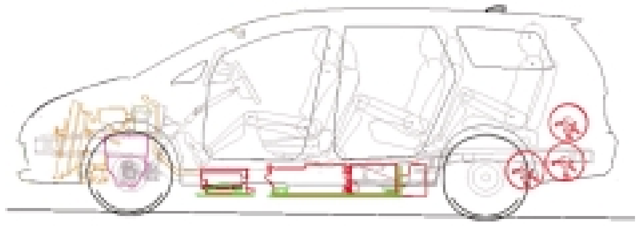

**Fig. 4 MFCV system layout (side view)**

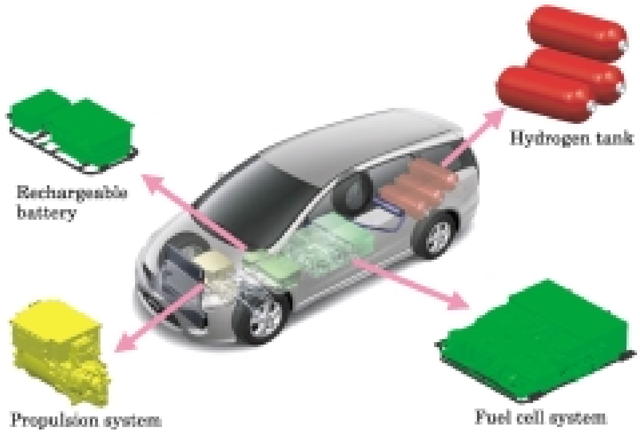


**Fig. 5 MFCV system layout (exploded view)**

### 4.2 Fuel cell system of MFCV

The MFCV is a hybrid electric vehicle using fuel cells supplied with compressed hydrogen. Its power system, which consists of fuel cells and rechargeable batteries, is mounted under the floor of the cabin. The fuel cells are PEFCs that were manufactured by Ballard Power Systems, Inc. and have a 68 kW output. The PEFCs consist of a fuel cell stack box, which generates electricity, and a system module that supplies fuel, air, and distilled water necessary for operation of the stack. The MFCV also carries nickel metal hydride batteries as rechargeable batteries. Three high-pressure hydrogen tanks, each of which has a 35 MPa filling pressure and a 39-liter capacity (117 liters in total) are located under and inside the luggage area at the rear of the vehicle. Each tank has a built-in solenoid cutoff valve and a built-in tank safety valve (melting type). The pressure of hydrogen from the tanks is reduced to 0.3 MPa in two steps by reducing valves before the hydrogen reaches the fuel cells.

### 4.3 Functions of instruments in MFCV

An external view of the meter cluster in the MFCV is presented in **Fig. 6**. The meter cluster looks similar to that of the GRANDIS, but it incorporates modifications for FCV use. A power meter, which indicates the state of the fuel cells, is located on the left of the speedometer, and a hydrogen level meter (this shows the level of remaining hydrogen) and a rechargeable battery level meter are located on the right of the speedometer. Coolant level warnings and other warnings are given by icon-type lights and by a liquid crystal display, which functions also as an odometer/tripmeter. This meter cluster design allows the driver to ascertain the state of the vehicle at a glance.

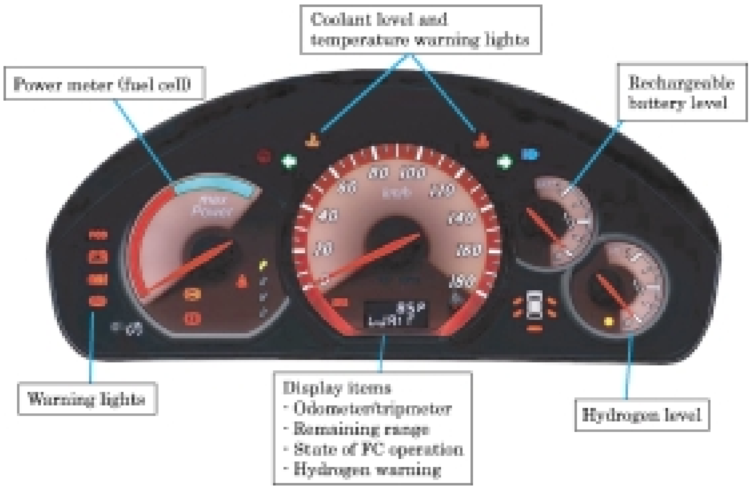


**Fig. 6 MFCV meter cluster**

### 4.4 Safety equipment in MFCV

Hydrogen has a wide combustible mixture range of 4 % to 75 %, and it can burn and explode when its concentration in air exceeds 4 % (the minimum concentration for ignition). To ensure safe use of hydrogen and safe use of the high voltages that exist in an electric vehicle, the MFCV has various items of safety equipment (**Fig. 7**). The overall level of safety for people inside the MFCV and for people outside the MFCV is comparable with that of a conventional vehicle.

(1) Measures against hydrogen leakage

The MFCV has eight hydrogen sensors: two inside the cabin, two inside the tank compartment, three in the stack module, and one in the system module. When a sensor detects hydrogen of a certain concentration in the air, it causes a warning to be issued to the driver and brings the system to an emergency shutdown.

(2) Measures for safe use of high-pressure hydrogen

The hydrogen tanks and related parts comply with all applicable provisions of Japan's High Pressure Gas Safety Law. In addition, the piping and the check valves, reducing valves, and all other valves can withstand pressure 1.5 times as high as the pressure to which they are normally subjected.

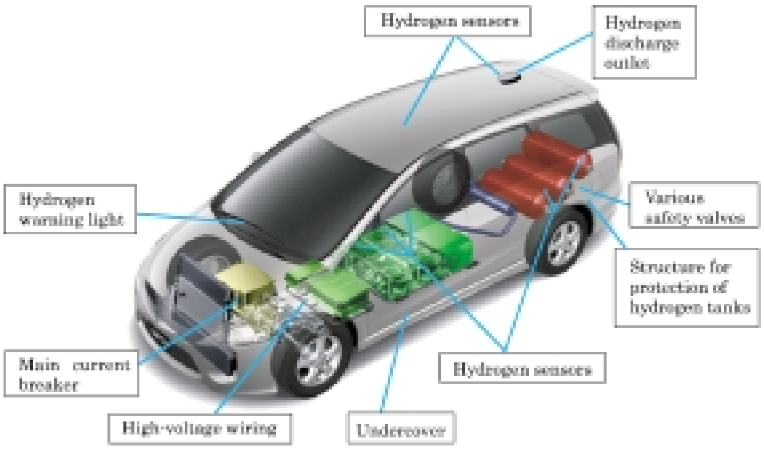


**Fig. 7 MFCV safety equipment**

(3) Crash safety and protection from stones

The MFCV has a crash switch that shuts down the system in the event of a collision at an acceleration rate of 98 $m/s^2$ or higher. An aluminum honeycomb undercover is fitted over the entire bottom surface of the vehicle to protect the fuel cell stacks and batteries from stones thrown up by the wheels.

(4) Measures for safe use of high voltages

If the insulation in a high-voltage circuit becomes defective and a reduction in insulation resistance is detected, the system alerts the driver and shuts itself down. Also, the high-voltage circuits have a monitoring function employing an interlock signal system. This function shuts off the power to the high-voltage circuits whenever any signal interruption (caused, for example, by disconnection of a socket) is detected.

## 5. MFCV fleet tests

### 5.1 Testing history

The MFCV has been entered in various tests and events in the Okazaki and Kanto areas since receiving ministerial approval in November 2003. Further, MMC is conducting trials with the MFCV at its present state of development using public roads and hydrogen filling stations in order to acquire basic data on performance, environmental characteristics, and safety. MMC will use these data to enhance its knowledge base for future commercialization of FCVs.

MMC began participating in the JHFC Project, Japan's first large-scale fuel cell testing project, with the MFCV in 2003. Participants in this project must each conduct a so-called 'free test run' covering 200 km, a so-called 'planned test run' on a predetermined route, and a so-called 'stationary test' each month and use the resulting data to demonstrate the energy efficiency and environmental benefits of FCVs. They are also required to take part in publicity campaigns.

MMC exhibited the MFCV as the core of its strategy for environmental preservation at the 2003 Tokyo Motor Show. MMC is also striving to promote its environment-friendly image by participating in green vehicle events and by providing the MFCV as a support vehicle for runners in marathons (**Fig. 8**).


**Fig. 8 MFCV as support vehicle in Osaka International Ladies Marathon (January 2004)**


**Fig. 9 FCV maintenance garage**

### 5.2 Vehicle Homepage

During the MFCV's trial runs, data are transmitted to a Vehicle Homepage (VHP) (http://www.mitsubishi-motors.com/corporate/about_us/technology/environment/j/fcv.html) through an on-time vehicle-to-center network that was developed using telematics technology (see **Fig. 9** in 'Evolution of Vehicles in the Age of Ubiquitous Networks' in this edition of the Mitsubishi Motors Technical Review). The main types of data available on the VHP are data on driving performance, fuel consumption, and other aspects of the vehicle's condition (these data are obtained through an in-vehicle network), camera images showing the driving environment, and reports from the onboard team concerning reliability and maintenance. These data are collected for in-house use, but selected portions are made publicly accessible.

### 5.3 FCV maintenance garage

As a company base for fleet tests carried out in the Kanto area, MMC has a maintenance garage at the premises of Mitsubishi Automotive Techno Service (MATS; located in the Shinagawa district of Tokyo) for inspection, and service of FCVs. MMC constructed this garage in October 2003 in collaboration with DaimlerChrysler Japan, which controls activities related to DC's FCV, the F-Cell.

The garage is equipped with various items of equipment to ensure hydrogen safety.

(1) Preventing static electricity: Antistatic touch panels for FCVs and workers are connected to a central ground and the floor of the garage has an antistatic coating.

(2) Preventing buildup of hydrogen: The garage is continuously ventilated through ducts. If a dangerous concentration of hydrogen is detected in the air, ventilatory volume is automatically increased, the FC system is automatically shut down, and power for all electrical equipment except explosion-proof emergency lighting and ventilation equipment is automatically turned off. Portable hydrogen sensors are used in other areas of the MATS premises to ensure the same level of operational safety as that in the garage.

## 6. Summary

Using the Mitsubishi GRANDIS, which was launched in May 2003, as a base vehicle, MMC developed the MFCV, a compressed hydrogen supply type FCV, in conjunction with DC and conducted fleet tests on it. Using its proprietary technologies for propulsion motors, rechargeable batteries, and other elements of FCVs, MMC will continue to pursue basic research on FCVs with a view to realizing their commercialization.

Eizo TABO

Noriaki KUZUOKA

Morihiro TAKADA

Hiroaki YOSHIDA

# Evaluation of CFD Tools Applied to Engine Coolant Flow Analysis

Toyoshige SHIBATA* Hideo MATSUI**
Masao TSUBOUCHI* Minoru KATSURADA**

## Abstract

**Many automobile manufactures now evaluate coolant flow in water jackets using computational fluid dynamics (CFD) technologies. Compared to conventional experimental methods, CFD methods provide clearer and more detailed data on flow velocities and pressure contours. In addition, automatic mesh generating tools now available help reduce the time taken for building meshes indispensable to this type of analysis. This paper evaluates some software tools for CFD analysis of engine coolant flow.**

***Keywords:*** *Engine Component, Computational Fluid Dynamics, Computer Aided Engineering, Simulation*

## 1. Introduction

To prevent damage and knock in vehicle engines, excessive thermal stress must be prevented by evenly cooling areas around combustion chambers. For this purpose, smooth flow of coolant must be ensured throughout the water jacket. Until recently, coolant flow in the water jacket was investigated experimentally, by making the water jacket visible through a transparent acrylic board window fitted in the engine to allow direct observation by the eye or video recording of coolant flow.

Along with developments in computer technology, computational fluid dynamics (CFD) technology has advanced rapidly in recent years and is now used in many fields including research on coolant flow in the water jacket. Use of the CFD method for coolant flow analysis, however, was initially considered impractical, as it took two or three months to build calculation meshes because of the complex structure of the water jacket.

Today, automatic mesh generating tools are being used increasingly widely in engine development with positive results and are able to solve this problem. This paper presents the results of test application of some automatic mesh generation tools to the CFD calculation of coolant flow, and compares the functional characteristics and features of these tools. The paper also discusses coolant flow items that can be evaluated by CFD analysis and the merits of applying CFD to these items.

## 2. Comparison of automatic mesh generating software and numerical calculation software packages

### 2.1 Objects of comparison

**Table 1** shows the three combinations of automatic mesh generating software packages and numerical calculation software packages (hereinafter referred to as “solvers”) used for three-dimensional (3D) CFD analyses of water jacket coolant flow in MMC, which are compared in this paper. A 3D calculation model was created simulating the water jacket included in the cylinder head and cylinder block of a 1.5-liter in-line four-cylinder engine (**Fig. 1**), and was used for the comparison. The coolant passage leading to the inlet of the water pump of the model was extended upstream to give an appropriate flow velocity distortion to the inlet. The calculating conditions are shown in **Table 2**.

**Table 1 Combinations of automatic mesh-generating software and solver**

| | Automatic mesh-generating software | Solver |
|---|---|---|
| Case 1 | SCRYU/Tetra*1 | SCRYU/Tetra*1 |
| Case 2 | HEXAR | STAR-CD |
| Case 3 | CATIA/CAE | STAR-CD |

*1: Automatic mesh-generating software and solver are provided as a set.

### 2.2 Comparison of automatic mesh-generating software packages

**Table 3** compares the calculation meshes created based on the 3D CAD data calculation model using the three different mesh-generating software packages. It also compares the characteristics and features of these software packages. Mesh generation time was the biggest concern in the past, but is now so short that it does not pose any problem in the case of SCRYU/Tetra and CATIA/CAE. The coolant holes in the thin cylinder head gasket and the small-diameter portion in the coolant passage require finer meshes, thus necessitating some manual operation including specification of

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** MMC Computer Research, Ltd.

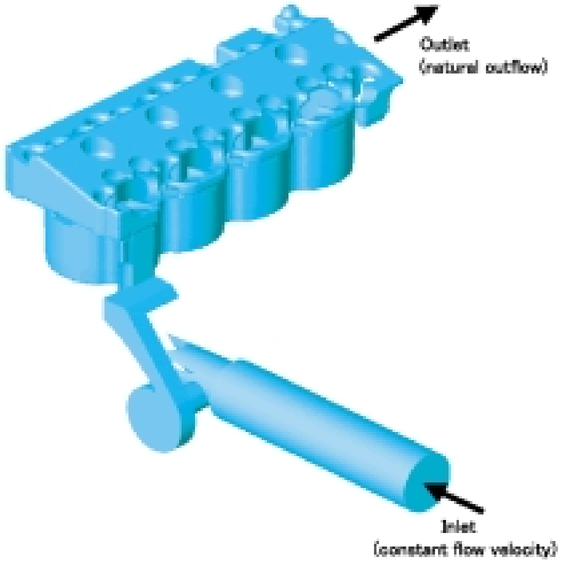



**Fig. 1 Calculation model**

**Table 2 Calculation conditions**

| | | | |
|---|---|---|---|
| Boundary conditions | Inlet | Flow velocity (flow rate) | 0.25 m/s ($4.28 \times 10^{-3}$ $m^3$/s) |
| | | Vortex scale | $1.00 \times 10^{-4}$ m |
| | Outlet | Natural outflow | |
| Properties | Water (20˚C) | Density | 998.2 kg/$m^3$ |
| | | Viscosity coefficient | $1.002 \times 10^{-3}$ kg/m·s |
| Others | Steady flow; incompressible | | |

the fine mesh areas. The required time indicated in the table is mainly accounted for by such manual operations, and the manual operation took an exceptionally long time in the case of HEXAR. The CATIA/CAE package took the shortest calculation time and the quality of the generated meshes was fine, but it has a functional problem of being incapable of generating boundary layer meshes on a wall surface; this makes CATIA/CAE inferior to the other two packages in terms of precision. The number of mesh elements that CATIA/CAE can generate is of the order of 1,670 thousand, which will make it incompatible with larger models.

### 2.3 Comparison of solvers

In the 3D CFD analysis of coolant flow in water jackets, the number of mesh elements often exceeds one million, and so requires several dozen hours for calculation. It is therefore important to reduce the calculation time in such calculations. **Table 4** compares the time required for calculation by two different solvers when applied to the meshes generated by the automatic mesh-generating software packages. **Table 5** compares the characteristics of the two solvers. Application of SCRYU/Tetra could significantly reduce the calculation time; it took about two-thirds of the time taken by STAR-CD when calculating a tetrahedron mesh generated by CATIA/CAE. Further, since this solver requires relatively little memory, it is compatible with calculation of a tetrahedron formed of approximately seven times as many mesh elements as those of a tetrahedron that can be calculated by STAR-CD. Although STAR-CD is well able to handle combustion and injection calculations, if such calculations are unnecessary, SCRYU/Tetra is useful for reducing the calculation time.

### 2.4 Comparison of calculation results

**Fig. 2** compares coolant flow velocity distortions on a horizontal plane in the cylinder head that are calculated using each of the three mesh-generating software and solver combinations shown in **Table 1**. In this figure, colors represent velocities and arrows represent flow directions. Although the diagrams are not identical due to differences in the mesh creating method and way of presentation between the software combinations, they all show similar results, implying that differences in the mesh and solver do not lead to large differences in the calculation result. The calculation model used in this study has a 4.5 mm-diameter coolant hole in the cylinder head. The flow rate of the coolant through this hole was calculated using each of the three software combinations and the results were compared. The comparison revealed that there was a difference of only several percent between the calculation results, showing that there are no remarkable differences between the outputs of the three software combinations also when local flow velocities and flow rates are concerned.

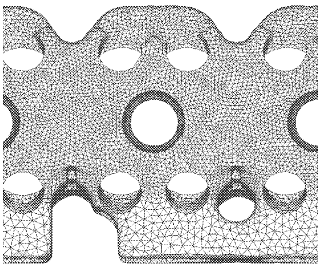
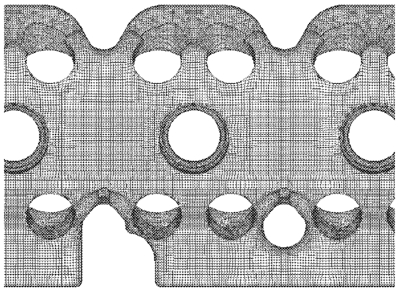
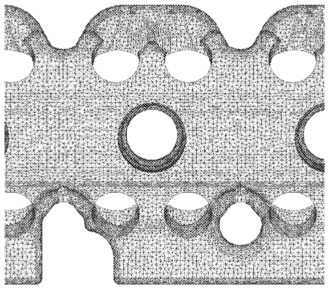
**Fig. 3** shows the pressure contours calculated by the three software combinations for the same plane in the cylinder head as in **Fig. 2**. In these diagrams, the ratios of pressure drop are represented using different colors by contrast with the pressure loss in the whole water jacket. As the figure shows, the ratios of local pressure drop calculated by the three software combinations are not significantly different.

## 3. Water jacket coolant flow analysis by CFD – applicable items and merits

### 3.1 Velocity distortions

For even and sufficient cooling of areas around the combustion chamber, the coolant must flow smoothly with minimum flow rate differences throughout the passage from the inlet to the outlet. Since heat transfer at a given point increases with higher flow velocity, faster coolant flow will cause a greater temperature reduction. In conventional experimental methods used for coolant flow analysis, fine particles are mixed in the coolant and their movements are directly observed by the eye or video recorded through a transparent acrylic board window attached to a part cut in the cylinder head and cylinder block. This method may not provide accurate results because the visible area is limited and cutting a part of the cylinder head and cylinder block may change the coolant flow. With the CFD method, it is possible to perform 3D numerical calculation on a 3D CAD model of an intact water jacket, and also to select a desired location and plane for visual display of the flow velocity

**Table 3 Comparison of automatic mesh-generating software packages**

| | | SCRYU/Tetra | HEXAR | CATIA/CAE |
|---|---|---|---|---|
| Generated mesh | Surface view |  |  |  |
| | Number of elements | 1,898,313 | 3,407,482*1 | 1,674,276 |
| | Number of nodes | 499,874 | 3,773,408*1 | 384,789 |
| | Time required*2 | 2 hours | 56 hours*3 | 1.3 hours |
| Function | Automatic tetrahedral meshing | Good | Poor | Good |
| | Automatic hexahedral meshing | Poor | Good | Poor |
| | Boundary layer generation | Good | Good | Poor |
| | Maximum number of elements*4 | Good: 8 million | Good: 5 million or more | Acceptable: 1,670 thousand |
| | Mesh density setting | Good:<br>Zones are specified and each zone is subdivided into target density. | Acceptable:<br>Division is made into zones according to mesh size, then zones are connected together. Requires a long time. | Good:<br>Necessary parameters including mesh size are specified. |
| | Mesh quality*5 | Good | Good for zones with identical elements;<br>problem with mesh size ratio at non-continuous surface*6 | Excellent |
| | Manual element adjustment | Required | Required | Required |
| | Others | | | Compatible with 3D CAD solid data without need for additional processing |

*1: The numbers are larger than those for the others because of finer meshing especially around the cylinder head gasket holes.
*2: Time required for calculation using MMC's computer.
*3: May be about 20 hours assuming an element number equivalent to that of the other software packages.
*4: When using a computer with 2 GB of memory.
*5: Calculation convergence and quality are better when element involves smaller distortions and its shape is closer to a cube or regular tetrahedron.
*6: A surface joining two zones with different mesh size; has nodes of both zones, which do not agree with each other.

**Table 4 Comparison of calculation time of solvers**

| Solver | SCRYU/Tetra | STAR-CD | |
|---|---|---|---|
| Automatic mesh-generating software | SCRYU/Tetra | HEXAR | CATIA/CAE |
| Calculation time*1 | 21 hours | 435 hours*2 | 33 hours |
| Calculation iterations | 280 times | 5,795 times | 309 times |
| Necessary memory size | 360 MB | 1,826 MB | 1,450 MB |

*1: Time required for calculation using MMC's computer.
*2: May be about 48 hours assuming an element number equivalent to that of the other software packages.

distortions as shown in **Fig. 2**, allowing a more detailed evaluation and study of the results.

### 3.2 Pressure contours

Ideally, the pressure loss in the water jacket should be kept to a minimum. As with velocity distortions, the CFD method, which enables the pressure at a desired location and plane to be observed easily, is effective for evaluating the pressure contour (**Fig. 3**). The authors confirmed in this research that, with a given flow rate of coolant circulating in the water jacket, the absolute

**Table 5 Comparison of performance and features of solvers**

| Solver | SCRYU/Tetra | STAR-CD |
|---|---|---|
| Element type | Tetrahedron, triangular prism, quadrangular pyramid, hexahedron | Tetrahedron, triangular prism, quadrangular pyramid, hexahedron |
| Maximum number of elements (tetrahedron)*1 | 13 million | 1.95 million |
| Maximum number of elements (hexahedron)*1 | – | 4.5 million |
| Physical quantity calculation point | Node | Element |
| Completely non-continuous joints*2 | Yes | Yes |
| Moving mesh | Yes | Yes |
| Application | • Suitable for analysis of relatively simple phenomena.<br>• Can be used for complex shapes. | • Compatible with high-precision analysis.<br>• Can be applied to spray and combustion physical models and various turbulent models. Compatible with analysis of complex phenomena. |

*1: When using a computer with 2 GB of memory.
*2: A joint between zones with different meshes sizes; nodes of both zones do not agree with each other.

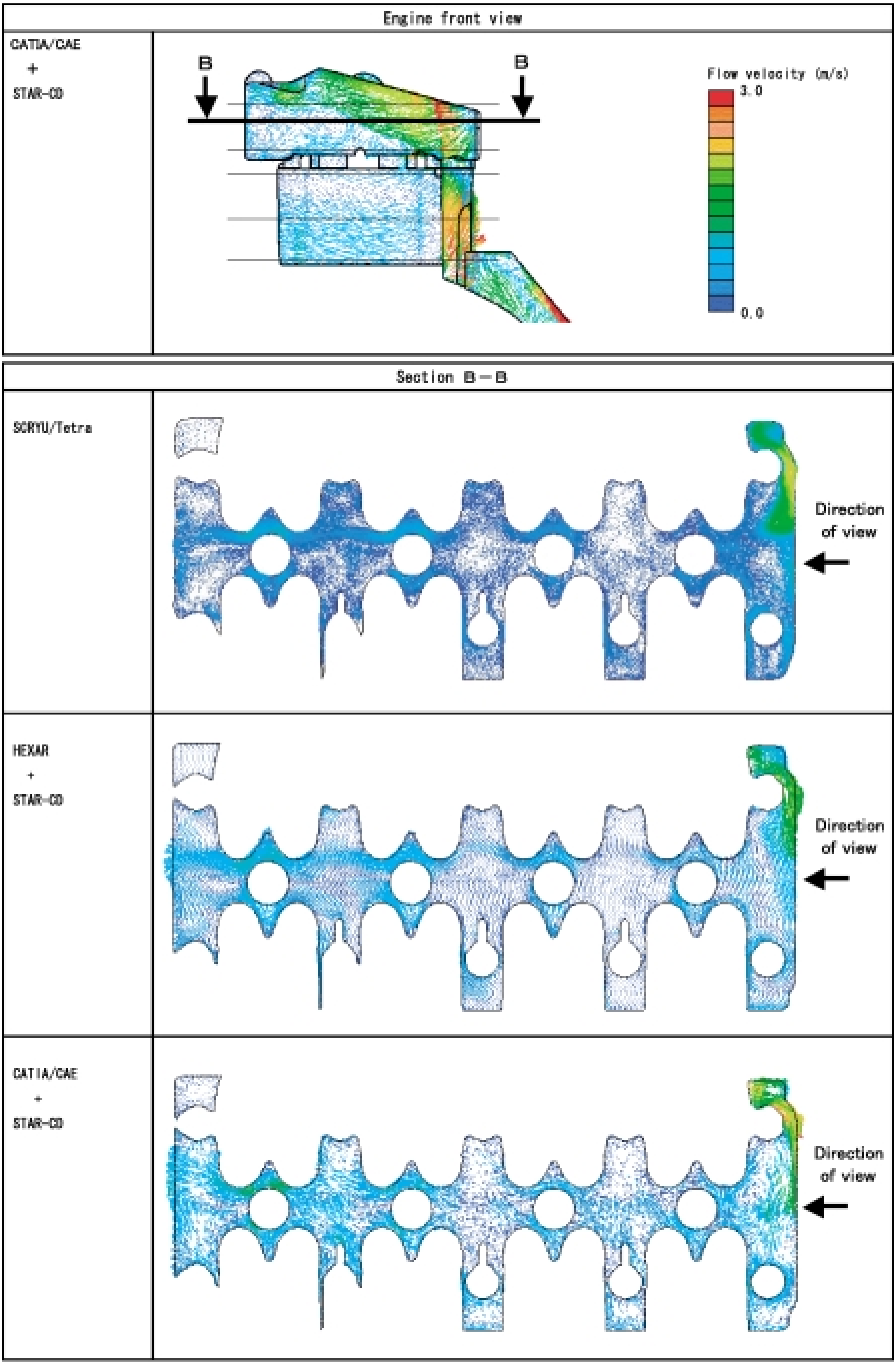



**Fig. 2 Comparison of velocity distortions**

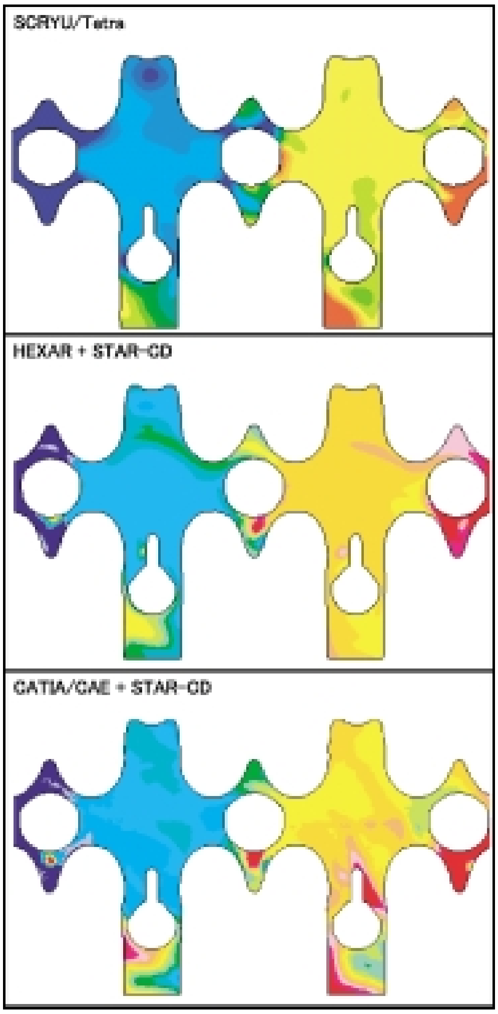



**Fig. 3 Comparison of pressure contours**

pressure value at each local point was not always the same between the results derived from calculations using different meshes and solvers. However, as mentioned in section 2.4 above, the pressure reduction ratios are almost identical between these calculation results, indicating that CFD analysis is useful for identifying areas that involve large pressure losses and for finding ways for reducing pressure losses.

### 3.3 Heat transfer coefficient

If the flow velocities of coolant inside the water jacket are determined using CFD, it is possible to determine the heat transfer coefficient for the wall surfaces at different locations of the water jacket. If a structural analysis is conducted using these thermal conductivity data, the analysis results will provide temperature predictions for different locations of the cylinder block and cylinder head that will result from coolant flow. However, CFD has rarely been used in this field due to the long analysis time required and lack of accuracy in predicting the amount of heat transferred from the combustion chamber.

## 4. Conclusion

Automatic mesh-generating software packages now available enable CFD analyses to be used to evaluate coolant flow in the water jacket within a practically short time. CFD is an effective development tool that yields more data than conventional experimental methods. We will strive to broaden its application not only in the field of coolant flow analysis but also in temperature and stress predictions by combining it with structural analysis techniques.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# Development of Occupant Classification System for Advanced Airbag Requirements

Shigeyuki NOZUMI*


## Abstract

**United States Federal Motor Vehicle Safety Standard (FMVSS) No. 208, which specifies performance requirements for the occupant crash protection, was recently upgraded to require every passenger vehicle to be equipped with an automatic airbag suppression system for protection of children on the front passenger seat. (The revised standard applies to vehicles produced from the beginning of September 2003.) Mitsubishi Motors Corporation (MMC) thus developed an occupant classification system (OCS) that accurately determines the need for airbag suppression in accordance with the weight on the front passenger seat. The new OCS not only complies with the revised standard but also provides a high level of practical usability in diverse environments.**


***Key words:*** *Safety, Occupant Protection, Occupant Classification, Advanced Airbag*

## 1. Introduction

Automobile manufactures face increasing legal requirements and customer demand for measures to protect vehicle occupants in collisions. Since the mid-1990s, FMVSS No. 208 (an instrument of United States legislation) has defined requirements for occupant protection by means of airbags for drivers and front passengers. In May 2000, FMVSS No. 208 was upgraded to additionally include requirements (described in this paper as 'advanced airbag requirements') for measures to protect children and small adults on front passenger seats.

This paper gives an overview of an OCS that MMC developed for compliance with the advanced airbag requirements.

## 2. Overview of legal requirements and advanced airbag systems

With the advanced airbag requirements, the pre-existing crash-test requirements for an average-size adult sitting on the front passenger seat are supplemented by crash-test requirements for a small adult sitting on the front passenger seat and by out-of-position (OOP) test requirements for a child or small adult who is sitting out of position at the time of a collision (**Fig. 1**).

The OOP test requirements prescribe specific conditions for both the driver seat and the passenger seat. For protection of a child sitting out of position on the passenger seat, an automaker may employ either of two options: (a) Automatic suppression feature or (b) Low-risk deployment that does not completely disable the airbag but ensures that the airbag deploys in a way that minimizes the risk of airbag-inflicted injuries.

Accordingly, the automobile manufacture needs to introduce either an airbag system that permits control of the deployment force or an advanced airbag system that has occupant-classification capability for the front passenger seat (**Fig. 3**). Current airbag technologies are not sufficiently advanced to satisfy all requirements for low-risk deployment. An airbag suppression system is thus considered the more practical option. Such a system must have an occupant-classification function that enables it to determine the size classification of the occupant from the occupant's weight (**Fig. 2**).

## 3. MMC's OCS

### 3.1 Construction and functions

The OCS consists of a seat; occupant classification sensors (incorporated into the seat); an OCS electronic control unit (OCS ECU) (also incorporated into the seat); and a seatbelt (**Fig. 3**). The flow of OCS operation is shown in **Fig. 4**.

(1) Occupant classification sensors

The occupant classification sensors each take the form of a unit that is located under one of the passenger seat rails (one sensor under the left-hand seat rail; one sensor under the right-hand seat rail). Each sensor receives loading inputs from the seat at two points (front and rear), giving a total of four input points. A built-in strain gauge for each input point (there are four strain gauges in total) produces signals corresponding to the loading and feeds the signals, which represent data on the weight of the seat occupant, to the OCS ECU.

(2) OCS ECU

The OCS ECU determines the size classification of the occupant using the data from the OCS sensors and feeds the resulting data to the airbag ECU. In accordance with this information, the airbag ECU enables or disables the passenger airbag. If the airbag ECU dis-

* Basic Chassis & Body Development Department, Research & Development Office

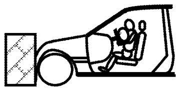
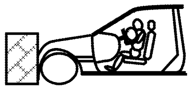
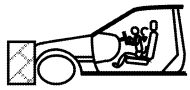
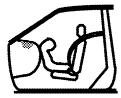
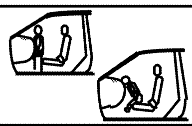
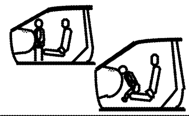
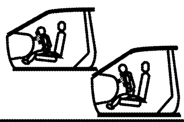
| Item | | Occupant | Conventional airbag 1996 onward | Advanced airbag 2003 onward | | |
|---|---|---|---|---|---|---|
| | | | | | Seatbelt | |
| Crash test | Driver and passenger | Average-size adult (AM50 %) |  |  | Fastened | Unfastened |
| Crash test | Driver and passenger | Small adult (AF5 %) | ―――― |  | Fastened | Unfastened |
| | | | | | Option | |
| Out-of-position test | Passenger | Child (Infant, 12 months) | ―――― |  | Automatic airbag suppression | Low-risk deployment |
| Out-of-position test | Passenger | Child (3 years, weight 13.4 – 18 kg) | ―――― |  | Automatic airbag suppression | Low-risk deployment |
| Out-of-position test | Passenger | Child (6 years, weight 21 – 25.6 kg) | ―――― |  | Automatic airbag suppression | Low-risk deployment |
| Out-of-position test | Driver | Small adult (AF5 %, weight 46.7 – 51.25 kg) | ―――― |  | Automatic airbag suppression | Low-risk deployment |

**Fig. 1 Overview of advanced airbag requirements**

ables the passenger airbag, it also turns on the PASSENGER AIRBAG OFF indicator (**Fig. 4**).

(3) Seat and seatbelt

To prevent the sensors from misinterpreting the pressure caused by seatbelt tension exerted on the seat when a child seat is fitted, the seatbelt anchor points are positioned above the OCS sensors (**Fig. 5**).

### 3.2 Practical usability

The OCS not only complies with legal requirements but also provides a high level of practical usability; it gives consistent size-classification performance regardless of variables in the operating environment.

(1) Sensitivity to vehicle's seat mountings

Thanks to the OCS's arm-type sensing arrangement and to high seat rigidity and high seat-installation precision, the OCS gives consistent size-classification performance regardless of inconsistency in the locations of the vehicle's seat-mounting points.

(2) Sensitivity to temperature changes

The OCS has a heat-conducting construction that prevents it from being susceptible to temperature changes. It gives consistent size-classification performance even when subjected to drastic changes in ambient temperature.

(3) Sensitivity to electrical interference

The OCS maintains consistent size-classification performance even in an electrically influenced environment thanks to an optimal filter circuit and to digital communication between the sensors and the ECU.

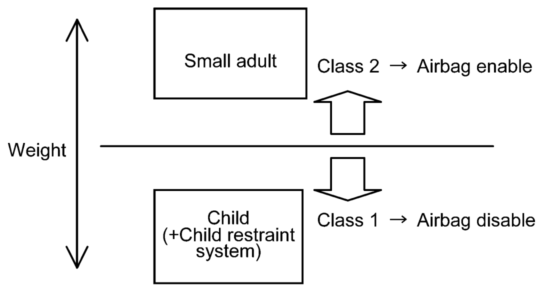



**Fig. 2 Body size class identification for children and small adults**

(4) Performance in actual driving conditions

The OCS uses a data-processing algorithm that mitigates the influence of momentary changes in loading, so it gives consistent size-classification performance in actual driving conditions.

(5) Durability

Endurance road tests proved that rigidity in the joints between the seat and sensors is high enough to ensure accurate size-classification performance for a long time.

(6) Serviceability

The connections of the OCS to the vehicle are rigid enough to enable the OCS to continue giving correct size-classification performance after a low-speed collision without having parts replaced.

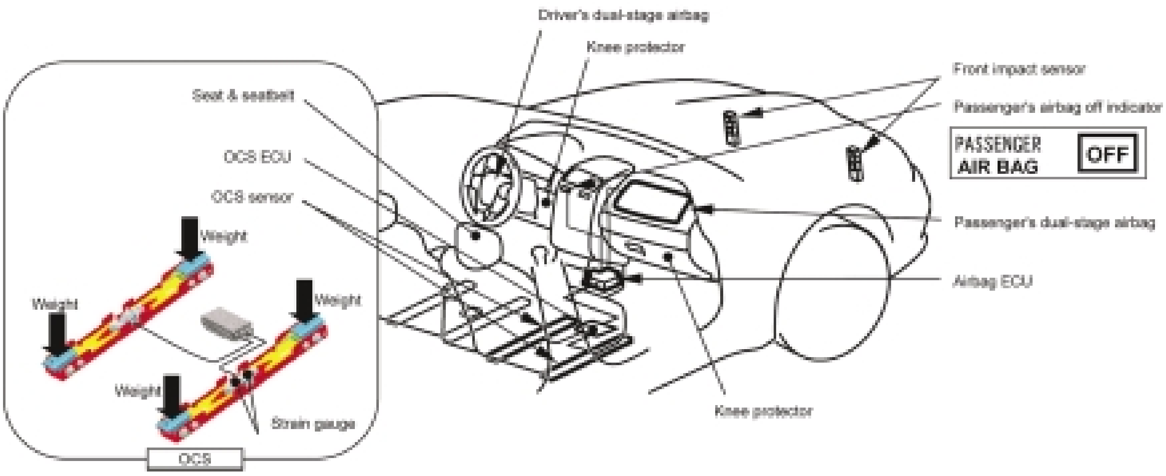



**Fig. 3　Advanced airbag system configuration**

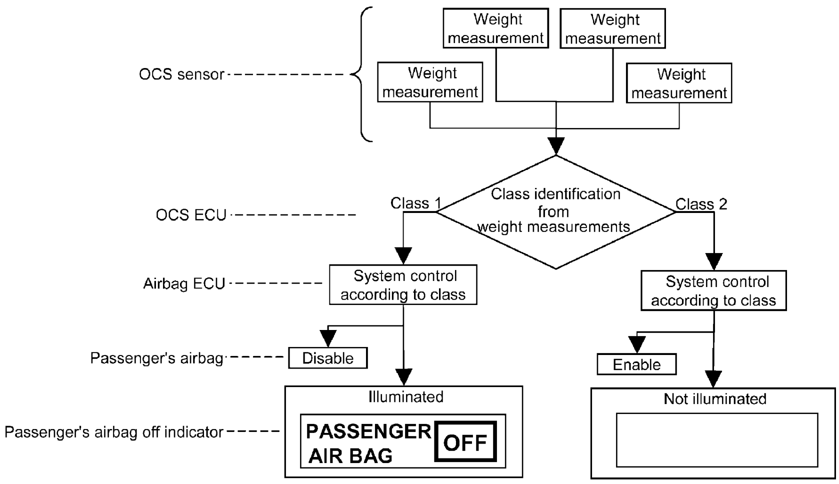



**Fig. 4　Advanced airbag system control flow**

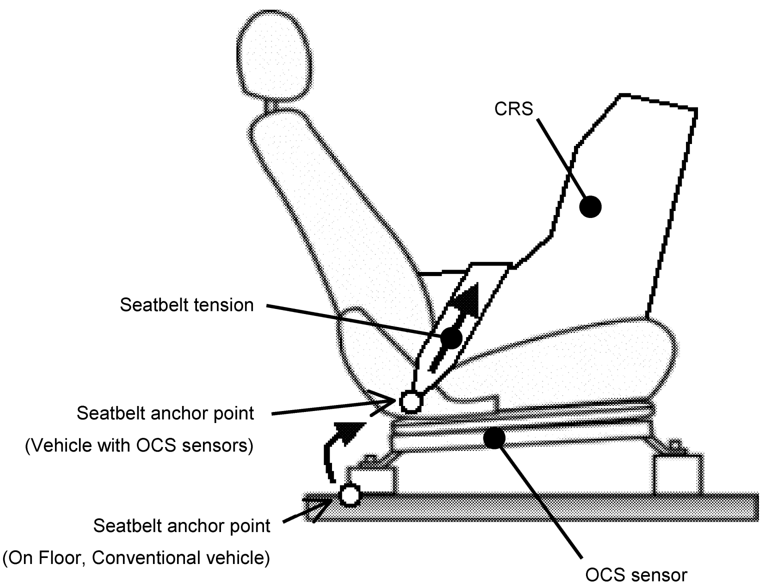



**Fig. 5　Structure of seat with OCS sensors**

### 3.3　Production quality

After the sensors and seat are installed, the OCS is zeroed and its sensor accuracy is checked. Data resulting from the pre-shipment inspection of each vehicle's OCS are properly managed to ensure traceability (**Fig. 6**).

## 4. Summary

The OCS is a new product made possible partly by close cooperation between design and evaluation staff and production staff from the early development stages and partly by the new technologies and quality-management arrangements described in this report. It is used in Mitsubishi GALANT vehicles produced in North America. In light of its significance as a means of improving occupant protection, the OCS will be further examined and

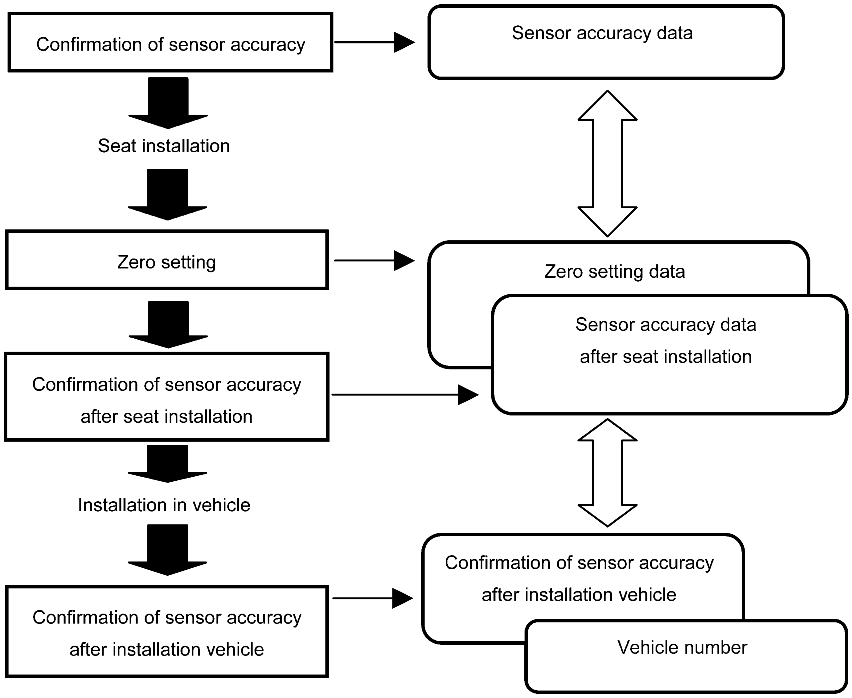



**Fig. 6 Inspection flow and traceability**

refined in pursuit of even better performance.

In closing, the author wishes to express sincere appreciation to Takata Corporation and to other personnel inside and outside MMC who assisted in development of the OCS.

Shigeyuki NOZUMI

# Development of Energy-Saving Air-Conditioning System for New COLT

Kenji AYA* Kazuo YANAGIMOTO**
Masaru KADOI*** Junichi MUROZONO**

**Abstract**

**Mitsubishi Motors has developed a new energy-saving air-conditioning system for compact cars. This innovative system incorporates a high-efficiency scroll compressor, which is controlled automatically according to ambient temperature, the driver's selection of fresh-air/recirculation mode, and solar radiation, and is highly effective in reducing power consumption. It saves energy and fuel by improving the refrigeration-cycle efficiency (through the use of high-efficiency component parts) and by preventing excessive cooling. Bench tests showed a 10 % reduction in annual fuel consumption with the newly developed air-conditioning system activated. This paper describes the system's specifications and the technologies with which the abovementioned improvements were achieved.**

***Key words:*** *Passenger Car, Air-Conditioning, Control, Energy, Efficiency, Energy-Saving*

## 1. Introduction

Demand for greater occupant comfort in recent years has made air-conditioning indispensable in all automobiles. Meanwhile, issues pertaining to environmental protection (notably prevention of global warming) have risen high on the global agenda, leading to stricter regulations on emissions of greenhouse gases such as carbon dioxide ($CO_2$) and on emissions of toxic pollutants such as nitrogen oxides ($NO_x$) and hydrocarbons (HC). Higher fuel efficiency in an automobile is vital for lower exhaust emissions. Minimizing the air-conditioning system's energy consumption is an important means of achieving higher fuel efficiency.

Compact cars are increasingly popular in Japan, so demand for further-improved fuel efficiency in compact cars is also growing rapidly. The new energy-saving air-conditioning system presented in this paper is a response to this demand. Achieved by means of improved component efficiency and optimized system control, it simultaneously meets the need for cabin comfort and the need for superior fuel efficiency.

The new air-conditioning system is used in the new Mitsubishi COLT. The following sections of this paper describe the system's new technologies, its energy-saving control arrangement, and its fuel-efficiency benefits.

## 2. Energy-saving process

**Fig. 1** shows the components of the new air-conditioning system and **Fig. 2** the process by which the system achieves energy savings. The new technologies employed for fuel-efficiency improvement are as follows:

(1) High-efficiency air-conditioner compressor, air-conditioner unit, and condenser;
(2) Energy-saving control arrangement including coordinated control of air-conditioning system and engine;
(3) Electronic control units (ECUs) for air-conditioner control and meter-cluster control integrated into a single unit.

## 3. High-efficiency components

### 3.1 Air-conditioner compressor

**Fig. 3** shows an external view of the newly developed scroll compressor, and **Fig. 4** shows a cross-sectional view. The scroll profile, which constitutes the heart of the compressor, was newly designed[1] for a higher refrigeration-cycle coefficient of performance (COP) (**Fig. 5**).

### 3.2 Air-conditioner unit

Computational fluid dynamics (CFD) simulation techniques (**Fig. 6**) were employed in the development of the air-conditioner unit from the basic design stage to optimize the airflow inside the air-conditioner unit and, in turn, minimize unwanted reheating (temperature increases caused inside the unit by heat released from the heater core), which detracts from cooling performance. The heat-release characteristics of the unit were further improved by the employment of a high-efficiency evaporator (**Fig. 7**).

* A&B Vehicle Design Team, Research & Development Office
** A&B Powertrain Team, Research & Development Office
*** Basic Chassis & Body Development Department, Research & Development Office

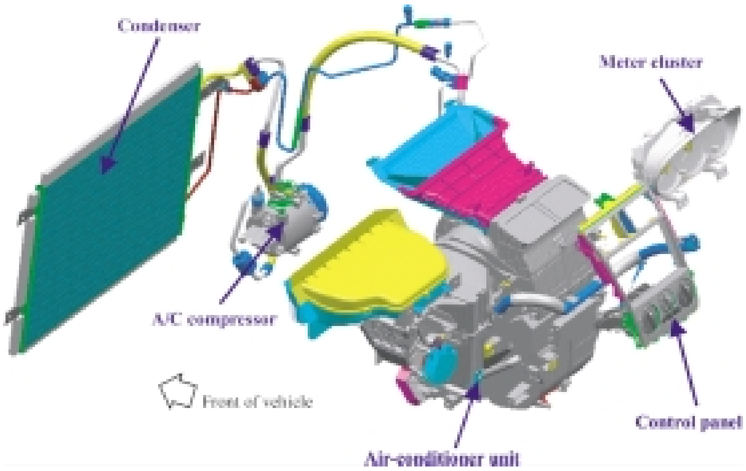



**Fig. 1 System components**

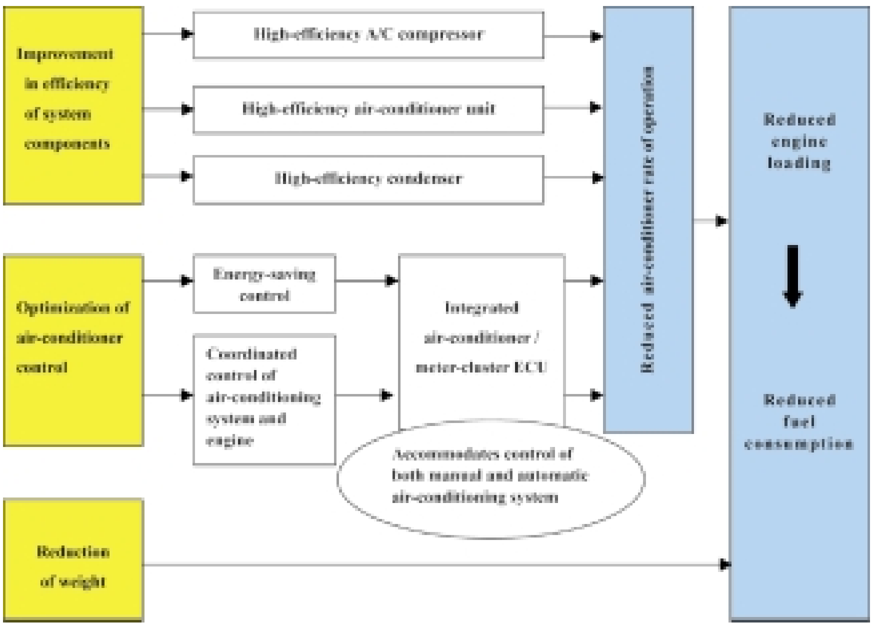



**Fig. 2 Energy-saving process**

### 3.3 Condenser

The condenser’s heat-release performance was improved by employment of a thinner core and narrower tubes (these effectively reduce airflow resistance), by reduction of the fin pitch, and by adoption of tubes with inner fins (**Fig. 8**).

## 4. Integration of air-conditioner and meter-cluster ECUs into single unit

The control circuits for the air-conditioning system and the control circuits for the meter cluster were integrated into a single ECU circuit board located in the meter cluster. This arrangement not only gives manual air-conditioning systems a level of controllability comparable with that of automatic systems but also makes the control circuits simpler and yields concomitant power savings (**Fig. 9**).

## 5. Air-conditioner control

### 5.1 Energy-saving control

Energy-saving control of an air-conditioning system requires a microcomputer that actually implements control operations and a means of providing the microcomputer with information about conditions inside and outside the vehicle. With the new COLT, the abovementioned integrated air-conditioner/meter-cluster ECU and a Controller Area Network (CAN) bus system is used in all model variants, making energy saving control possible not only in variants with an automatic air-conditioning system but also in variants with a manual air-conditioning system. Block diagrams of the automatic and manual air-conditioning systems are shown in **Fig. 10**.

The following is a brief description of the energy-saving control employed in the new COLT, taking the manual air-conditioning system as an example.

**Fig. 3 External view of new scroll compressor**

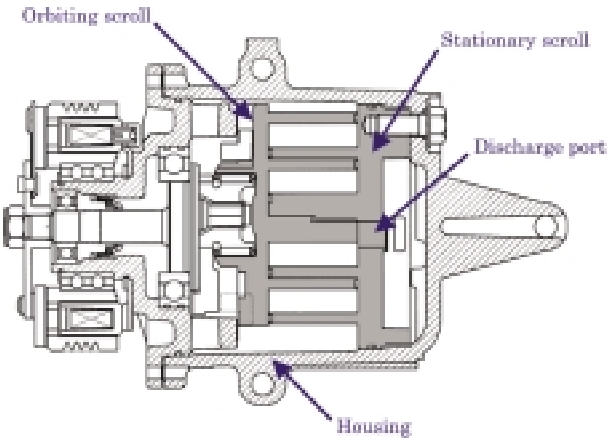



**Fig. 4 Cross-sectional view of new scroll compressor**

(1) Compressor energy-saving control

This control reduces the rate of compressor operation when demand for cabin cooling is low by varying the evaporator-airflow temperature at which the compressor is turned off (**Fig. 11**). It uses the following types of information:

- Ambient temperature (indicated by sensors)
- User's selection of fresh-air/recirculation mode (indicated by the position of the mode switch)
- Day/night (indicated by the position of the light switch)

(2) Automatic fresh-air/recirculation switching control

When demand for cabin cooling is high, running the air-conditioner in the recirculation mode yields a better cooling effect than running it in the fresh-air mode. Consequently, the system in the new COLT has a function that automatically switches from the fresh-air mode to recirculation mode in accordance with the ambient temperature. Mode selections made manually by the user over-ride this function.

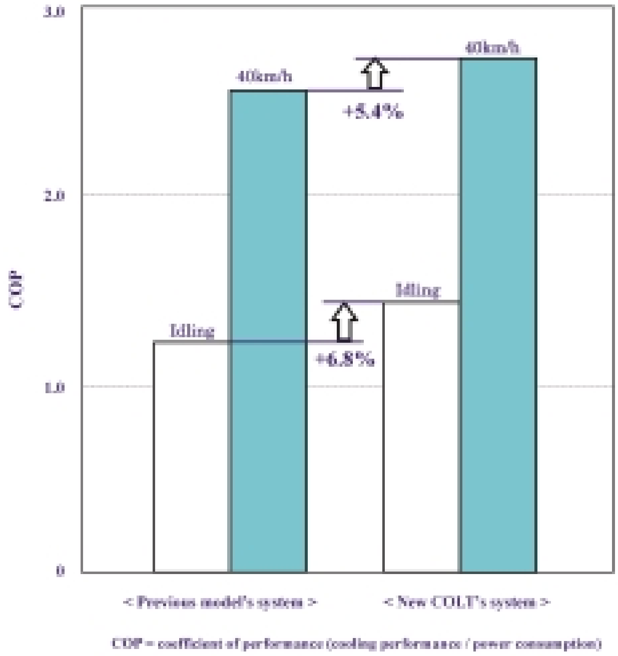



**Fig. 5 Benefits of improved air-conditioner compressor**

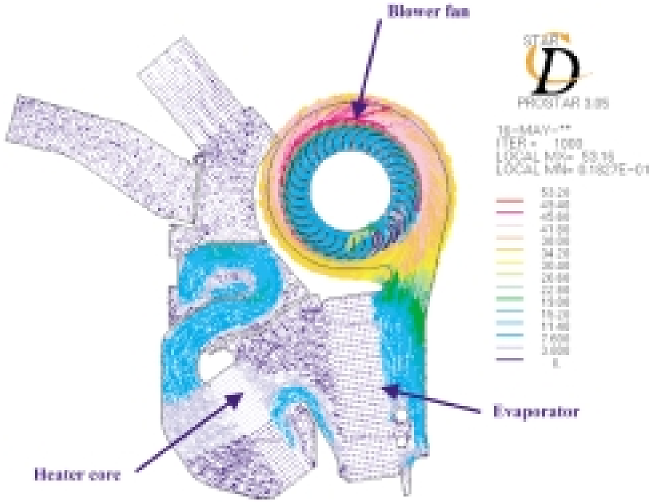



**Fig. 6 CFD simulation**

### 5.2 Coordinated control of air-conditioning system and engine

One of the main goals in the development of the energy-saving air-conditioning system was optimally coordinated operation of the air-conditioner system and its power source, the engine. In the new COLT, this goal was achieved using the CAN bus system. The following paragraphs describe major aspects of the coordinated control effected with the manual air-conditioning system.

(1) Engine idle up control

When a vehicle is stationary, the engine's idling speed is typically increased to ensure adequate cabin-cooling performance. If only slight cooling is required, however, the air-conditioning system can be powered

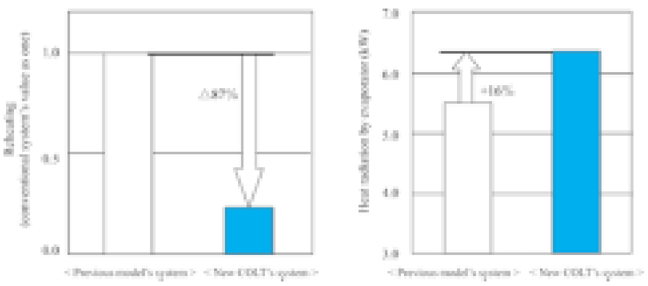



**Fig. 7 Benefits of improved air-conditioner unit**

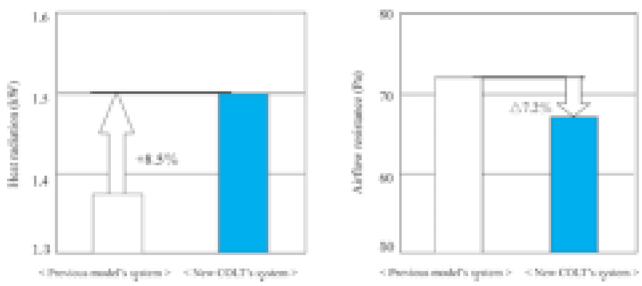



**Fig. 8 Benefits of improved condenser**

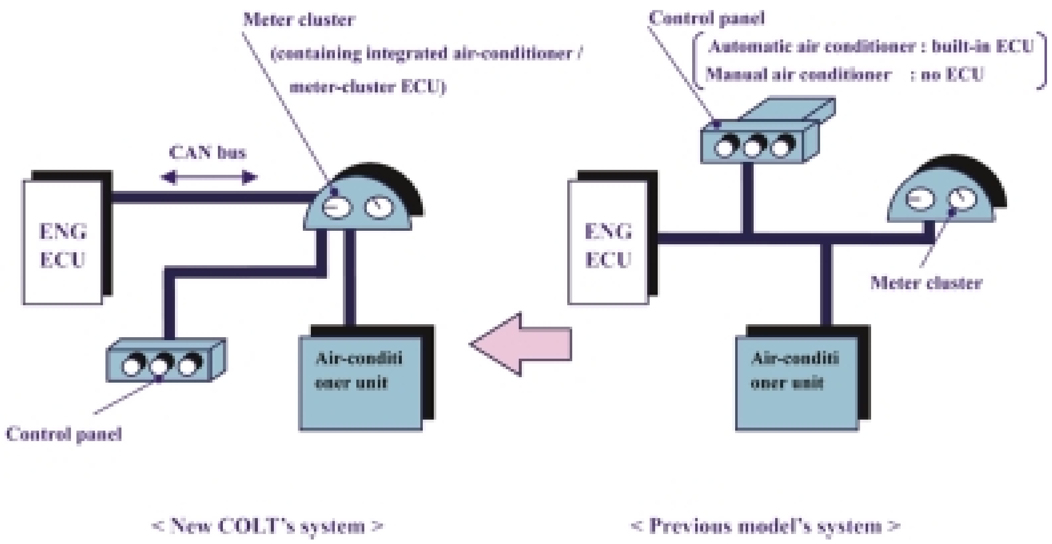



**Fig. 9 Integration of air-conditioner and meter-cluster ECUs into single unit**

adequately with the engine running at its standard idling speed. Consequently, there is scope for energy conservation.

In the new COLT, the air-conditioner/meter-cluster ECU estimates the required level of cooling performance and uses it to determine the appropriate idling speed for the engine. The engine ECU receives the resulting information via the CAN bus. As a result, the engine's idling speed is increased only as much as necessary. This process allows energy to be conserved.

(2) Cooling fan load control

When the new COLT is moving slowly or stationary, the electric-motor-driven cooling fan on the condenser is kept turning to improve system efficiency for adequate cooling performance. Like the engine's idling speed, the rotation speed of the cooling fan is varied in accordance with required level of cooling performance.

The air-conditioner/meter-cluster ECU calculates the appropriate cooling-fan speed based partly on the estimated cooling requirement and partly on vehicle-speed data that it receives through the CAN bus, and it transmits the calculated speed value to the engine ECU. The engine ECU compares this speed value with the speed value necessary for engine cooling (calculated from the engine coolant temperature) and causes the cooling fan to run at the higher of the two speeds. With fan operation optimized in this way, power consumption is reduced.

(3) Compressor-torque predictive control

An air-conditioner compressor is typically driven by the engine, so the engine's output must be controlled in a way that takes into account the power consumed by the compressor. However, the amount of power consumed by the compressor is difficult to predict with accuracy because it varies greatly in accordance with the vehicle's and air-conditioning system's operating conditions. To prevent the engine speed from decreasing due to compressor operation, the engine ECU predicts the torque required to drive the compressor and enables the resulting value to be used in control of the engine output.

The air-conditioner/meter-cluster ECU in the new COLT receives various vehicle-related data through the CAN bus system and is thus able to predict the compressor's torque requirement accurately for transmission to the engine ECU. The air-conditioner/meter-cluster ECU uses the following data:

- Refrigerant pressure (indicated by sensors)
- Engine speed (indicated by data obtained via the CAN bus)

Using the resulting data, the engine ECU effects optimal control over the engine output, thereby reduc-

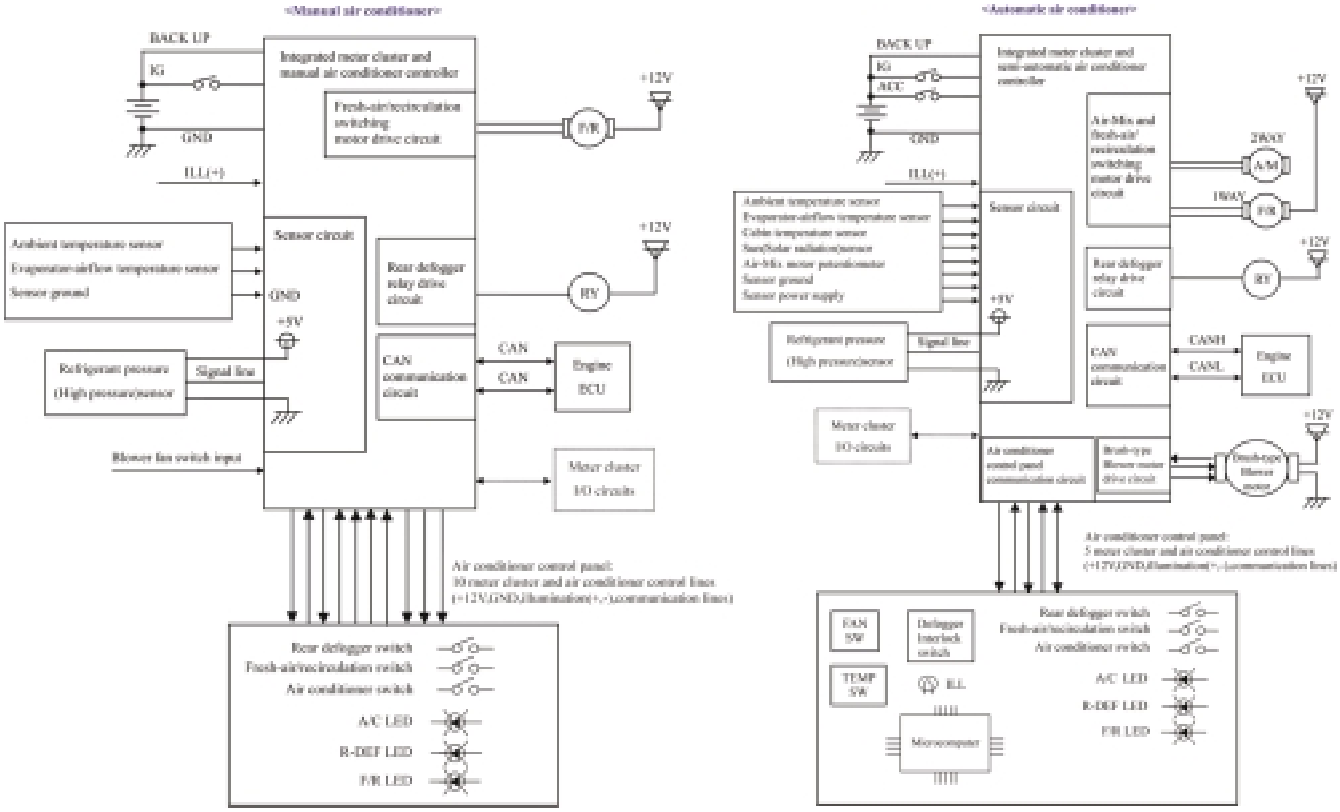



Fig. 10 System block diagram

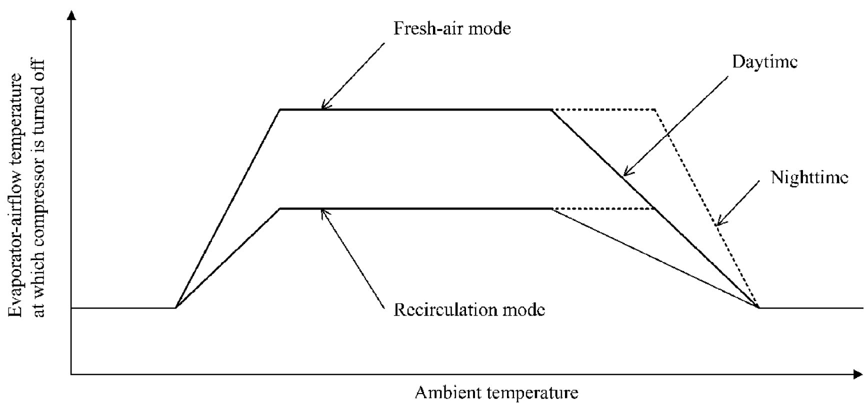



Fig. 11 Energy-saving control of compressor

ing fuel consumption and ensuring smooth idling. See **Fig. 12** for a flow chart showing the process of compressor-torque predictive control.

With the energy-saving control and the coordinated control of the air-conditioning system and engine, the new COLT's fuel efficiency during operation of the air-conditioning system is approximately 8 % higher than that of a Mitsubishi vehicle that does not have such control functions (calculated according to Total Equivalent Warming Impact test conditions).

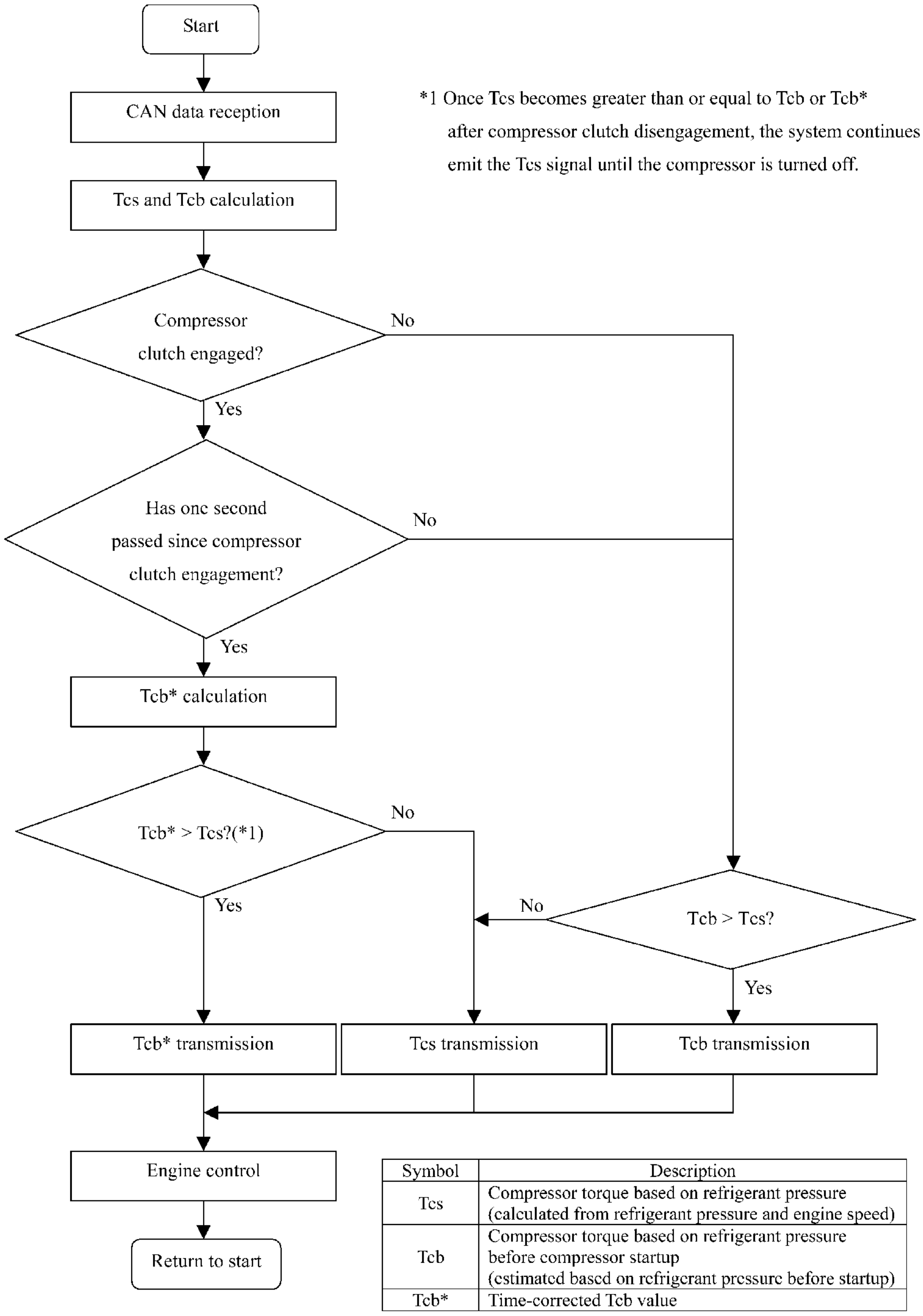
## 6. Weight saving and cost reduction

Weight saving and cost reduction are particularly important with compact cars. With the new COLT, they were achieved partly by means of the new technologies listed below. Indeed, the new COLT is 23 % lighter than the previous model and its production cost is 21 % lower with a manual air-conditioning system and 30 % lower with an automatic air-conditioning system.

(1) Air-conditioner compressor
Downsized (90 cc/rev. to 60 cc/rev.)

(2) Heater unit
Heater, air-conditioner, and blower fan integrated into a single unit

(3) Integrated air-conditioner/meter-cluster ECU
More efficient use of circuit board through integration of air-conditioner and meter-cluster ECUs




| Symbol | Description |
|---|---|
| Tcs | Compressor torque based on refrigerant pressure (calculated from refrigerant pressure and engine speed) |
| Tcb | Compressor torque based on refrigerant pressure before compressor startup (estimated based on refrigerant pressure before startup) |
| Tcb* | Time-corrected Tcb value |

**Fig. 12 Compressor torque prediction flow**

## 7. Cooling performance

The results of a cooling-performance test are presented in **Fig. 13**. These results show that the new COLT's system is capable of ensuring occupant comfort by achieving temperatures equivalent to or lower than those achieved by the system of the previous model during cooling-down operation at a vehicle speed of 40 km/h, during steady-state operation at a vehicle speed of 100 km/h, and during steady-state operation with the engine idling.

## 8. Benefits

To confirm the fuel-efficiency advantages of the new air-conditioning system, bench tests simulating actual vehicle operating conditions were performed. The results, which are shown in **Figs. 14** and **15**, show that fuel efficiency higher than that of the previous model was observed in all test modes.

## 9. Conclusion

Mitsubishi Motors has developed a new energy-saving air-conditioning system for compact cars (the vehicle category with the greatest scope for resource savings and $CO_2$ emission reductions).

The energy-saving air-conditioning system, which is employed in the new COLT, provides cooling performance equivalent to or higher than that of the system

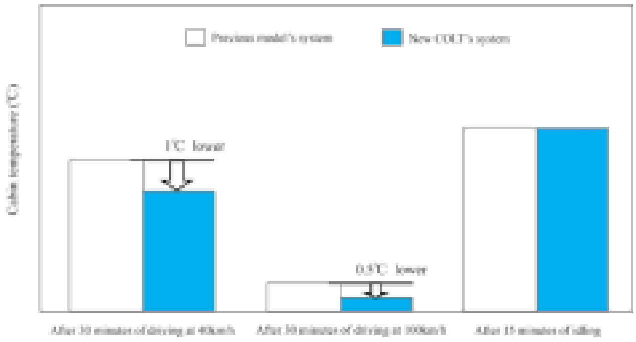



**Fig. 13 Cabin temperatures during air-conditioner operation (with ambient temperature of 35 °C)**

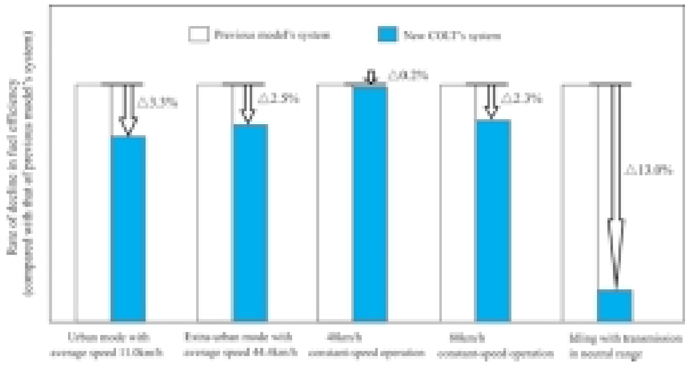



**Fig.14 Fuel-consumption benefits (with ambient temperature of 25 °C)**

used in the previous model but realizes a 10 % reduction in fuel consumption (with the air-conditioning system activated).

Mitsubishi Motors plans to expand its application to other vehicles in pursuit of further reductions in fuel consumption and reduce $CO_2$ emissions.

We would like to express our gratitude to everyone who helped in the development of this system.

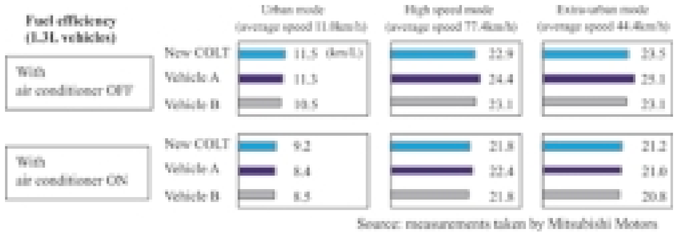



**Fig. 15 Fuel efficiency (km/L): new COLT vs. competing vehicles**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NEW TECHNOLOGIES

# Vehicles Evolving in the Ubiquitous Network Epoch – Today and the Future of Telematics Services –

Masayoshi ITO* Kenshin TSUCHIYAMA** Yoshihiro GOI***

**Abstract**

**This paper outlines various telematics services available today in the vehicle market in Japan where 'ubiquitous society' has become a common term. The paper also describes the trend of research and development in telecommunications-based information services for vehicle drivers in Japan and overseas. Mitsubishi Motors is now conducting research and development on Internet-based vehicle information exchange and sharing systems, which are collectively called 'Vehicle Home Page'. This paper outlines the concepts of such systems.**

***Key words:*** *Electronics, Navigation, Information System, Telematics, Vehicle Home Page*

## 1. Introduction

The Japanese people started becoming interested in the ubiquitous society early on, since when information technologies have steadily penetrated every aspect of daily life. Technology has moved inside car cabins in the form of car navigation systems, providing drivers with not only route guidance but also a variety of helpful information.

Information contained in a car navigation system is current at the time of its manufacture, but may be somewhat outdated by the time the user starts using it. People who take for granted real-time information available through the Internet in home and offices naturally want the latest information also when they are in vehicles. Automobile manufactures are therefore now working to meet this demand in view of widespread mobile phone services and the evolution of information technologies.

This paper first gives an overview of the current state of car telematics services and related technologies in Japan and overseas. Next, it examines MMC's research into the information-sharing community that will emerge in the vehicle society in the near future, which is being carried out through MMC's original Internet-based research web model "Vehicle Home Page". In this research, MMC is using several of the telematics test vehicle 'iT-Dion' (which was exhibited at the 2003 JSAE Automotive Engineering Exposition in Japan), each of which represents a mobile member of the information-sharing community, and the telematics interactions using the Vehicle Home Page of the terminal on each test vehicle are being surveyed. The Vehicle Home Page serves to store data and make it available to the public.

## 2. Current state of telematics service in Japan

### 2.1 What is telematics?

"Telematics" is a new word coined by combining "telecommunication" and "informatics" and usually means a bilateral information service provided through multimedia-compatible computers on vehicles that have a mobile telecommunications network terminal such as a mobile phone or telecommunications module. There are two main types of service: automobile information specific services and generalized information services; the former generally concerns bilateral communications of vehicle position and condition information, and the latter refers to amenity information usually provided over the Internet through personal computers and mobile phones compatible with Internet protocol (IP) (**Fig. 1**).

On the automobile manufacturers' side, telematics offers a promising means of adding new functions and values to their products or improving the quality of the products themselves (sometimes called 'vehicle relationship management' or VRM profits) and also improving their relationship with customers through communications (called 'customer relationship management' or CRM profits). Also, telematics will provide a tool for streamlining business, from manufacturing to sales and after-sale service. Telematics thus offers huge potential and encompasses such fields as the communications industry, content providers and electronics equipment manufacturers in addition to the automotive industry, and so expectations are growing for the development and popularization of telematics services.

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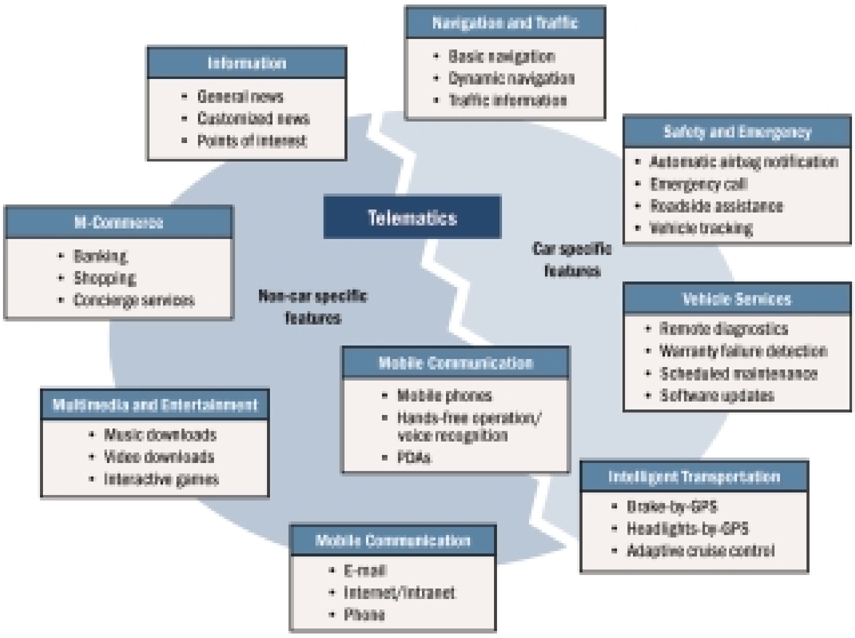


**Fig. 1 Overview of telematics features (Source: Roland Berger)**

### 2.2 From first-generation telematics to second-generation telematics

In the latter half of the 1990s, Japanese telematics services first emerged when Nissan and Toyota began their COMPASSLINK and MONET services, respectively. The services covered operator support, emergency calls, real-time information provision, etc., thus providing new value to drivers. Following these, Mazda and Honda started offering telecommunications services based on the Internet, called respectively Mazda Telematics and Honda InterNavi. Almost simultaneously, NTT DoCoMo began providing its iNaviLink service that enables the driver to retrieve desired content through the screen of an onboard navigation system and use the content to set his/her destination. The telematics services of this period are called “first-generation telematics service” in this paper.

Although the first-generation telematics service included various functions, there were fewer than 100,000 users even five years after the start of service, and so could not be called ‘popular’. Possible reasons were the explosive popularity of mobile browser phones at the same time in Japan, scope of coverage, initial cost of modem and other onboard hardware items, regular service and dialing charges, communication speed of mobile phone network, usability of onboard terminals, and maturity of the business model.

Based on such experience and the state-of-the-art communications infrastructure called third generation (3G) mobile communications (such as Freedom Of Mobile Multimedia Access (FOMA) and CDMA200 1X), Nissan launched CARWINGS and Toyota launched G-BOOK in 2002 expecting the telematics market to grow. Honda also advanced its InterNavi and launched that year a new service named InterNavi Premium Club. The telematics services in this period are called ”second-generation telematics service” in this paper. The second-generation telematics service is characterized by the combination of an onboard terminal with a navigation system, thereby reducing the cost of additional hardware, the total of regular service and dialing charges is around 1,000 yen a month, and the human-machine interface of the onboard terminal has been improved. An improved multimedia environment provided by Toyota’s G-BOOK is also a characteristic of the second-generation telematics service. Honda’s InterNavi Premium Club offers a DVD-ROM map update service free of charge for the first three years.

### 2.3 Second-generation telematics service

The key features of Nissan’s CARWINGS (released in March 2002 and offered for its compact car MARCH using a 1-DIN type onboard terminal) are the channel-by-channel program selection system, human-machine interface using voice recognition, and Japan’s first application of a telecommunication-supported navigation function (Nissan does not call it ‘navigation’ as the function provides more limited guidance compared with that provided by a DVD-ROM type navigation system). To strengthen the original system’s navigation function, Nissan then developed an onboard terminal that integrates the functions of CARWINGS into a DVD-ROM type navigation system and offered it for its ELGRAND and other models in May 2003. In mid 2003, the company also lowered the service charge including operator-assisted services, while building the system into additional car models.

In October 2002, Toyota started the G-BOOK service for its WiLL CYPHA that was equipped with a original multimedia onboard terminal. The main features of this service are the use of a 3G-compatible data communication module as standard, broad range of services from multimedia content to security services such as vehicle position tracking, and flat-rate charge system including dialing charges. At first, Toyota offered the service only for WiLL CYPHA, but in September 2003, the company added to its range of terminals a new navigation terminal that incorporates the G-BOOK function, installed the service in almost all models, started offering the service as a dealer option, and revised the service charge system.

Honda's InterNavi Premium Club was first offered in August 2002, for its ACCORD. The main features of the onboard terminal for the service include voice-operated command function for navigation operation, air conditioning and audio system control functions, voice note dictation function, and hands-free conversation on the mobile phone.

All the above-mentioned telematics services are led by the automobile manufactures, but in 2003, MobileCast, a company independent from automobile manufactures, announced its entry into the telematic service sector (service will start in or after 2004). The company's service is named MobileCast Club and will provide traffic information, music, movie news, and many other services through an originally designed gateway terminal in the car.

### 2.4 Development of second-generation telematics service

The second-generation telematics service is characterized by improved quality of content and more companies and vehicle models that support the service.

Honda's InterNavi Premium Club improved the information quality of its Vehicle Information and Communication System center (VICS) supplied through the navigation system. The information includes two types: one is the on-demand VICS information, for which the InterNavi Information Center comprehensively collects, compiles and offers route-related information for several prefectures to users who want route guidance, and the other is the floating car information in which the InterNavi Information Center creates its own traffic information for non-VICS service coverage using velocity information of the vehicles having a terminal of this system.

In February 2003, the Tokyo Metropolitan Government and Tokyo Metropolitan Parking Corporation jointly conducted an experiment(2) on providing information on whether car-parks are full or not, from the centers of telematics service providers to car navigation terminals. The experiment was for the 'IT car navigation parking information and guidance system' in which the driver sets the destination on the car navigation terminal and is guided to the desired parking lot that he/she has specified in advance depending on the fee and other relevant conditions. The objective of the system is to reduce 'drifters' who cause traffic jams by driving around a city looking for a parking space after reaching the destination.

Automobile manufactures need to offer services through the entire time the car is used, in addition to manufacturing and selling vehicles. Telematics services are no longer confined to those automobile manufactures that first provided them, but are now offered by all major automobile manufactures. The latecomers are not building their own telematics services but are forming alliances with leading automobile manufactures and non-automobile manufacture service providers in order to offer services to their users. Examples include Fuji Heavy Industries' announcement that it will use G-BOOK (February 2003), Daihatsu's announcement that it too will use G-BOOK (January 2003), and Suzuki's announcement that it will use CARWINGS (June 2003). These companies can avoid the risk of developing their own systems and obtain profits from the increasing number of customers of the telematics service they employ.

MMC had been considering forming an alliance with a telematics service provider in order to be able to offer the service, and has reached a basic agreement with Toyota by adopting G-BOOK, and made the following press announcement on September 3, 2003.

> Mitsubishi Motor Corporation (MMC) and Toyota Motor Corporation (TMC) today announced that they have reached a basic agreement on providing MMC users with G-BOOK, a TMC- developed information network service.
> (1) MMC will install G-BOOK compatible information terminals in MMC models sold in Japan starting in 2005 and offer G-BOOK services to its customers.
> (2) MMC will develop its own G-BOOK membership system and manage it in combination with its customer management system when offering this service.
> (3) TMC will provide MMC with information and telecommunication services, infrastructure, and application technology necessary for realizing the above.

Unlike the alliance of Fuji Heavy Industries and Suzuki with Toyota, MMC is free to establish its own membership system and conduct its own customer relationship management. The service includes sharing of content with G-BOOK and MMC's own content, with the latter enabling MMC to add original functions to its vehicles and develop new sales policies.

## 3. Trend of technical development projects

This section summarizes the technical development projects that are in progress and are scheduled both in and out of Japan, and predicts the future of third-generation telematics service.

### 3.1 Technical development projects overseas

In Europe, the joint initiative of the European Commission and industry, 'eSafety Project' (which aims to halve traffic accident deaths by exploiting technology in the next ten years), has started, and the focus is on popularizing the emergency reporting system (E-Call) and Advanced Driver Assistance System in Europe (ADASE). They have already started providing traffic information service using the floating car data or FCD (collection of data by using the cars as information sensors), and this service will expand quickly prior to the Olympics in Athens in 2004. The intelligent speed adap-

**Table 1 Overseas information support projects using wireless communication technologies**

| Area | Project name | – 2002 | 2003 – | 2008 – |
|---|---|---|---|---|
| Europe | eSafety (joint initiative of European Commission) | Information: Emergency call (E-Call), HMI, traffic and tourist information, etc. → Safety: Accident analysis, advanced driver assistance system, etc. | | |
| Europe | Others | Start of FCD service → ISA assessment experiment → | Legislation in Sweden → | European communications satellite (GALILEO project) → |
| USA | A Ten-Year Vision (governmental project) | E911: Mandatory position data report → 511: Tourist information service over telephone → Studies on safety of controls of driver assistance system and information equipment → | | Realization of safe and efficient traffic system that provides good mobility |
| USA | Private-sector services | OnStar service, satellite radio, digitalized terrestrial broadcast radio → | | |

FCD: Floating Car Data (data collection by vehicle); ISA: Intelligent Speed Adaptation (maximum vehicle speed control)
This table is based on "Surveillance Study Report on Trend of ITS Industries"(3).

tation (ISA) evaluation experiments were conducted mainly in Northern Europe, and since it was shown to be effective in reducing accidents, Sweden plans to make legal regulations. The GALILEO project is now underway, aiming to set up a satellite communications system unique to Europe by 2008.

The United States announced its National Intelligent Transportation Systems (ITS) Program Plan 'A Ten-Year Vision' in January 2002 which aims to create a traffic system that is safe, free of congestion and highly mobile. Since the diffusion of car navigation systems is lagging in the United States, the service will be offered through telephone for the time being, and the E911 Emergency Reporting System that must be accommodated in vehicles containing GPS and other position fixing technologies and 511 tourist information service are in progress. The E911 and 511 services offer required information over the telephone on the same number nationwide. As the information system technology advances, problems of privacy and distraction (safety of using equipment while driving) have emerged, and the United States Government has started a large-scale research program. As to services in this field provided by the private sector, various charged services are competing in the automobile information service market. Regarding the expanding OnStar service offered by General Motors, satellite radio is facing a tough fight, and the digital terrestrial broadcast service is scheduled to start operation (**Table 1**).

### 3.2 Technical development projects in Japan

Car navigation systems have become very popular in Japan, and are installed in around 40 % of newly registered vehicles. A VICS receiver is installed in about 90 % of vehicles equipped with navigation systems, and the navigation systems themselves are transforming into systems that can handle communications through mobile phone network or telematics services. Onboard systems with a built-in data communication module are sold to be compatible with higher-class services through constant connection.

For the development of communication-supported navigation systems and telematics services, a telecommunications infrastructure that can be used cheaply by customers is necessary in addition to the mobile phone network. One promising candidate is the dedicated short-range communication (DSRC) function provided by electronic toll collection (ETC) receivers (installed in 1.35 million cars in Japan as of August 2003). A private/public partnership study is now being carried out to test DSRC for multi-purpose applications other than ETC, and DSRC is expected to be broadly available by 2006. Furthermore, a succession of digital terrestrial television broadcast tests for mobile terminals started in 2003, and if data broadcast is multiplexed on broadcast waves, a new form of communications service infrastructure will be established (**Table 2**).

In view of the advancing automobile communications field, the InternetITS Consortium was established with over 100 private-sector members and supported by the Ministry of Economy, Trade and Industry. The Consortium is working on the standardization of an open platform and service models based on which users can freely select necessary services through the Internet. The results are to be reported and large-scale open verification experiments are planned to be conducted as a showcase experiment at the Aichi/Nagoya Convention of the ITS World Congress in 2004 and at the Aichi International Expo 2005. MMC plans to participate in the experiments through technical development and evaluation (**Fig. 2**).

## 4. Research and development activities at MMC

Telematics services are expanding as a revenue generating business, but the services are not yet a mature business model. MMC's Research and Development department is now conducting research on desirable forms of telematics services in the future automobile society in addition to business models for the service.

### 4.1 Telematics platform technologies

In-vehicle telematics services now being offered by automobile manufactures generally provide informa-

**Table 2 Japanese information support project using wireless communication technologies**

| Technology category | – 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|---|---|
| Navigation, VICS | Distribution of navigation systems: 40 % of new vehicles → VICS: 90 % of navigation systems | | Start of map download navigation (telematics) service → | | | Distribution of telematics → (Expected next-generation VICS) | | |
| Mobile phone | | Start of high-speed (3G) technology and embedded communication modules → | | | | Expected distribution of high-speed, low-price data communications → | | |
| ETC, DSRC | Start of ETC → | | 1.35 million; Study for multi-application ETC → | Expected experiments in service areas, road side parkings → | | Expected distribution of multi-application ETC → | | |
| Digital broadcasting (datacasting) | | | | Start of satellite mobile broadcasting →; Start of digitalized terrestrial broadcasting → | | | | Start of use of quasi-zenith satellite system → |
| Internet ITS project | | Establishment of consortium, study of basic platform specifications → | | Showcase experiment → ITS-WC Nagoya, Aichi; Aichi Expo | | Development into business model → | | |

ITS-WC: 11th World Congress on ITS, Nagoya, Aichi 2004
This table is based on "Surveillance Study Report on Trend of ITS Industries"(3).

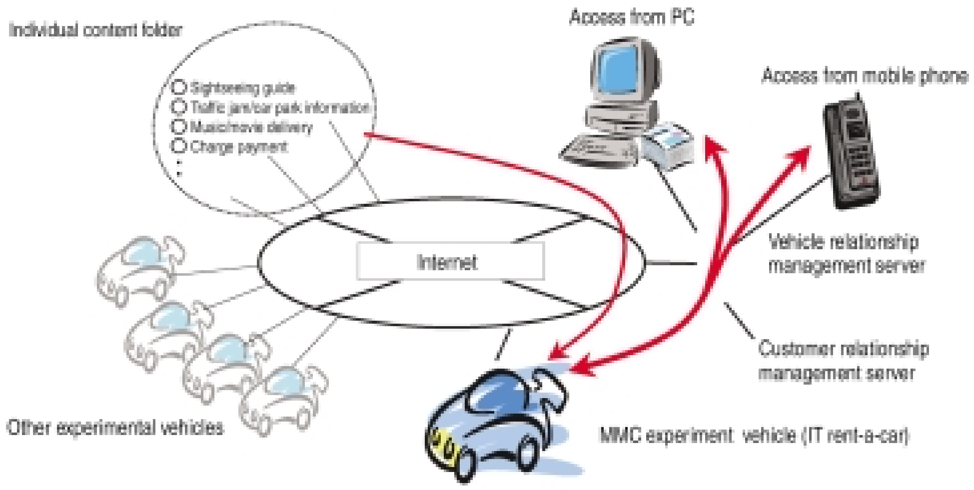


**Fig. 2 MMC's proposed experimental system for the InternetITS project**

tion content from a dedicated server through a dedicated onboard terminal for display. It is thus a closed form of service in which information is basically downloaded. There is another conceivable form of service in which the onboard terminal actively transmits information to the outside of the vehicle, such as a vehicle that acts as a data-gathering probe in a probe information collecting system. In this case, individual data transmitted from the vehicle are reclassified macroscopically to create a set of data with new value that can be reused for a particular purpose.

In-car telematics services may take another form in which each vehicle has its own Internet website and vehicle function control computers (or electronic control units for the engine and transmission, and security functions such as door locks, for example) automatically update the website content or the vehicle user updates the content manually. MMC's Research and Development department is now studying this form of service in collaboration with the Vehicle Home Page Study Group in the Japan Automobile Research Institute, using multiple vehicles with equipment that has such functions and based on the concept that these vehicles constitute a community in which each vehicle makes its website public and all vehicles share the same information in the Internet environment. The following section 4.2 describes how each onboard web server (that retains the vehicle's website content) is operated, and section 4.3 describes how the ground-based web server creates the Vehicle Home Page from data transmitted from the vehicle. **Fig. 3** shows an overview of the Vehicle Home Page with regard to the onboard web server and ground-based web server.

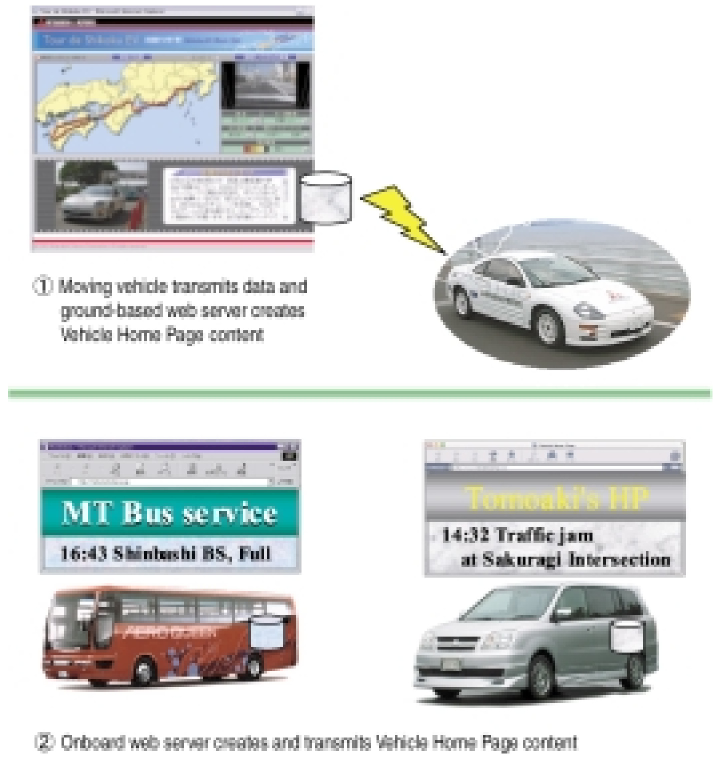


**Fig. 3 System overview of Vehicle Home Page**

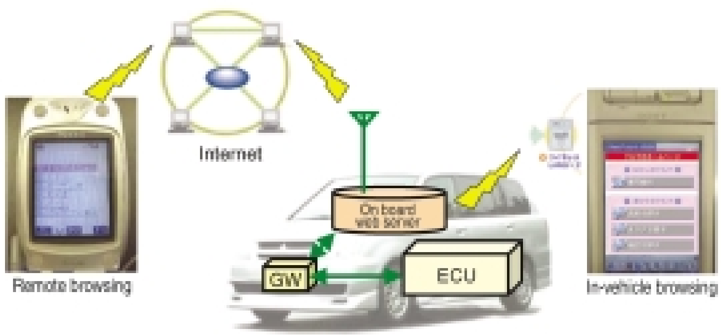


**Fig. 4 "iT-Dion" system configuration**

### 4.2 Telematics test vehicle "iT-Dion"

The telematics test vehicle "iT-Dion" was constructed for experiencing and evaluating the usage of vehicle system data and information received and transmitted by the vehicle user in order to study whether it is feasible to use information in this way. As one of the evaluation processes, the iT-Dion was displayed in the 2003 JSAE Automotive Engineering Exhibition held by the Society of Automotive Engineers of Japan in May 2003. The information-related functions unique to the vehicle are as follows:

- Vehicle hotspot function

The system stores downloaded Internet content in the onboard web server. The content can be browsed using a mobile phone or other devices while driving.

- Remote control of vehicle functions

The onboard web server monitors vehicle functions, interprets them and updates the web content. The onboard web content is browsed through a mobile phone terminal over the Internet, and the vehicle's functions are remote-controlled.

- Vehicle Home Page

The Vehicle Home Page of each vehicle is made public, which assumes an information-sharing community.

The configuration of the telematics system on the test vehicle is shown in **Fig. 4**. All the above-mentioned functions incorporated in the iT-Dion's system are expected to form the core technology of the coming ubiquitous network society.

### 4.3 Vehicle information remote collection and redistribution

The previous section described the concept of storing and distributing through the onboard web server the data handled by the vehicle and user. This subsection describes an experiment in which the ground-based server collects information from test vehicles and redistributes information to Internet to make it to public in real time through the Vehicle Home Page. The communication-related test conditions are shown in **Table 3** and the network system configuration is shown in **Fig. 5**.

**Table 3 Test conditions**

| Item | Description |
|---|---|
| Test vehicle | ECLIPSE (prototype electric vehicle) |
| Test route | MMC Tokyo headquarters to Tokushima College of Technology (1,200 km) |
| Collected data | • Vehicle conditions (13 items, every 10 seconds)<br>• Forward landscape photos taken by onboard camera (320 x 240 pixels, every 1 minute) |
| Communications infrastructure | NTT DoCoMo DoPa network (for vehicle data); FOMA network (for photo data) |

The objective of the experiment is to investigate the feasibility of "real-time updating of data and retrieval of stored data" both when making the data public and handling information data through the Internet website as a tool. The experiment will be continued using the Vehicle Home Page installed in other types of vehicle such as MMC's fuel-cell prototype vehicle MFCV and through operation tests of the remote data collection and redistribution system in order to comprehensively investigate the telematics service. The MFCV's Vehicle Home Page is at:

http://www.mitsubishi-motors.com/corporate/about_us/technology/environment/j/fcv.html

## 5. Future perspectives

The development of telematics service technologies is largely influenced by the development of the infor-

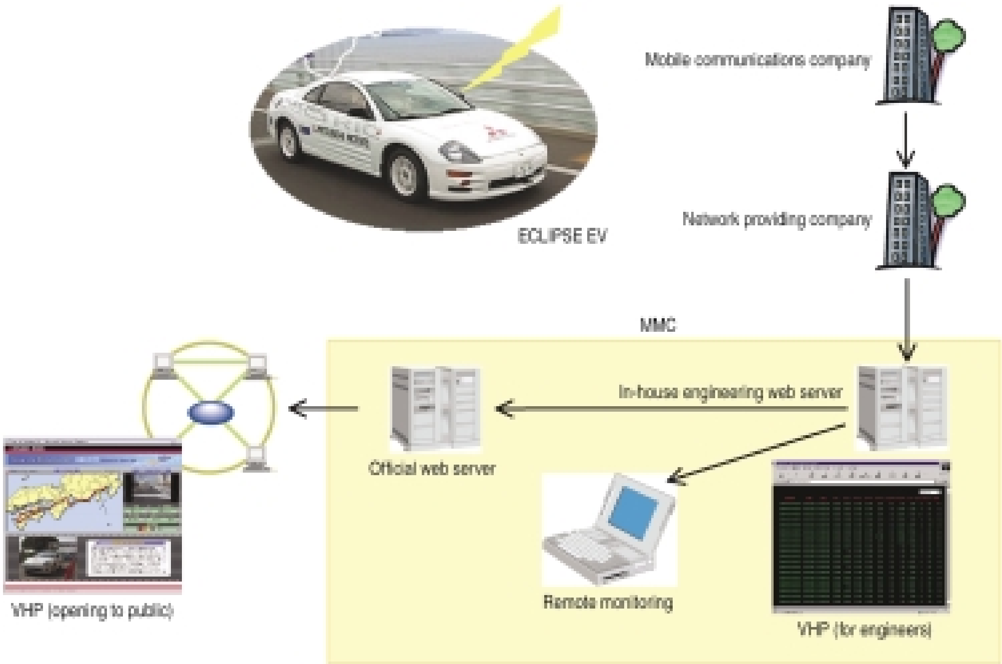


**Fig. 5  Network system configuration**

mation providing/reception environment existing in daily life. With this background, future perspectives for telematics service technologies can be summarized as follows:

- In view of the current information access environment in vehicles, which is inferior to that in home and offices, technologies are needed to improve information access appropriate for the vehicle cabin.
- Onboard telematics terminals will need added functions, updating capability, versatility (open architecture), and compatibility with different systems, in the same way that such convenient features are already found in personal computers.
- A high-speed, large-capacity, seamless radio communications environment will be needed, in which dedicated short-range communication (DSRC) or wireless LAN and wide area communications means such as 3G mobile phone networks are mutually used.
- For more advanced telematics services, information distribution over digital terrestrial broadcasting will need to be combined with existing communications service networks.
- Telematics services will become more open to the public. In addition to the server-based information service (closed service), the need for an Internet-based information service (open service) will increase.

## 6. Summary

The key issue of future telematics services is the man-machine interface, which is the interface between the user and onboard terminal. MMC will continue research to enable customers to use new information services effectively and safely in their vehicles, and for the benefit of the whole automobile society.

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# Weight Reduction Technology for Improved Handling Performance of LANCER EVOLUTION

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**Abstract**

**To be exceptional in all aspects of vehicle dynamics, a high-performance car like the LANCER EVOLUTION must be well balanced in weight, in addition to having excellent powertrain and suspension performances. In order to maximize the effect of weight reduction enhancements on the LANCER EVOLUTION's handling performance, Mitsubishi Motors Corporation considered employing an aluminum material for the roof, the highest part of the vehicle. This paper describes the aluminum roof forming and joining technologies we developed in order to reduce vehicle weight.**

***Key words:*** *Aluminum, Weight Reduction, Joining Technology*

## 1. Introduction

Since its debut in first-generation form in 1992, the LANCER EVOLUTION has been continually evolved and refined through participation in worldwide motorsports competitions (most notably the World Rally Championship). The latest generation, the LANCER EVOLUTION VIII MR, went on sale in February 2004. For this vehicle, an aluminum roof was developed by Mitsubishi Motors Corporation (MMC) as an effective means of cutting weight for superior handling performance. Information on the aluminum roof is presented in this paper. It is noteworthy that the LANCER EVOLUTION VIII MR is the first Japanese production vehicle to have an aluminum roof on a steel body.

## 2. Targets

A number of automobile manufacturers have developed and produced all-aluminum bodies as a means of weight reduction. However, these bodies have been used with only a limited number of vehicle models for the reason of significant production costs. With the LANCER EVOLUTION, aluminum materials have been used for the hood and fenders because reduction in weight of these parts is effective for improvement of vehicle dynamics and change of their material is relatively easy. With the latest generation, the use of aluminum was extended to the roof in pursuit of even better handling performance.

Since the roof is the highest-positioned part of the vehicle, a weight reduction in the roof effectively lowers the vehicle's center of gravity and can thus greatly improve the vehicle's handling performance. (Calculated with respect to distance from the vehicle's roll axis, the benefit of a weight reduction in the roof is three times as great as a weight reduction in the hood (**Fig. 1)** ). However, roof's weight reduction may carry a risk of reduced roof strength and increased cabin noise. The aluminum roof model was developed so as to achieve body strength and cabin quietness comparable with those of the current steel-roof model.

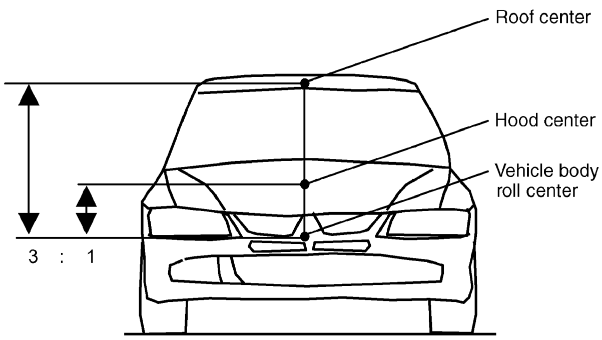


**Fig. 1 Effect of aluminum roof**

## 3. Structure of aluminum roof

A 45 % weight reduction in the roof was achieved by the use of the same 6000-series bake-hardened aluminum-alloy sheet (strength-enhanced in a paint oven) that was already used for the outer panel of the hood. The roof panel of the aluminum roof vehicle is fitted with design beads on both sides. The reasons for fit-

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*** Body Production Engineering Department, Global Production Office
**** Mitsubishi Aluminum Co., Ltd.
*****Kobe Steel, Ltd.

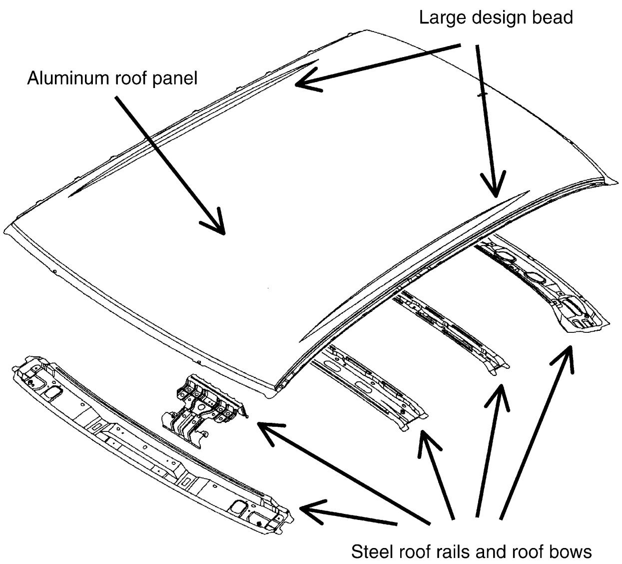



**Fig. 2 Structure of aluminum roof**

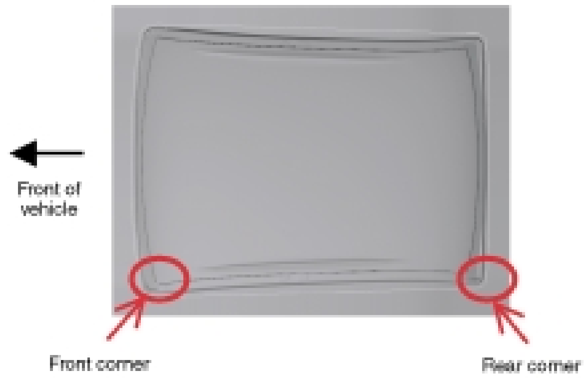



**Fig. 3 Model for the forming analysis**

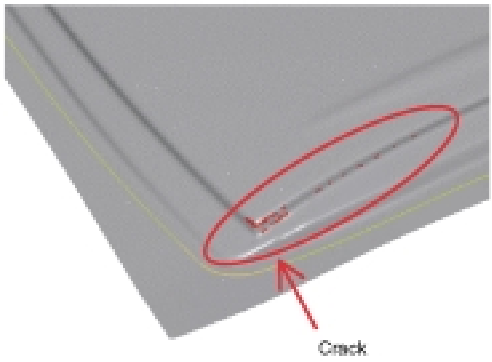



**Fig. 4 Crack at front corner shown by roof forming analysis**

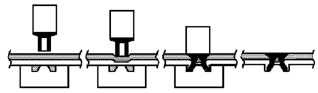
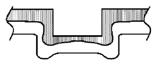
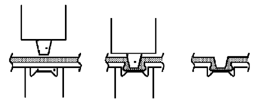
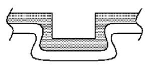
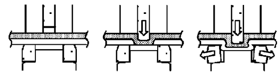
| Joining method | | Joint sectional | Joining procedure |
|---|---|---|---|
| SPRs | |  |  |
| Mechanical clinch | TOX |  |  |
| | TOG-L -LOC |  |  |

**Fig. 5 The way to joining different metals**

ting the design beads are to counter heat deformation (discussed in section 4) and to give the aluminum roof a distinctive styling feature (**Fig. 2**).

## 4. Technological hurdles related to aluminum roof

Many technological hurdles in areas such as joining methods were overcome for adoption of the aluminum roof. An overview is given hereafter.

### 4.1 Pressing

Aluminum has elongation smaller than steel. Resulting inferiority in the press-formability makes it prone to cracking. Indeed, cracking occurred at the corners of the roof at the beginning of the design study. Computer-aided-engineering analysis using the model shown in **Fig. 3** was performed. As a result, an optimal roof shape that could solve the problem of cracking at corners was successfully determined (**Fig. 4**).

### 4.2 Joining technology

It was not possible to join the aluminum roof to the steel body by means of resistance spot welding (the joining method generally used to join steel panels to other steel panels). Study was conducted on three different joining methods that could conceivably be used to join the different materials (**Fig. 5**). The results showed that self-piercing rivets (SPRs), which have been successfully used in European vehicles, were the most suitable among these three different methods. An overview is given hereafter.

(1) Static strength

The shear strength and separation strength yielded by the three different joining methods are shown in **Fig. 6**. It can be seen that SPRs are superior to the other usable methods. Although the shear strength and separation strength of SPRs are inferior to those of spot welds, they comfortably satisfy MMC's Spec. This supported that SPRs could be used without problems in this regard.

(2) Fatigue strength

The shear strength and separation strength of an SPR after $10^7$ times of stress application are shown in

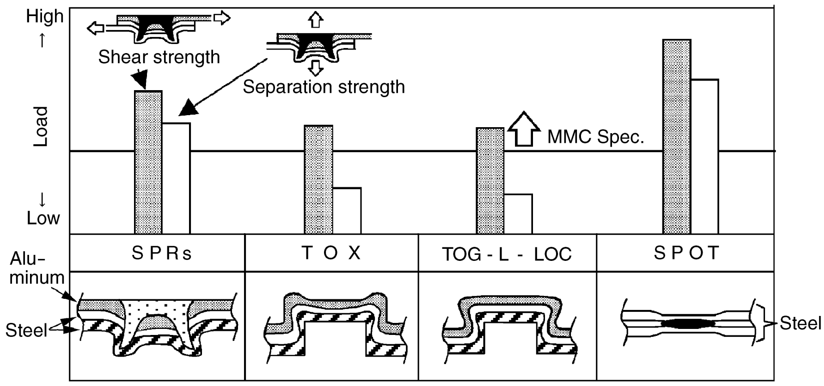



Fig. 6 Static joint strength of joining methods

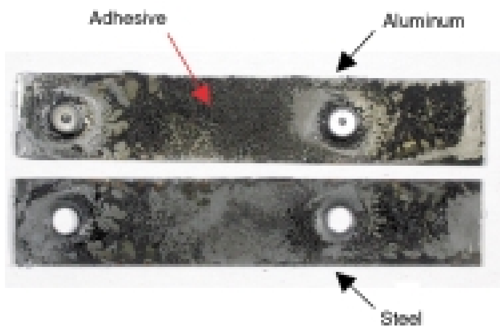



Photo 1 Results of corrosion cycle test

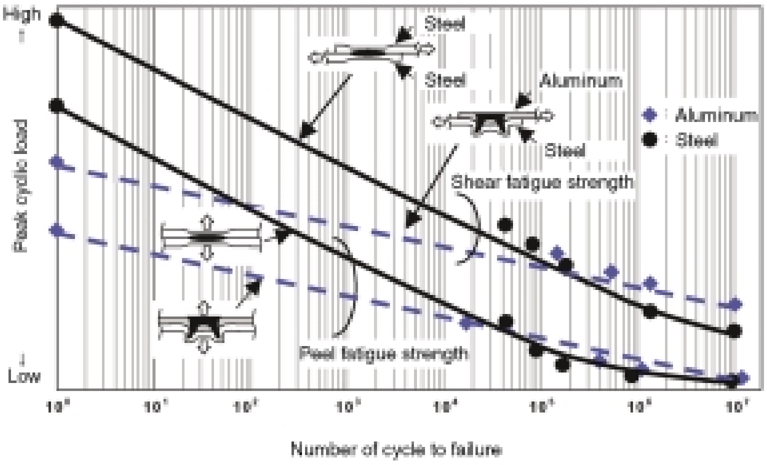



Fig. 7 Fatigue strength of SPR

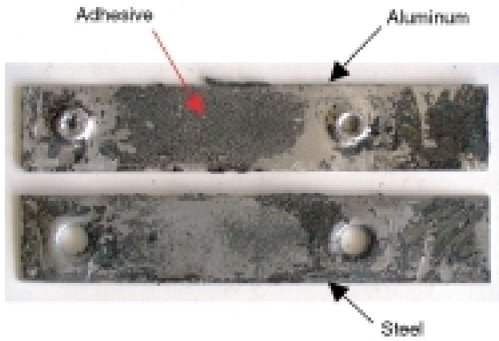



Photo 2 Results of outdoor exposure test

**Fig. 7**. It can be seen that the shear strength and separation strength at this point are at least equivalent to those of a steel-to-steel spot weld. With a spot weld, the area of the material subjected to heat becomes soft. With an SPR, by contrast, the material in the vicinity of the joint gets work-hardened, meaning that repeated stress does not greatly reduce the fatigue strength of the joint[1].

### 4.3 Measures against electric corrosion

With joints between different metals, the difference between the metals' ionization trends makes electric corrosion a potential problem. For this reason, adhesive was applied to the mating areas of the aluminum and steel to insulate them from each other. The selected adhesive was a structural adhesive that not only offered adequate electric insulation but also was superior in joint strength. Test pieces were made of aluminum and steel joined together with the adhesive; they were subjected to MMC's in-house corrosion cycle test and outdoor exposure test (for 1 year) in Okinawa, Japan. The results are shown in **Photos 1** and **2**. As shown, electric corrosion was not observed. The effectiveness of adhesive application as a means of preventing electric corrosion was thus confirmed.

### 4.4 Heat deformation of panel

When aluminum and steel, which have different thermal expansion coefficients, have been joined together, the heat used to cure subsequently applied paint can cause heat deformation that is unacceptable by the MMC's quality standard. Large contoured beads were adopted as a means of dealing with this problem.

(1) Heat deformation with pre-existing panel shape

At the beginning of the development program, a prototype aluminum roof was made with the shape used on the LANCER EVOLUTION VII (which was in production at the time) and an inspection for heat deformation was performed when paint had subsequently been applied and heat-treated. It was found that unacceptably significant heat deformation had occurred at each side of the panel.

(2) Action taken to deal with heat deformation

Ways to solve the aforementioned heat deformation problem were considered using the analysis model shown in **Fig. 8**. A design bead shaped to suppress heat deformation (**Fig. 9**) was thus located at each side of the roof and checked for effectiveness on an actual vehicle.

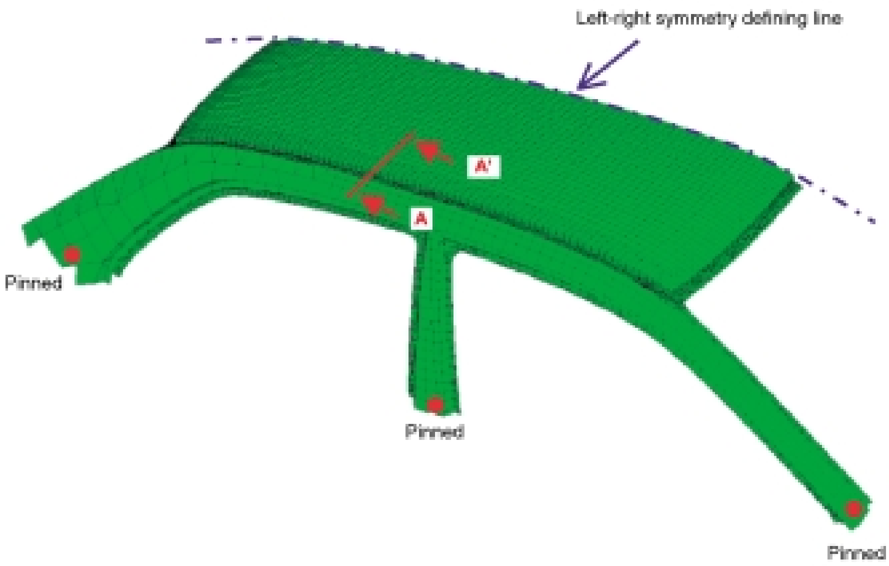



**Fig. 8　Analysis model to analyze heat deformation**

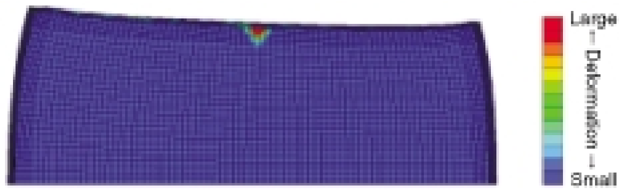
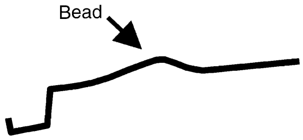
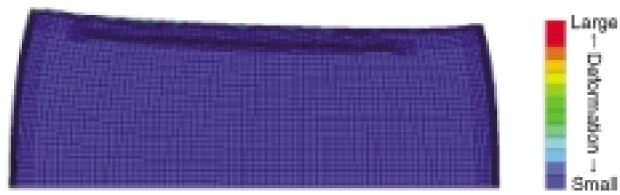
| Structure | A - A' section (see Fig. 8.) | Results of analysis |
|---|---|---|
| Without bead (conventional structure) |  |   |
| With bead |   |   |

**Fig. 9　Effect of bead at edge of the roof**

It was found that there was no heat deformation that detracted from external appearance quality of the body.

### 4.5　Reparability

Since SPRs represent a special joining method and require costly equipment, they cannot readily be used for repairs. Joining methods that allow repairs to be performed less expensively than is possible with SPRs were thus considered. As a result, blind rivets, which offer at least the same strength as SPRs with the joining method used when repairs are performed, were adopted (**Figs. 10** and **11**). Unlike SPRs, blind rivets require holes to be made prior to insertion, meaning that sealant must be used to prevent water ingress.

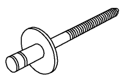
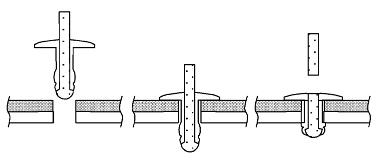
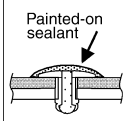
| Blind rivets | Joining method | Prevention of water ingress |
|---|---|---|
|  |  |   |

**Fig. 10　Blind rivets**

## 5.　Results of evaluation with actual vehicle

A vehicle with an aluminum roof was tested. The

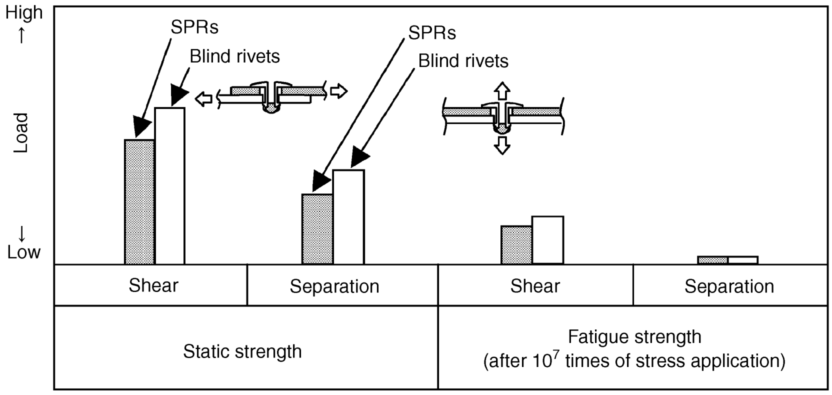



**Fig. 11 Static joint strength and fatigue strength of blind rivets**

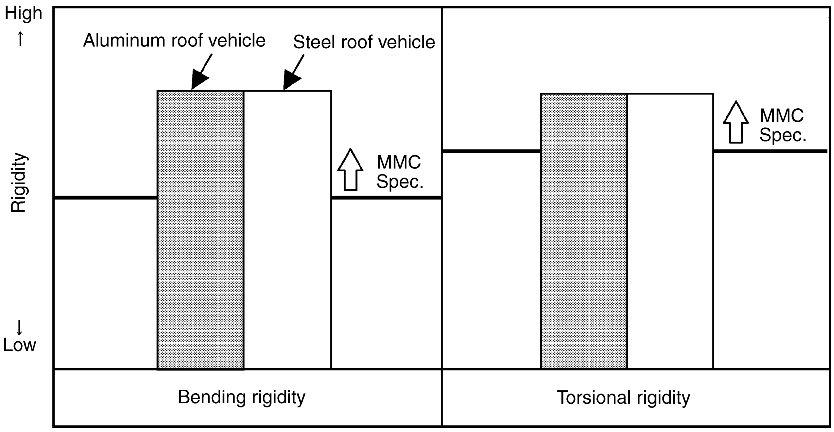



**Fig. 12 Static rigidity of body-in-white**

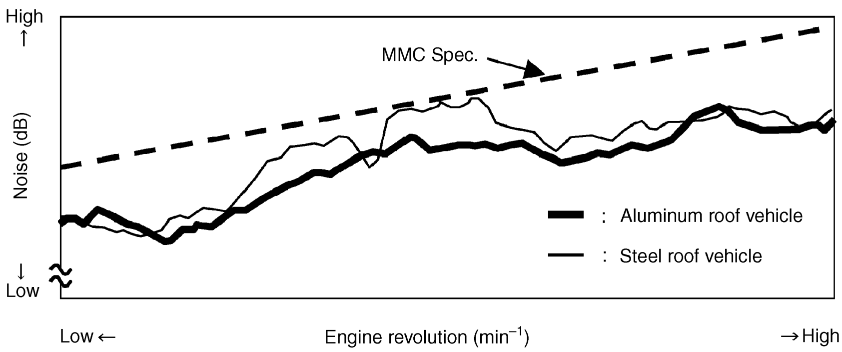



**Fig. 13 Noise of front seats center**

results are as follows:

(1) Vehicle handling performance

The aluminum roof yielded a 3 mm reduction in the height of the vehicle's center of gravity and a 1.3 % reduction in roll. These benefits are equivalent to those that would be yielded by a 70 mm reduction in the roof height of a vehicle with a steel roof. During steering manoeuvres, they were found to translate into the following handling-stability benefits:

- Roll feel and steering response during steering manoeuvers were improved.
- Vehicle movements when the steering wheel was returned to its original position after steering inputs were smoother, and the vehicle felt nimbler and was concomitantly more enjoyable to drive.

(2) Body strength, durability, and reliability

Body rigidity (bend and torsional) is shown in **Fig. 12**. It can be seen that the body rigidity of the aluminum roof vehicle is approximately the same as that of the conventional steel roof vehicle. Further, MMC's in-house durability and impact tests were performed. The results indicated adequate body strength, durability, and reliability.

(3) Comfort

Oil canning in the roof outer panel and dynamic rigidity in the overall roof were achieved at levels comparable with those of the conventional steel roof. As a result, cabin noise during acceleration (a key index of noise) was found to be low enough to satisfy MMC's standards (**Fig. 13**).

## 6. Summary

(1) Adoption of an aluminum roof yielded a 45 % weight saving over the conventional steel roof, resulting in handling-stability improvements that cannot be achieved by means of regular suspension and tire tuning.

(2) SPRs were used to attach the roof, and adhesive was used to prevent electric corrosion. These constituted a new method for combining aluminum roof with the vehicle's steel body established successfully.

(3) Positioning a large design bead at each side of the roof was found effective as a means of preventing the difference in thermal expansion coefficient between aluminum and steel from causing unacceptable heat deformation.

(4) A method for using CAE analysis to prevent unacceptable heat deformation was established.

In closing, the development team would like to express its sincere appreciation to Mitsubishi Aluminum Co., Ltd., Kobe Steel, Ltd., Tokai Metallic Manufacturing Co., Ltd., and all other parties inside and outside MMC who co-operated in the development program.

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# Development of New In-Vehicle Communications System

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Kunihiro SAKAI* Ryoichi HINO* Takahiro ARASHIDA**

**Abstract**

**Beginning with the new COLT, Mitsubishi Motors Corporation (MMC) has introduced into its products a new-generation in-vehicle communications system based on the Controller Area Network (CAN) protocol. The new system achieves a far higher transmission rate and greater reliability compared with the former MMC communication system. In addition, the system realizes various significant advantages such as fewer harness circuits, improved functionality and performance of individual electronic control units (ECUs), and enhanced ECU diagnosis functions by including all major ECUs and sensors.**

***Key words:*** *Multiplexing, Communications System, Diagnostics*

## 1. Introduction

MMC introduced its original multiplex communications Smart Wiring System (SWS) into the company's products beginning with the first DIAMANTE model in order to reduce the weight and volume of wiring harnesses that continued to increase along with the increase in electric/electronic equipment.

The SWS was mainly applied to multiplex signals used among body electronic units (such as power window, steering column switch, etc.) and it successfully reduced the amount of wiring harnesses. Recently, however, the need for higher-speed, higher-reliability communications systems has arisen in order to realize communication powertrain ECUs, high-performance fault diagnosis, etc..

CAN, now being widely used in European cars, is a multiplex communications protocol developed for application to high-speed in-vehicle communications. Along with the recent increase in supply of low-cost communications devices, DaimlerChrysler and many other automobile manufactures are using CAN buses as main in-vehicle communications buses.

In order to accommodate the need for high-speed, high-reliability communications and make parts sharing with DaimlerChrysler feasible, MMC developed a new communications system using CAN as the main bus and has applied it to the new COLT and GRANDIS.

## 2. Outline of CAN protocol

CAN is a serial data communications protocol that was proposed by Bosch in Germany and standardized as ISO11898. It was originally designed for use in automobiles, but due to high transmission reliability and cost performance, it has been widely used in other fields such as industrial machinery, ships, and medical equipment. The main features of CAN protocol are high-speed data transmission up to 1 Mbps, bus access control depending on a multi-master principle, and "bus off" function in the event of transmission abnormalities.

The multi-master principle is a bus access control principle in which each unit linked to a communication network can transmit data at an arbitrary timing. In a CAN system, data is transmitted in unit called "frame" (**Fig. 1**). A unique number, referred to as the "ID", is assigned to each data frame and defines its priority. Each receiver unit determines by the ID if the unit should receive the data (**Fig. 2**).

The bus off function is the capability by which a unit disconnect itself the bus logically if data transmission errors occur in this unit exceeding a given number of times. After checking the bus idle state for a given period, the unit restarts communication. This function is a fault confinement mechanism unique to CAN, separating a unit that repeats a transmission error and assuring communication between normal units.

## 3. System configuration

The configuration of MMC's new in-vehicle communications system is described below, taking the system used in the new GRANDIS as an example.

As a result of a study for maximum cost effectiveness and performance efficiency in the context of current conditions, MMC decided to configure the new system leaving the conventional SWS intact and newly adding one CAN bus to which all the powertrain and body electronic system ECUs are connected. Selected for connection to the GRANDIS's CAN bus with a transmission rate of 500 kbps are the engine-A/T ECU, 4 WD ECU, Active Stability Control (ASC) ECU, steering angle sensor, combination meter ECU, Electronic Timer & Alarm Control System (ETACS), air conditioner ECU, and Multi-display Station (MDS). A fault diagnostic con-

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** Vehicle Testing Department, Mitsubishi Automotive Engineering Co. Ltd.

| SOF | Arbitration field | Control field | Data field | CRC field | ACK field | EOF |
|---|---|---|---|---|---|---|

**SOF :** Bit that indicates beginning of frame
**Arbitration field :** Field that contains frame ID
**Control field :** Field that contains information such as data length
**Data field :** Field that contains data (0 to 8 bytes)
**CRC field :** Field that contains code for error check
**ACK field :** Field that contains bits to notify that ECUs have received
**EOF :** Bit string that indicates end of frame

**Fig. 1 CAN frame format**

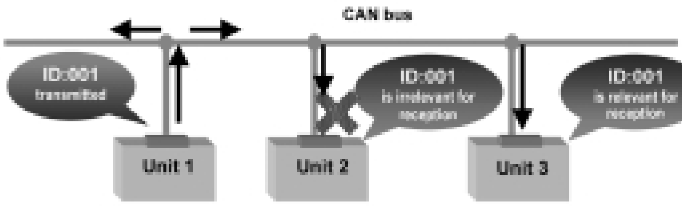


**Fig. 2 Message reception process**

nector is also equipped to the CAN bus. Connected to the SWS with a transmission rate of 5 kbps are the ETACS, which works as a core unit in the control of body electronic equipment, the steering column switches, power window switches, front ECU, and sunroof ECU (**Fig. 3**). The following description concentrates on the CAN bus communication part of the new system, as the SWS part remains almost the same as the conventional SWS system.

**Table 1** shows an overview of the data transmitted/received by the ECUs connected to the CAN bus. The total number of data items is between 200 and 300, which varies depending on the vehicle model. The data items include the steering wheel angle, vehicle body acceleration, engine torque and other powertrain-related data (which require high speed and high reliability), and body electronic equipment data such as indicator illumination requests and switch state data.

In addition, a new-generation diagnosis system based on the protocol KWP2000 on CAN (KWP is an acronym of Key Word Protocol) is employed in the ECUs connected to the CAN bus. This protocol has been standardized as ISO15765 and is becoming a global standard in the field of automotive diagnostics.

To enhance both delivery inspection efficiency at factories and servicing efficiency at service shops, the new diagnosis system improved the check speed and enriched the check items. To reduce ECU variations the new diagnosis system also supports the "variant coding" function (parameter writing function to fit ECU for a specific vehicle model) and the reprogramming function. The new-generation diagnosis system is discussed in further detail in the paper entitled "Development of Next-Generation Diagnosis Functions", which is included in this issue of the *Mitsubishi Motors Technical Review*.

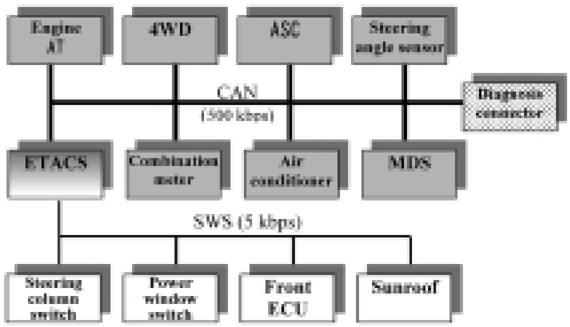


**Fig. 3 System configuration (in GRANDIS)**

## 4. Technical features

The core part of the new system's communication functions depends on the global standard CAN protocol, but it is also based on the specifications originally defined by MMC for some functions that are not covered by the CAN protocol. In these functions, "sleep/wakeup" and "network fault diagnosis" are described in the following subsections.

### 4.1 Sleep/wakeup function

The body control ECUs need to make communication even when the ignition switch is in the OFF position. The sleep/wakeup function is intended to prevent IOD from flowing to these ECUs. The operation logic of this function is as described below.

In general, CAN bus supports a mechanism in which all control units can be woken up by data transmission from one of the units. Therefore, the basic method on wakeup event is that a unit in which transmission request arises arbitrarily starts data transmission and then the transmission wakes up the other units. On the other hand, when the units go into a sleep state, a

**Table 1 Overview of communication signals (in GRANDIS)**

| Signal name | ECU | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Engine-A/T | 4WD | ASC | Steering angle | Combination meter | Air conditioner | ETACS | MDS |
| Throttle position | S | R | R | | | | | |
| Idle switch ON | S | | R | | | | | |
| Engine speed | S | R | R | | R | R | | |
| Vehicle speed | S | | | | R | R | | |
| CHECK ENGINE warning illumination | S | | | | R | | | |
| Engine coolant temperature | S | | | | R | R | | |
| Gearshift lever position | S | | R | | | R | | |
| Present gear | S | | R | | | | | |
| Coolant temperature warning ON | S | | | | R | | | |
| 4WD mode indicator | | S | | | R | | | |
| Rear wheel torque distribution | | S | R | | | | | |
| ASC request torque | R | | S | | | | | |
| Gear selection command | R | | S | | | | | |
| Stop lamp switch | R | R | S | | | | | |
| 4WD limit torque request | | R | S | | | | | |
| Wheel speed | | R | S | | | | | |
| ASC operation indicator ON | | | S | | R | | | |
| Steering angle | | | R | S | | | | |
| Steering wheel angular speed | | | R | S | | | | |
| Speedometer-indicated vehicle speed | | | | | S | | R | |
| Fuel data | R | | | | S | | | R |
| Turn signal/stop lamp ON | R | | | | S | | | |
| Rheostat data | | | | | S | | | R |
| Predicted compressor torque | R | | | | | S | | |
| Compressor ON request | R | | | | | S | | |
| Cooling fan speed level request | R | | | | | S | | |
| Air conditioner refrigerant pressure | R | | | | | S | | |
| Outside temperature | | | | | | S | | R |
| Air flow mode | | | | | | S | | R |
| ACC ON | | | | | R | R | S | R |
| IG1 ON | | | | | R | | S | R |
| Left turn signal indicator ON | | | | | R | | S | |
| Right turn signal indicator ON | | | | | R | | S | |
| Seatbelt indicator OFF request | | | | | R | | S | |
| All doors open | | | | | R | | S | |
| Adjustment request | | | | | | R | R | S |
| Functional mode | | | | | | R | R | S |
| Beep data | | | | | | R | R | S |
| Air conditioner display | | | | | | R | | S |

S: sender unit; R: receiver unit

mechanism is needed in which transmission from all units is stopped simultaneously to prevent the units from waking up again. With these preconditions, we configured the sleep/wakeup control function by defining a single master unit (or control-tower unit) and multiple slave units.

The wakeup control method is described below referring to **Fig. 4**.

(1) A unit in which a communication request arises arbitrarily starts regular transmission. The first transmission data becomes a trigger to wake up the other units (W1 in **Fig. 4**).
(2) Upon receipt of the trigger through the CAN bus, all the other units wake up but they only execute data reception until they normally receive data from the master unit (W2 in **Fig. 4**).
(3) The master unit starts regular transmission as soon as it wakes up (W3 in **Fig. 4**).
(4) The slave units start regular transmission as soon as they receive the data from the master unit (W4 in

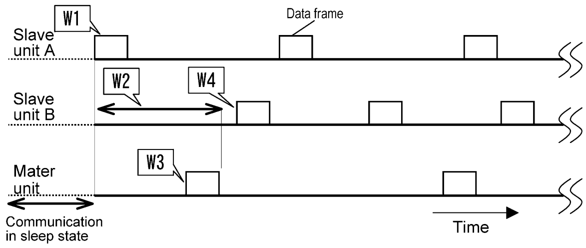


**Fig. 4 Wakeup control time chart**

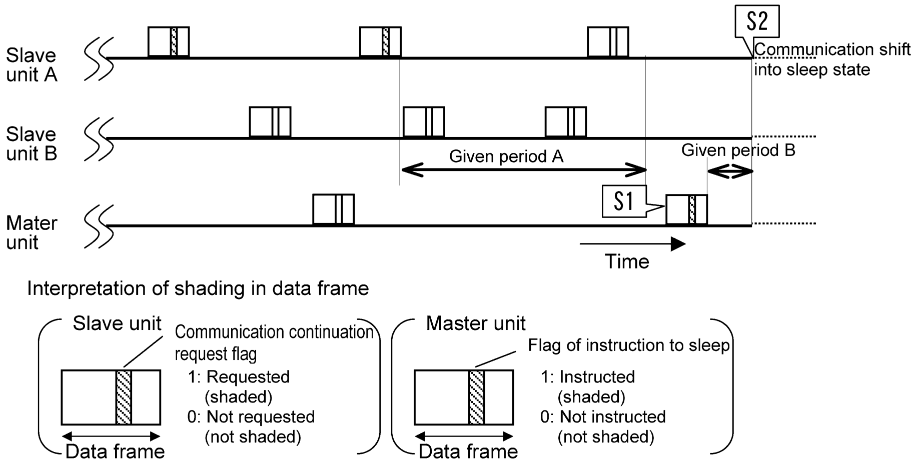


**Fig. 5 Sleep control time chart**

**Table 2 Diagnosis function**

| Trouble | Trouble determination condition | Object of trouble detection |
|---|---|---|
| Timeout | When relevant regularly transmitted datacannot be received for given consecutive periods. | Sender ECU of each received frame (each ECU for diagnostic trouble code) |
| Bus off | When own ECU is in bus-off state. | ECU |
| Trouble data | When the trouble flag of received data indicates twice consecutively that a trouble exists. | Each data (each ECU for diagnostic trouble code) |
| Data length | When received frame contains a number of data bytes less than that specified in CAN matrix specification. | Each frame |
| Dynamic range | When received data is outside the minimum or maximum value ranges specified in CAN matrix specification. | Each data |

**Fig. 4**).

By incorporating the above rule that prevents slave units from transmitting data until they receive data from the master unit normally, any accidental wakeup of a slave unit does not cause a chain-reaction wakeup of all other slave units.

Next, the sleep control method is described below, referring to **Fig. 5**.

(1) Each slave unit makes regular transmission of data while setting a communication continuation request flag in one of the transmission data frames. The flag's bit level 1 indicates that communication continuation is requested and bit level 0 indicates that it is not requested (see note in **Fig. 5**). If no transmission occurs for a given period, it is considered as no communication continuation is requested.

(2) The master unit constantly monitors the communication continuation request flags and if there are no units with the flag set for a given continuous period, it issues a communication sleep command to all units (S1 in **Fig. 5**).

(3) Upon receipt of the communication sleep command, each slave unit immediately stops data transmission and, after a given period of time, makes the transition into the communication sleep state (S2 in **Fig. 5**).

Since the master unit checks for absence (not presence) of communication continuation requests, the slave units can make the transition into the sleep state even if there is a slave unit in a fault status or if a unit is optional equipment and is not connected.

### 4.2 Diagnosis function for in-vehicle communication network

To search the causes of troubles is often more difficult for ECUs connected to a network than for ones operating as stand-alone. For this reason, a diagnosis function that accommodates the trouble items listed in **Table 2** is incorporated in the ECUs connected to the network in order to facilitate troubleshooting. In particular, providing a timeout detection function to all ECUs facilitates locating the causes of transient troubles that may occur in the network. The mechanism of the function is described below.

Suppose that, in the network shown in **Fig. 6**, one of

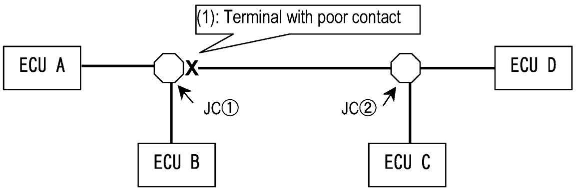


**Fig. 6　Example of wiring topology trouble**

**Table 3　Diagnostic trouble codes stored in ECU**

| ECU-A | ECU-B | ECU-C | ECU-D |
|---|---|---|---|
| ECU-C timeout | ECU-C timeout | ECU-A timeout | ECU-A timeout |
| ECU-D timeout | ECU-D timeout | ECU-B timeout | ECU-B timeout |

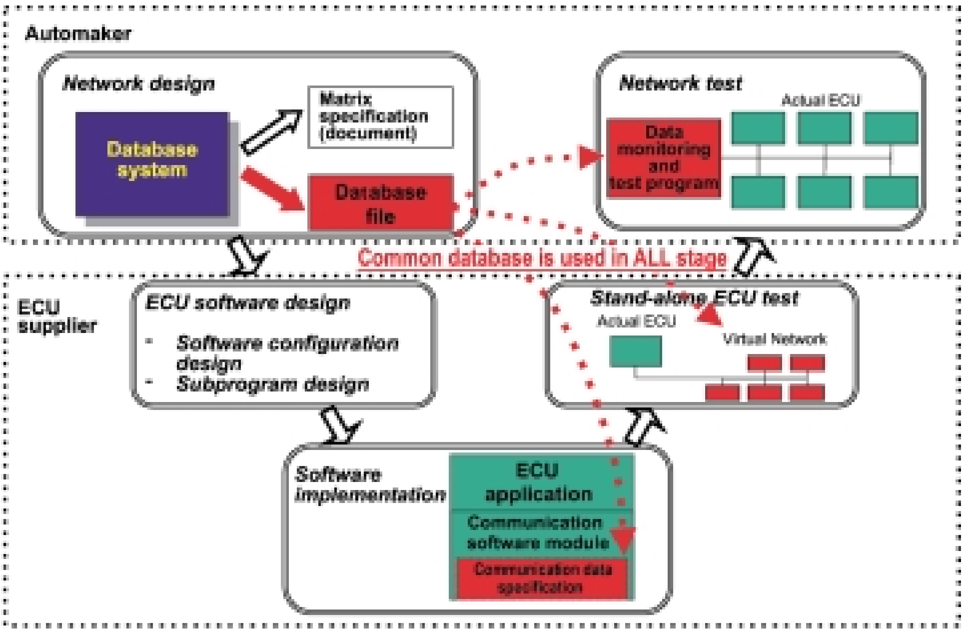


**Fig. 7　Flow of software development for communications system**

the terminals of the junction connector (JC) ((1) in **Fig. 6**) has poor transient contact. If this occurs, communication is impossible in the section following the fault point on the CAN bus; ECU-A can communicate with ECU-B but it cannot communicate with ECU-C and ECU-D. This results in diagnostic trouble code (DTC) stored in the memory of ECU-A, which indicate timeout trouble for ECU-C and ECU-D. Likewise, trouble codes are stored in the memories of each ECU as shown in **Table 3**. It is interpreted as follows: If the trouble codes stored in the ECUs are as indicated in **Table 3**, it would be suspected that some trouble has occurred between JC ① and JC ②. In this way, if the timeout trouble codes stored in the ECU memories are checked, the faulty location can be narrowed to a certain area.

## 5. Construction of system development process

The new in-vehicle communications system provides many benefits such as reduction of wiring harnesses and improvement of functionality, but the system requires software of increased complexity for each ECU and the reliability of the software must be sufficiently raised. To cope with this challenge, MMC newly constructed a development process for software of the communications system in order to improve its reliability and development efficiency.

**Fig. 7** shows an overview of the software development process. The process is configured so that an MMC original database system is incorporated in the network designing stage (the most upstream stage of the development) and data files generated by the database system are shared by all downstream stages ranging from software installation to the network testing. In the software implementation stage, an automatic implementation system of communication data specifications using the database files and a communication software module (described below) is introduced in order to reduce development man-hours and improve the reliability of the communication processing software. In addition, the same database files as those used in the design stage are used in the testing stage for stand-alone ECUs and those connected to a network for the purpose of network simulation and test programming, thereby improving the test efficiency and assuring consistency of communication specifications between the design and the test.

The communication software module employed in the above-mentioned software implementation stage is a modular package of the software for processing communication between the CAN controller and application

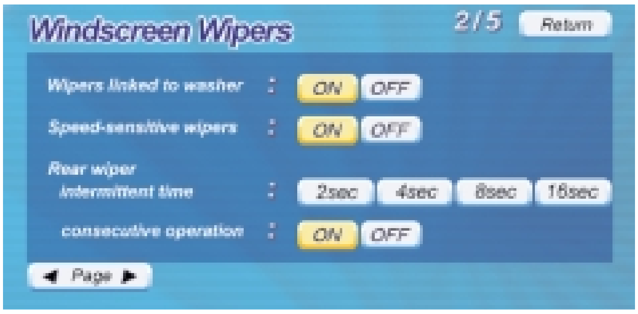


**Fig. 8 Function customization screen (example showing wiper-related functions)**

software. By multiple ECUs sharing software of pre-assured quality, both reduction in man-hours for development of individual ECU's software and minimization of variation in software quality between ECUs are intended.

## 6. Effects yielded by new communications system

### 6.1 Reduction of number of wiring harnesses

The ECUs on the new communications system network do not need dedicated circuits for signals used between themselves. In the case of the new GRANDIS, a total of 30 circuits (70 in the number of harnesses) could be reduced compared with the earlier model GRANDIS. The reduced circuits include those for air conditioner compressor and condenser fan control signals (from air conditioner to engine), gearshift position signals (from automatic transmission to combination meter), and vehicle speed, engine speed, and coolant temperature signals (from engine to combination meter).

### 6.2 Improvement in performance

In the vehicles using the conventional communications system, many ECUs could not use data that would be helpful for better control, such as vehicle speed data, engine speed data, and gearshift position data, for cost reasons. The new communications system solved this problem, making it possible for these ECUs to receive additional information through a network and hence improve their functionality and control performance. Some of these improvements are described below.

In the air conditioner control area, the new communications system allows the air conditioner ECU and engine ECU to establish new coordinated energy saving control. Through mutual communication of data between both ECUs, such as for engine speed, compressor torque prediction, and refrigerant pressure, the Engine ECU can delicately control the engine output, idle speed, and cooling fan speed. As a result, the fuel consumption during air conditioner operation is reduced by approximately 8 %(1).

In the area of body control, the new communications system has enabled sophisticated controls such as the vehicle speed-sensitive wiper-speed control and selector lever position interlocked door-unlocking control to be applied even to moderately priced vehicles.

The new communications system has also made it possible for vehicle users to perform customized setting of body controller, which has been realized by coordinated operation of the ETACS and MDS. With this function, the driver can select options offered as amenity functions such as automatic lighting intensity of headlamps, number of headlamp flashing times in response to operation of the keyless entry system, activation/deactivation of the headlamp automatic cutoff function, intermittent operation interval of the rear wiper, activation/deactivation of the washer interlocked-wiper operation, and activation/deactivation of the door ajar warning (**Fig. 8**).

## 7. Evaluation of system reliability

In order to assure the reliability of the new in-vehicle communications system, tests are conducted for both the hardware and software qualities. The following subsections describe some of these tests.

### 7.1 State transition check tests

The sleep/wakeup control of the bus is tested minutely for operational conformity to the specifications. Any abnormality in this control causes a significant problem. For instance the sleep malfunction would lead to a discharged battery due to increase of electric power consumption when the engine is shut down. The wakeup malfunction would lead to a loss of normal communication when the ignition switch is in the ON position. In practice, a network system equivalent to one on the actual vehicle is set up on a test bench and state transition takes place by imitating input signals to each ECU. During this test, the transition of the state inside each ECU and the state of sleep control data on the bus are checked by using a RAM monitor, data monitor tool for the CAN bus, and a oscilloscope.

### 7.2 Open-/short-circuit tests

Open circuit (including poor contact) or short circuit occurring in the communication lines routed throughout the vehicle are considered to be one of the major causes of faults of the in-vehicle communication system. In order to check for an open or short circuit in the communication line, the communication line faults listed in **Table 4** are artificially prompted to occur in all the

**Table 4 Fault modes checked by open-/short-circuit tests**

| | |
|---|---|
| 1 | CAN_H is open-circuit |
| 2 | CAN_L is open-circuit |
| 3 | Both CAN_H and CAN_L are open-circuit |
| 4 | CAN_H is shorted to 12 V |
| 5 | CAN_L is shorted to 12 V |
| 6 | CAN_H is shorted to ground |
| 7 | CAN_L is shorted to ground |
| 8 | CAN_H and CAN_L are shorted to each other |

communication lines between the ECUs and junction connectors to see the resulting behavior of the vehicle, state of communication in each ECU, and fault codes recorded in each ECU.

### 7.3 Transmission delay time tests

The bit encoding method employed in the CAN communication is not compatible with bit-by-bit synchronization, so a delay in communication signals could cause loss of synchronization between ECUs. To prevent this, an electrical delay time in transfer of communication signals is checked between the CAN controller's I/O terminals of all ECUs.

## 8. Summary

MMC developed a new-generation in-vehicle communications system using CAN as the basis of the network design, and using this system, the company successfully achieved the targeted objectives, including reduction of wiring harnesses, improvement of control performance, and introduction of a new-generation diagnosis system. In addition to CAN, other communication protocols such as those for applications to distribution real-time control and to multimedia communications will be put into practical use. MMC will continue efforts to optimize the electric and electronic system architecture of the whole vehicle employing these new technologies.

In closing, we wish to express our gratitude to all the people inside and outside the company who provided valuable co-operation in the development process.

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NEW TECHNOLOGIES

# Development of Next Generation Diagnosis Functions

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Toshiki FUKAYA* Yoshiaki ITO****

## Abstract

**Mitsubishi Motors Corporation (MMC) has developed the following new functions for diagnosing electronically controlled systems:**

- **"CAN Bus Diagnosis Function" for diagnosing the controller area network (CAN) communications bus**
- **"MUT-III/Pro-METS" (Multi-Use Tester III/Mitsubishi ECU Test System for Production), a software development tool compatible with the new communications protocol "KWP*2000 on CAN"**

**MMC has also developed the following functions for utility applications, not limited to diagnosis:**

- **An ECU variant coding function to minimize ECU types**
- **An ID data read function to ensure parts traceability**

*** KWP = Keyword Protocol**

***Key words:*** *Multiplexing Diagnostics, Electronics*

## 1. Introduction

MMC started introducing the CAN communications system as the new in-vehicle communications system in its products beginning with the new Mitsubishi COLT. To enable the diagnosis system to accommodate this new communications system, MMC has introduced the following next generation diagnosis tools for more efficient, thorough and effective inspections and diagnoses:

- "E-tester" for development
- "Pro-METS" for manufacturing
- "MUT-III" for service

The Pro-METS and MUT-III are new diagnosis tools originally developed by MMC and they share the same communications interface and diagnosis database. In addition, they are designed in compatible with the "Common Access to Electronic Systems of Automotive Requirements (CAESAR)" System on which the E-tester (the tester used by DaimlerChrysler as a standard diagnosis tool) is based. Adaptation of CAESAR prevents the differential of diagnostic data between MMC's original tester and E-tester.

Although the new in-vehicle communications system offers many advantages, their complexity makes it difficult to identify the causes of problems of a defect or fault. To counter this difficulty, MUT-III incorporates a CAN bus diagnosis function capability for diagnosing the CAN bus. On the other side, the ECUs are compatible with the new communications protocol, KWP2000 on CAN. This communications protocol has very high extensibility and allows completely new functions to be incorporated, such as the ECU variant coding function (which is essential in the strategy for minimizing the number of ECU types) and the parts traceability function. These functions were developed using cutting-edge technologies that are new to the Japanese automobile industry. This cross-field development serving diverse functions was realized through collaboration among the development, production, and service departments of MMC.

## 2. New diagnosis system "Pro-METS" for manufacturing

The Pro-METS was developed as a new ECU diagnosis system for the delivery inspection of vehicles whose diagnosis communications depend on the CAN system. This ECU diagnosis system was developed with the following target features:

(1) Capable of diagnosing ECUs through CAN communications system
(2) Capable of diagnosing ECUs also through conventional communications system
(3) Flexible designation of any diagnosis items
(4) Interface function to accommodate the diagnosis needs of future ECU functions (such as the ECU variant coding function)
(5) Shared use by all MMC plants for ECU diagnosis and other purposes

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*** Service Information Management Department, Global Aftersales Office
**** Assembly Production Engineering Department, Global Production Office

### 2.1 Features

Since the Pro-METS uses the same V.C.I. (vehicle communication interface) of the new service-use diagnosis tool MUT-III (described in the next section), the Pro-METS can share the diagnosis information database with MUT-III. This eliminates the need to check diagnosis items that have already been checked at the development stage again during service operations.

In order to minimize the work when developing hardware systems, the Pro-METS is configured utilizing personal-computer functions for controlling inspection terminal devices and the V.C.I., and a server is used for data storage and management.

Inspection data are accumulated in the inspection result database in the server together with vehicle specification data to ensure traceability.

### 2.2 Overview of Pro-METS system

**Fig. 1** shows an overview of the Pro-METS. The system consists of the Line Side Station (LSS) and multiple Mobile Test Terminals (MTTs). The LSS is a server that stores and manages ECU diagnosis data, vehicle specification data and the MTTs, whereas the MTT is an inspection terminal.

### 2.3 Extensibility

**Fig. 2** shows the three variations of the Pro-METS system. Owing to the new generalized basic functions they have in common, these variations assure that the Pro-METS system can be adapted to suit delivery inspections conducted in a variety of factories, from mass production plants to small-scale knockdown production plants.

Type 1 is for use in mass-production plants, where the production data provided from a plant's higher hierarchy system and stored in the LSS are used for automatic delivery inspection of ECUs. Type 2 is for use in mid-scale plants where the LSS is used for storing and managing vehicle specification data (not production data) and data from the LSS can be used as delivery inspection data. Type 3 is a stand-alone version of the Pro-METS for small-scale knockdown production plants, where it is used on its own for rather slow diagnosis. MMC's Okazaki plant, where the new Mitsubishi COLT is manufactured, uses the Type 1 Pro-METS system.

The MTT can be used as a mobile terminal when it is combined with an IEEE802.11x wireless LAN.

### 2.4 Pro-METS's future prospects

In order to accommodate the increasing complexity of ECU variant coding and contents of ECU inspection while guaranteeing consistent quality standards for all ECUs in all vehicles produced in all MMC and affiliate factories around the world, MMC will continue to upgrade the functions of the Pro-METS.

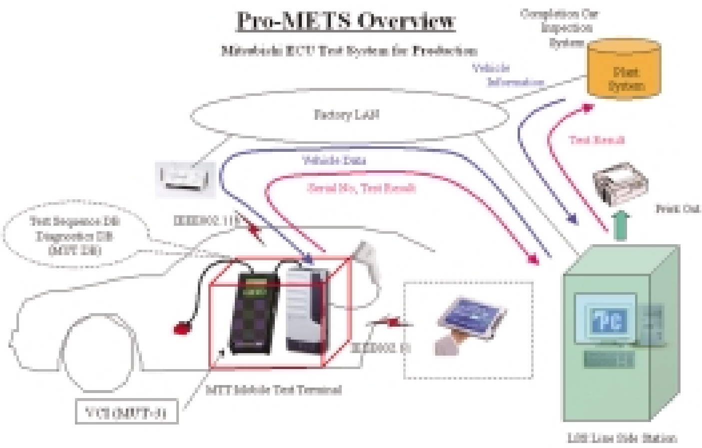


**Fig. 1 System overview of Pro-METS**

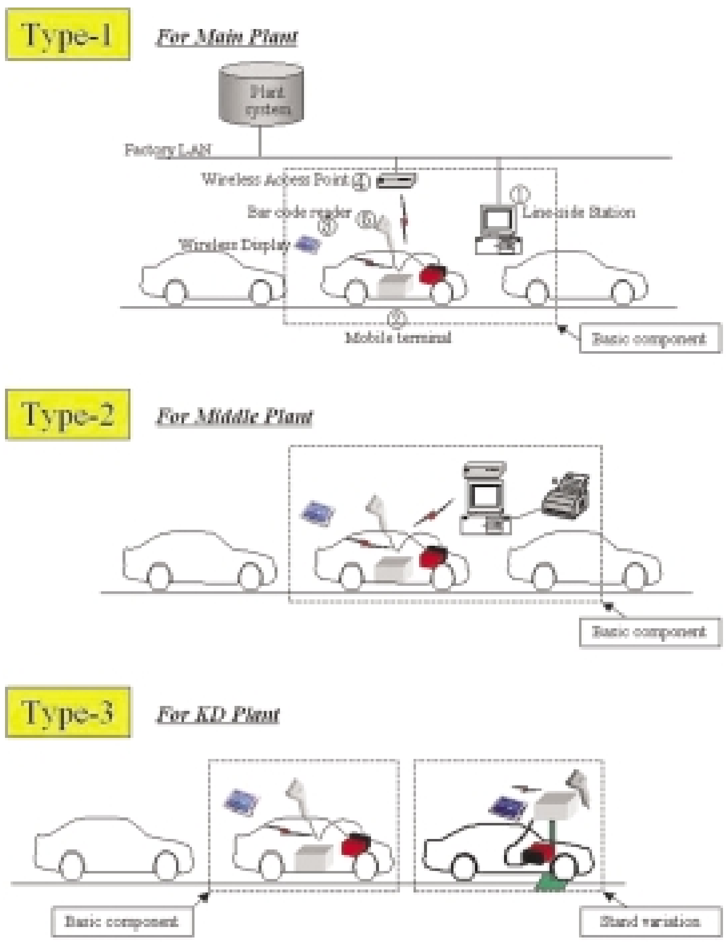


**Fig. 2 Variations of Pro-METS**

## 3. New diagnosis system "MUT-III" for use by service personnel

### 3.1 Overview

In accordance with releasing new products that introduce CAN communications systems, MMC has

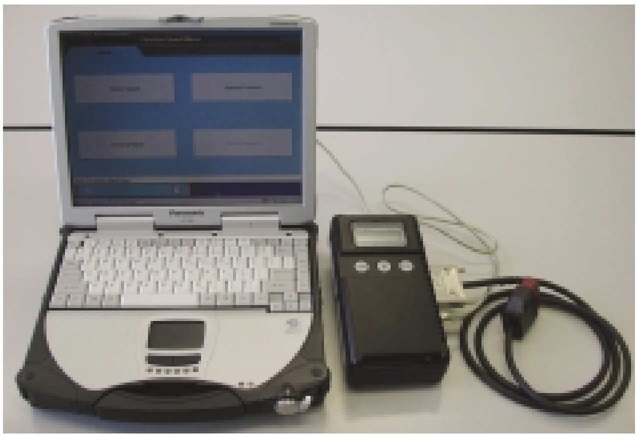

Fig. 3 MUT-III

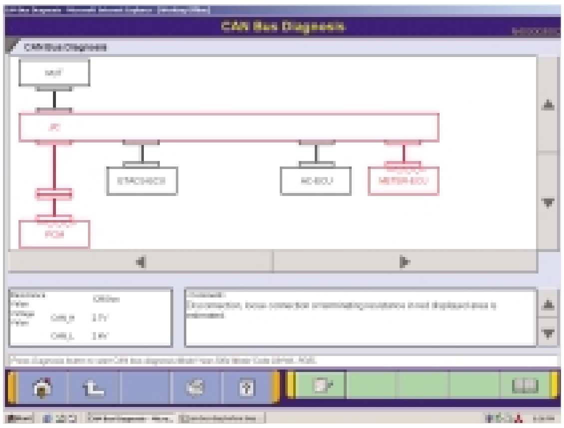


Fig. 4 CAN bus diagnosis

developed the MUT-III as a next generation diagnosis tester for servicing these new and future vehicles (**Fig. 3**).

A personal computer (PC) is connected to the MUT-III unit and used as a system's control terminal, and communicates with a vehicle ECU through the V.C.I.. In addition to being able to handle all diagnosis functions covered by the conventional MUT-II tester, the MUT-III system can display data as easy-to-understand diagrams and graphs on a large screen of the PC.

Unlike the MUT-II, the MUT-III can retain data on all vehicles, from old to new models, classified according to destination in the PC's hard disk. This eliminates the awkward but essential job with the MUT-II, of switching the data list (communications protocol data and diagnosis item list database) by replacing the ROM pack with another according to the vehicle model and year model.

New functions that make use of the advantages of the PC are also being developed. For example, the workshop manual viewer is a useful function for mechanics as they no longer have to carry around a thick manual and search for relevant pages while working on a vehicle. The workshop manual viewer is currently available for certain vehicle models, and allows users to retrieve the pages containing the failure code for a particular problem at the push of a button.

### 3.2 CAN bus diagnosis function

The high-speed CAN bus used in the new in-vehicle communications system is of a two-wire structure that is highly resistant to failure, and will work even when one wire circuit becomes open. This high resistance to failure allows the bus to operate without notable adverse consequences even if small problems are present, but it prevents problems from showing up until they build up and appear as a fault, which makes diagnosis difficult. To overcome this situation, we developed a "CAN bus diagnosis function" which can identify the presence of abnormalities in the CAN bus and narrow down the source of the problem to a certain area.

This CAN bus diagnosis function is available on the MUT-III through a screen like that shown in **Fig. 4**. When the user presses the diagnosis button after selecting a vehicle model and ECU type, MUT-III automatically detects the presence of an abnormality based on the voltages of the CAN_H and CAN_L wires, the resistance between the two wires, and whether or not each ECU is sending signals. The results are then displayed on the screen. If the problem is an open circuit, the function can isolate the problem to a small area. In designing the CAN bus diagnosis function, we allocated the function of determining the presence or absence of problems to the Pro-METS and the function of narrowing down problems to suspect areas to the MUT-III.

## 4. Data sharing between diagnosis tools

As against the Pro-METS and MUT-III, we use the E-tester for development, which is used by DaimlerChrysler as the standard tool. Although the Pro-METS and MUT-III database differ from E-tester database at first after development, we later incorporated CAESAR (DaimlerChrysler's standard basic software for diagnosis communications) used in E-tester into the MUT-III in order to allow the tools to share the same database. This data sharing has effectively reduced data buildup lead-time and improved data reliability, and it will be applied to the Pro-METS in the near future.

## 5. "KWP2000 on CAN" protocol

Conventional MMC vehicles introduced the ISO9141 defined K-LINE technology for diagnosis communications. However, the new in-vehicle communication system allows the CAN technology to be used not only for control communications but also as a backbone network bus for diagnosis communications. To use the CAN bus for diagnosis communications, we adopted the ISO15765 defined "KWP2000 on CAN" communications protocol. All the above-mentioned new diagnosis tools are based on this protocol.

### 5.1 Features

The main features of the KWP2000 on CAN protocol

are as follows:
- It is becoming a global standard communications protocol. In North America, other communications protocols will no longer conform to the On-Board Diagnosis (OBD) regulations.
- The same CAN communications wire can be used for control and diagnosis, thus reducing the number of harnesses.
- Many standard functions (services) can be provided.
- High-speed communications of CAN provides high-speed data transfer, which in turn provides quick ECU flash reprogramming.

### 5.2 Application

KWP2000 on CAN allows any ECU connected to the CAN bus to have the diagnosis communication function without additional hardware. This capability of the protocol enables such ECUs as those of the Electronic Time Alarm and Control System (ETACS) and combination meter, which originally are not given full-scale diagnosis functions, to have diagnosis communications functions.

### 5.3 Functions

Next generation diagnosis functions made possible by adopting KWP2000 on CAN communications protocol include the following:

[Read-out ID data function]

This function is useful for storing and retrieving vehicle history data to ensure traceability. Data read by using this function include ECU software version, hardware version, and serial numbers.

[Diagnosis trouble code (DTC) related function]

Using DTCs compliant with the SAE standard (two-byte system), adding status data to present and past failures, and freeze-fame data, among others.

[ECU variant coding function]

This function is essential for reducing ECU types. The ECUs on each vehicle are programmed to their specifications by means of the ECU variant coding function, and the diagnosis tool uses these to send the specification data to the ECUs on the vehicle. This minimizes the number of basic ECU types required.

## 6. Acknowledgement

Next generation diagnosis tools and ECU functions were successfully developed through the combined efforts of the development department, production department and service department at MMC.

The authors would like to take this opportunity to thank everyone who contributed to the development of the diagnosis system adapted to the new in-vehicle communications system.

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# Development of PAJERO EVOLUTION Rally Car for 2003 Dakar Rally

Yoshihiko OTOTAKE* Shuusuke INAGAKI*

In mid-2001, the rules of the Dakar Rally, which had until then limited entry to modified production models (T2-class), were revised to make completely new prototype four-wheel-drive (4WD) vehicles eligible to take part. Taking advantage of the freedom yielded by the new rules, Mitsubishi Motors Corporation (MMC) developed a new-concept cross-country rally car, the PAJERO EVOLUTION, with a view to securing victory in the 2003 Dakar Rally. Two PAJERO EVOLUTIONs took part in 2003, one crossing the finishing line in first place, the other in third place (**Fig. 1**). A technical overview of the PAJERO EVOLUTION is given in this paper.

## 1. The Dakar Rally

The competition now known as the Dakar Rally first took place 25 years ago (in 1979) and is renowned as the longest and toughest rally in the world. Starting in midwinter, participants race from Europe into Africa, where they experience mountains, rocky roads, dirt tracks, deserts, sand dunes, savanna, and other challenging terrain over a period of about three weeks and a total distance of about 10,000 km.

MMC has entered PAJEROs every year since 1983 (the year after the first-generation PAJERO was launched). In this 20-year period, MMC has achieved eight victories, including three consecutive victories in the last three years.

## 2. Concepts behind new PAJERO rally car

### 2.1 Vehicle classification

The minimum mass of a competing vehicle is determined in accordance with the engine's swept volume as shown in **Table 1**.

### 2.2 New PAJERO EVOLUTION rally car (Fig. 2)

Taking advantage of its existing technological base, MMC gave the new PAJERO EVOLUTION superior competitive strength and reliability using the following features:

- Repositioned drivetrain (yielding a lower center of gravity)
- Lightweight, high-rigidity tubular frame
- Four-wheel independent suspension (superior in terms of both handling stability and roadholding) combined with a long wheelbase (superior in terms of dynamic stability and load capacity)

**Fig. 1 PAJERO EVOLUTION rally car at 2003 Dakar Rally finishing line**

**Table 1 Minimum vehicle mass by engine swept volume**

| Engine swept volume (cc) | 4WD vehicle (kg) | 2WD vehicle (kg) |
|---|---|---|
| Smaller than 1,600 | 1,300 | 920 |
| 1,600 – 2,000 | 1,525 | 1,040 |
| 2,000 – 2,500 | 1,600 | 1,100 |
| 2,500 – 3,000 | 1,675 | 1,160 |
| 3,000 – 3,500 | 1,750 | 1,220 |
| 3,500 – 4,000 | 1,825 | 1,280 |
| 4,000 – 4,500 | 1,900 | 1,340 |
| 4,500 – 5,000 | 1,975 | 1,400 |
| 5,000 – 5,500 | 2,050 | 1,460 |
| 5,500 – 6,000 | 2,125 | 1,520 |
| 6,000 – 6,500 | 2,200 | 1,580 |
| 6,500 – 7,000 | 2,275 | 1,640 |
| 7,000 – 7,500 | 2,350 | 1,700 |
| 7,500 – 8,000 | 2,425 | 1,760 |
| Larger than 8,000 | 2,500 | 1,820 |

- Newly tuned version of the previous model's proven engine

## 3. Engine specifications

The Dakar Rally rules permit competing vehicles to be powered by either gasoline engines or diesel

* Motor Sports Team, Research & Development Office

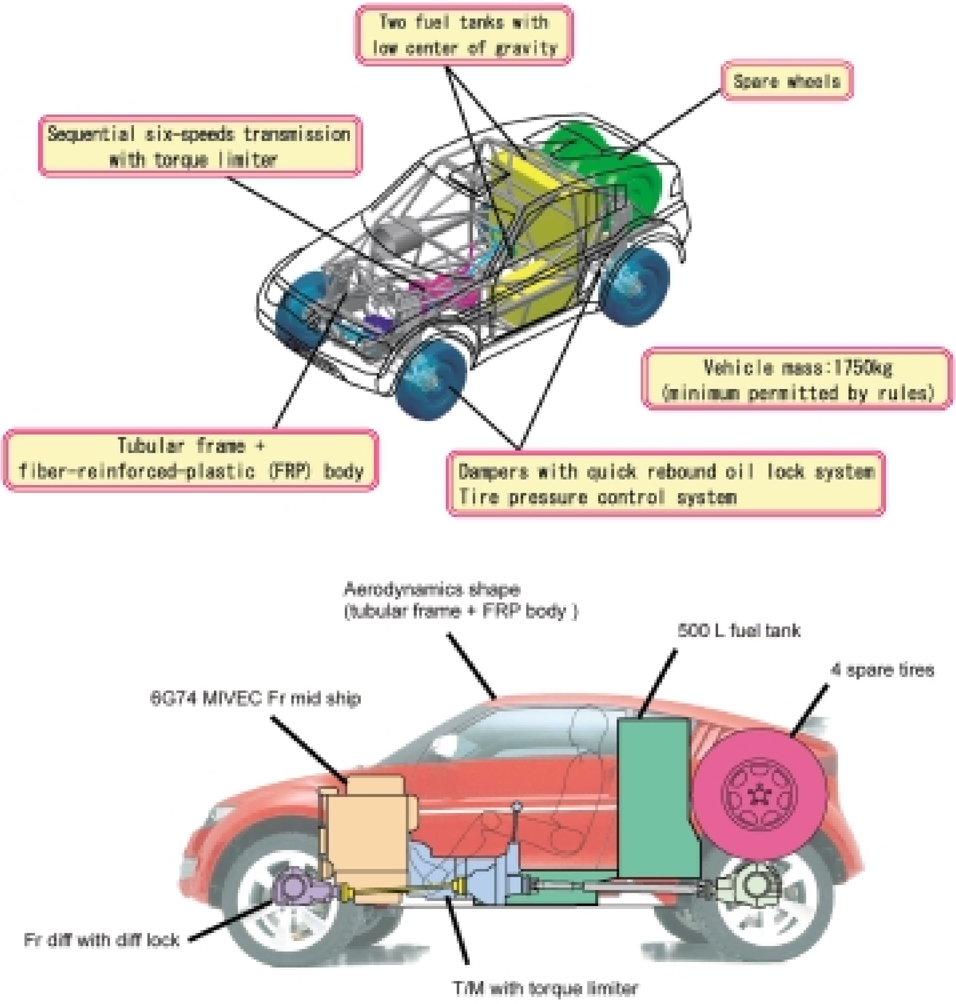


**Fig. 2 Key features of new PAJERO EVOLUTION rally car**

engines. Turbochargers are forbidden for gasoline engines but not for diesel engines. Each engine may have a maximum compression ratio of 10.5 and must have a restrictor to limit the rate of air intake (A 32 mm-diameter restrictor is mandatory for a four-valve-per-cylinder engine).

The PAJERO EVOLUTION is powered by an upgraded version of the proven 6G74 MIVEC engine. Enhanced torque characteristics yield stronger low-end torque and a flatter torque curve, and the engine is lighter than the original version. Also, an upgraded cooling system with increased radiator and oil-cooler capacities better enables the engine to withstand low-speed, high-load operation for long periods.

## 4. Drivetrain (Fig. 3)

In line with the revised rules, MMC lowered the vehicle’s center of gravity by repositioning the front differential in front of the engine (thereby flattening the profile of the engine-and-transmission assembly) and by lowering the engine-and-transmission assembly’s position. The full-time 4WD drivetrain has viscous coupling units (VCUs) for the center and front differentials and a mechanical limited-slip differential for the rear differential to ensure superior traction and reliability. A locking mechanism was added to the front-differential VCU (positioned in parallel with it) to aid extrication of the vehicle from sand dunes. With the transmission, a six-speed sequential shift mechanism was adopted to enable easy shifting. As a way to reconcile the need for a lower center of gravity with the conflicting need for increased ground clearance, MMC redesigned the entire drivetrain to enable large, weighty components to be arranged on a relatively flat profile over the bottom of the vehicle. Jumps and other rally maneuvers create frequent shock inputs that have the potential to cause drivetrain damage. Since the drivetrain of the PAJERO EVOLUTION rally car was built using newly specified components, the likelihood of such damage was deemed too difficult to predict. A torque limiter was thus employed to mitigate shock inputs. The torque limiter is based on a standard clutch mechanism and incorporates modifications for an optimal combination of slip-speed characteristics and thermal characteristics. In the drivetrain, the torque limiter is arranged in series with a standard clutch. The torque limiter and clutch proved successful in preventing sudden breakage of drivetrain parts, but the torque limiter was found to require careful wear management.

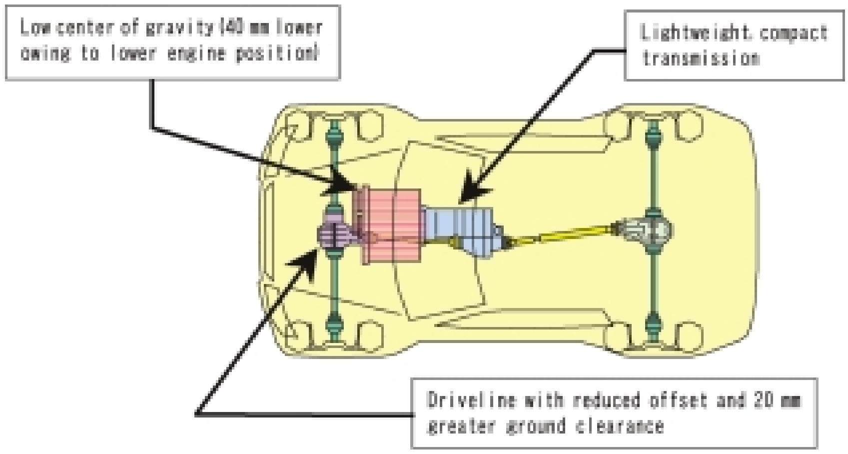


**Fig. 3 Drivetrain structure**

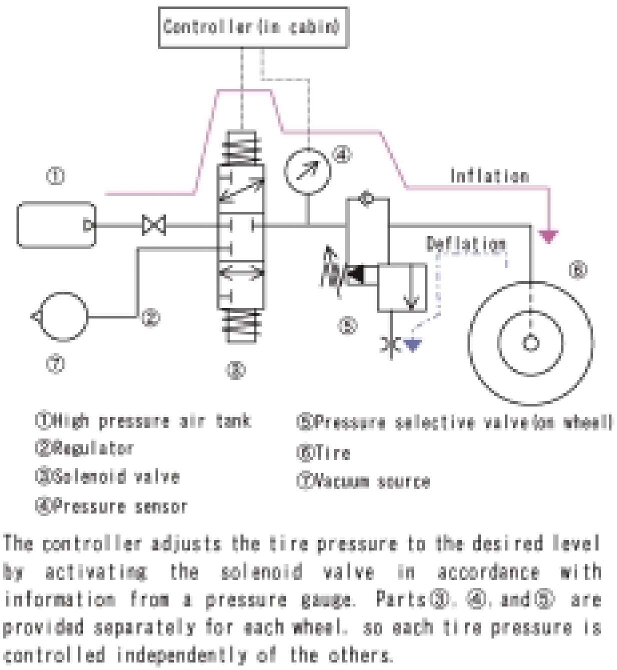


**Fig. 4 Air path of tire-pressure control system**

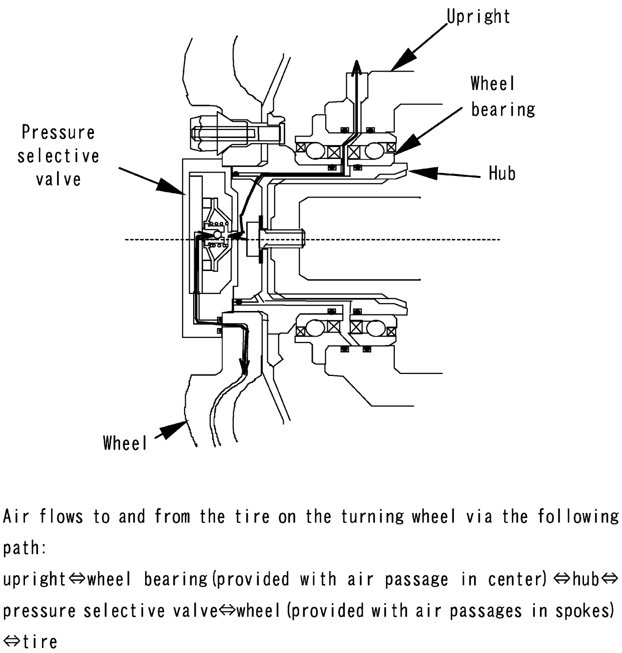


**Fig. 5 Air path**

## 5. Suspension

The suspension stroke, which is crucial with regard to rough-road performance, is limited by the Dakar Rally rules to 250 mm. MMC thus determined the optimal bump-to-rebound ratio within the permitted stroke with regard to body inputs and traction.

Know-how gained through experience with earlier vehicles enabled MMC to simultaneously achieve the best possible wheel alignment.

Each wheel has two shock dampers. This arrangement minimizes heat-induced deterioration in damper performance during rough-road driving. Also, each damper incorporates a quick-rebound oil-lock mechanism that limits the extension-stroke damping force during rapid strokes, thereby promoting rough-terrain roadholding and ensuring adequate ground clearance.

## 6. Tire-pressure control system

Vehicles in the Dakar Rally travel 300 – 800 km per day over a wide variety of surface conditions. The optimum tire pressure depends on the current surface condition; a high pressure is suitable for relatively hard surfaces as it ensures adequate longitudinal rigidity in the tires and thus helps to prevent blowouts, but a low pressure is suitable for sand dunes as it gives the tires relatively large contact patches and thus helps to prevent the tires from sinking into the sand. In earlier years, the team had to stop the vehicle and adjust the tire pressure manually each time they encountered a different surface condition. To eliminate this time-wasting task with the new PAJERO EVOLUTION rally car, MMC developed a tire-pressure control system that allows the team to adjust the tire pressure without stopping (**Figs. 4** and **5**).

## 7. Summary

Two decades of continual experience in the Dakar Rally and its predecessors since the introduction of the first-generation PAJERO have given MMC a wealth of knowledge on ways to maximize vehicle performance and reliability under long-distance, off-road conditions. By applying this knowledge to production vehicles, MMC has successfully evolved the PAJERO in terms of speed, reliability, safety, and comfort. As MMC continues to develop technologies for victory under harsh African rally conditions, it will continue to reflect the benefits not only in production PAJERO models but also in all other Mitsubishi vehicles.


Yoshihiko OTOTAKE


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# Shikoku EV Week 2003

Tohru URANO* Keiichi KANESHIGE*
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## 1. Introduction

Shikoku EV Week is Japan's only electric vehicle (EV) rally held on public roads. It took place for the sixth time this year. Mitsubishi Motors Corporation (MMC) entered the Mitsubishi ECLIPSE EV prototype in the EV Rally, the main event of the Week, but first test drove the vehicle from MMC's Tokyo headquarters to the Tokushima College of Technology, the central event site, over a total distance of 1,200 km in the EV Ekiden, a preliminary event. Our objective in the test drive was to prove that the ECLIPSE EV could be driven without any deficiency not only on normal flat roads and highways but also on alpine roads, on mountain tracks, and in other demanding conditions. This paper presents the specifications of the ECLIPSE EV together with details and results of the test drive.

## 2. Vehicle specifications

The ECLIPSE EV is shown in **Fig. 1**, and its major specifications are shown in **Table 1**. The ECLIPSE EV is equipped with a 100 kW permanent magnet synchronous motor (manufactured by Mitsubishi Heavy Industries Ltd.) and with lithium-ion battery packs (manufactured by Japan Storage Battery Co.) that have a total voltage of 355 V and a capacity of 95 Ah.

**Fig. 1 ECLIPSE EV**

**Table 1 Major specifications of ECLIPSE EV**

| | | | |
|---|---|---|---|
| Vehicle | Overall length | (mm) | 4,450 |
| | Overall width | (mm) | 1,750 |
| | Overall height | (mm) | 1,310 |
| | Mass when empty | (kg) | 1,515 |
| | Seating capacity | (persons) | 2 |
| | Drive system | | Front wheel drive |
| | Transmission | | 5 M/T |
| | Maximum speed | (km/h) | Over 180 |
| Motor | Type | | Permanent magnet synchronous |
| | Maximum output | (kW) | 100 |
| | Maximum torque | (Nm) | 250 |
| | Cooling system | | Water cooling |
| | Dimensions | (mm) | 300 x 200 |
| | Weight | (kg) | 47 |
| Batteries | Type | | Li-ion |
| | Capacity | (Ah) | 95 |
| | Total voltage | (V) | 355 |
| | Dimensions | (mm) | 388 x 175 x 116 |
| | Weight | (kg/module) | 14.5 |
| | Number | | 24 (series-connected) |

## 3. Shikoku EV Ekiden

### 3.1 Overview

The Shikoku EV Ekiden is a long-distance competition in which each participating team designs its own course to the central event site in Shikoku and uses battery chargers that are specially set up along the course.

The ECLIPSE EV left MMC's headquarters in the Shinagawa area of Tokyo at 6:30 a.m. on Tuesday, August 19, 2003. After covering a 1,200 km course including various road conditions, it arrived at the destination, the EV Week event site at Tokushima College of Technology, at 11:30 a.m. on Friday, August 22. Data collection on battery consumption was performed most intensively on alpine roads in the vicinity of Mount Fuji and on mountain tracks that cut across the center of Shikoku (**Fig. 2**).

### 3.2 Alpine roads in vicinity of Mount Fuji

The ECLIPSE EV was driven on the Mount Fuji Skyline road, which starts at an altitude of approximately 1,500 m and extends for approximately 12 km to its highest point, Shin-Gogome (**Fig. 3**), which has an altitude of approximately 2,400 m. The average gradient from the starting point to Shin-Gogome is 7.5 % (see the elevation diagram in **Fig. 4**). The battery consumption rate was measured continuously while the ECLIPSE EV was running in this demanding alpine environment. The measurements are plotted in **Fig. 5**.

The battery consumption rate during the 12 km

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Fig. 2 EV Ekiden route

Fig. 3 Mt. Fuji Shin-Gogome

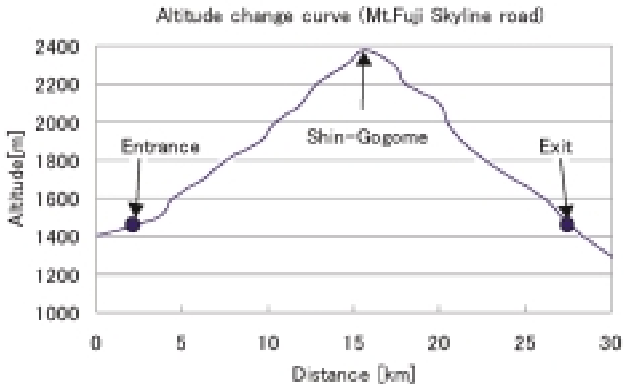


Fig. 4 Altitude changes on Mt. Fuji Skyline road

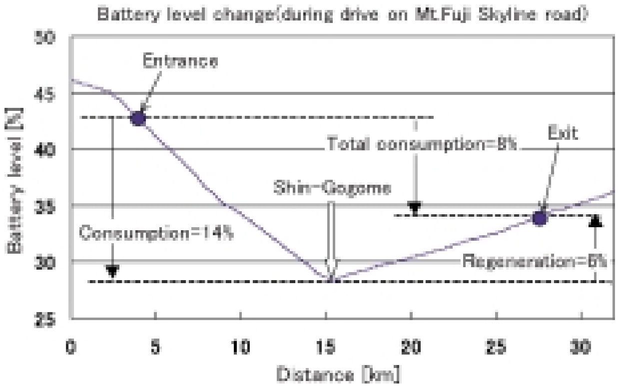


Fig. 5 Battery level changes on Mt. Fuji Skyline road

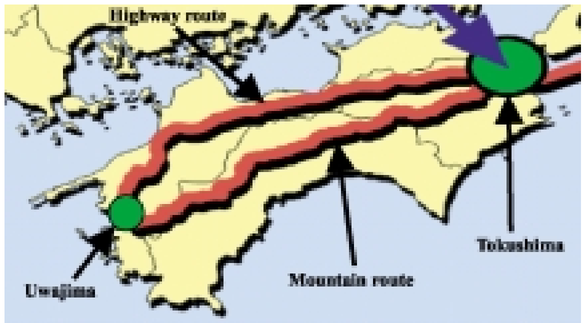


Fig. 6 Trans-Shikoku routes

climb was 14 % (with the full battery capacity taken as 100 %). The same vehicle driven for 12 km at 80 km/h on a level road consumes electricity equivalent to about 3 % of the battery capacity, so the figure of 14 % shows that the battery consumption rate significantly rises during uphill driving. Energy consumption similarly increases during uphill driving in a vehicle that has an internal combustion engine. On downhill roads, however, an EV and a vehicle with an internal combustion engine behave very differently with regard to energy consumption; an EV has a regenerative braking system, which allows braking energy (which would otherwise be released as heat into the air) to be recovered by means of the motor (which functions as a generator at this time) for charging of the batteries. Using its regenerative braking system in this way, the ECLIPSE EV was able to recover electricity equivalent to 6 % of the battery capacity on the downgrade of the Mount Fuji Skyline road (**Fig. 5**). Although the average battery consumption over the entire length of the Mount Fuji Skyline road exceeded the battery consumption rate that would be expected on a level road, the vehicle was capable, using its ability to recover braking energy (an ability that a vehicle with an internal combustion engine does not have), of recovering nearly half of the energy that it had consumed during uphill driving.

Since the test data made it clear that energy consumption on upgrades is considerably higher than energy consumption on flat roads, they will be used for reference in efforts to improve electric motor characteristics in pursuit of lower battery consumption.

### 3.3 Mountain tracks across Shikoku

The trans-Shikoku routes used in the 2003 EV Ekiden are shown in **Fig. 6**. In 2003, participants raced from Tokushima City to Uwajima City on a mountain route then back from Uwajima City to Tokushima City using a highway. With several mountains (including the 2,000 m Mount Tsurugi) to be crossed, the mountain route made the ECLIPSE EV consume much more electricity than on flat roads while providing the team with an opportunity to determine the benefit provided by the vehicle's regenerative capability (**Fig. 7**). **Fig. 8** shows the battery consumption rates of the ECLIPSE EV and the fuel consumption rates of a 2,400 cc gasoline vehi-

Fig. 7 Shikoku mountain route (Mt. Tsurugi)

ECLIPSE EV — Course: between Tokushima and Uwajima

| Route | Distance [km] | Battery consumption [kWh] | Average speed [km/h] | Average battery consumption rate [kWh/km] |
|---|---|---|---|---|
| Mountain route | 368.6 | 44.4 | 33.03 | 0.12 |
| Highway route | 280.0 | 25.8 | 59.96 | 0.09 |

Approx. 33% increase

Consumption rate: $\frac{1}{2}$

2,400 cc gasoline vehicle

| Route | Distance [km] | Fuel consumption [L] | Average speed [km/h] | Average fuel consumption rate [L/km] |
|---|---|---|---|---|
| Mountain route | 368.6 | 58.0 | 33.03 | 0.15 |
| Highway route | 280.0 | 25.7 | 59.96 | 0.09 |

Approx. 67% increase

Fig. 8 Comparison of energy consumption rates between ECLIPSE EV and accompanying gasoline vehicle

cle that accompanied the ECLIPSE EV for both the mountain route and the highway route. Whereas the battery consumption rate of the ECLIPSE EV on the mountain route was 33 % higher than that on the highway route, the fuel consumption rate of the gasoline vehicle on the mountain route was 67 % higher than that on the highway route. The gasoline-engine vehicle was 200 kg heavier than the ECLIPSE EV, so these figures do not permit accurate comparison of energy consumption between the two vehicles. However, the figures clearly indicate that the ECLIPSE EV's regenerative braking system played a significant part in limiting the increase in the battery consumption rate to 33 % and that EVs are suited to operation on mountain roads.

### 3.4 Data for individual route sections

**Fig. 9** shows the average speed and average battery consumption rate for each section of the 1,200 km route. The data for all route sections other than those in the vicinity of Mount Fuji (here, data for upgrade and downgrade sections are shown separately rather than averaged) show similar battery consumption rates. It can thus be concluded that energy consumption in an EV is less affected by changes in driving conditions than energy consumption in a gasoline vehicle is.

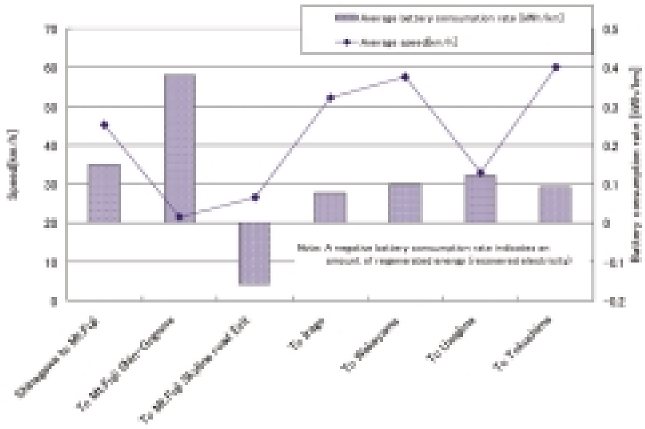


Fig. 9 Electricity consumed by ECLIPSE EV in each main route section

## 4. Summary

Participating in the EV Ekiden enabled us to confirm that the ECLIPSE EV's regenerative braking system has a significantly beneficial effect on the total battery consumption rate and that, although the ECLIPSE EV's energy consumption rises on mountain upgrades, its total energy consumption rate is, owing to the energy recovery that takes place on downgrades, greatly superior to that of a vehicle with an internal combustion engine. By continuing to participate in the Shikoku EV Week and other events held on public roads, we hope to communicate the merits of EVs, which are still not widely known, to the public. We will also continue to develop electric-motor-driven vehicles like hybrid electric vehicles and fuel cell vehicles.

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# Development of Tire-Pressure Monitoring System

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## 1. Introduction

A vehicle's tire performance has a major influence on the performance of the vehicle's three basic functions – running, turning, and stopping – as well as on ride comfort, noise, and fuel efficiency. To enable the tires to perform to their full potential, it is crucial to maintain the correct tire pressures at all times. However, many motorists continue to drive their vehicles without any awareness of decreased and otherwise inadequate tire pressures. Tire-pressure monitoring systems represent a solution that is attracting much interest. In the United States, it will soon be legally compulsory for every vehicle to have a tire-pressure monitoring system.

With regard to tire-pressure monitoring systems, Mitsubishi Motors Corporation (MMC) led the motor industry by providing the 1995 Mitsubishi DIAMANTE with a system that detected tire-pressure abnormalities indirectly by identifying differences between wheel speeds using information from the wheel-speed sensors of the antilock braking system.

MMC recently took a further step forward by equipping the ENDEAVOR, a new model for the North American market, with a tire-pressure monitoring system that measures the tire pressures directly (and with concomitantly superior accuracy) using a pressure sensor located inside each tire. This paper presents an overview of this new tire-pressure monitoring system.

## 2. System configuration and operation

As shown in **Fig. 1**, the ENDEAVOR's tire-pressure monitoring system consists mainly of sensor/transmitter units, a receiving antenna, a receiver, and a warning lamp.

Tire-pressure values measured directly by the sensor/transmitter units are transmitted as radio signals to the receiver via the receiving antenna. The receiver determines whether the tire-pressure values are acceptable. If it identifies an abnormality, it causes the warning lamp (this is located in the meter cluster) to illuminate to warn the driver of the need for a tire-pressure check.

Since tire-pressure values are transmitted as radio signals, there is a risk that the receiver will receive signals from the sensor/transmitter units of other vehicles equipped with the same type of system. To enable the receiver to identify and use signals from its own sensor/transmitter units and ignore those from other vehicles' sensor/transmitter units, each sensor/transmitter unit has a unique identification code, which it transmits together with tire-pressure data. The receiver is programmed to recognize the identification codes of its own sensor/transmitter units, so it uses only the relevant tire-pressure data to determine the necessity of activating the warning lamp.

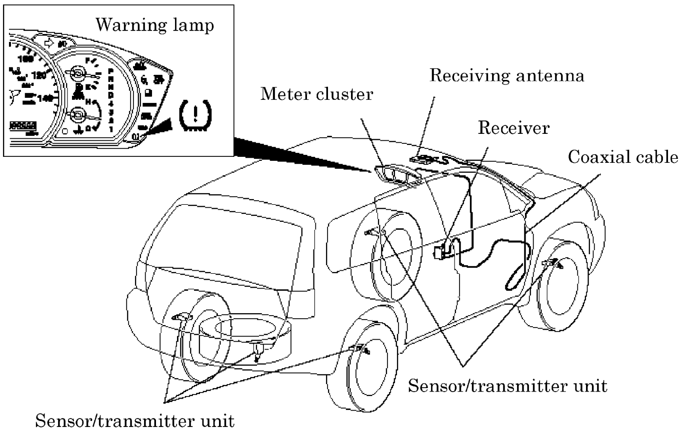


**Fig. 1 System configuration**

Further, the receiver is programmed to activate the warning lamp not only in the event that it receives abnormal tire-pressure signals but also in the event of an abnormality in the system's operation (for example, failure to receive signals from the sensor/transmitter units). The receiver causes the warning lamp to illuminate continuously for a tire-pressure warning and to flash for a system-malfunction warning, so the user can differentiate between the two types of warning.

With a direct-detection-type tire-pressure monitoring system that uses radio signals, the antenna must be located in such a way that it can constantly receive all signals emitted by each sensor/transmitter unit. The ENDEAVOR's antenna is mounted in the roof (between the roof panel and the trim) in the position that best enables it to receive signals from all four sensor/transmitter units. The coaxial cable that connects the antenna to the receiver is routed in a way that prevents it from being affected by electromagnetic noise generated by other electrical and electronic devices in the vehicle.

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Fig. 2 Sensor/transmitter unit on wheel

**Table 1 Specifications**

| | |
|---|---|
| Detection system | Direct detection |
| Warning method | Continuous illumination of warning lamp (for abnormal tire pressure)<br>Flashing of warning lamp (for system malfunction) |
| Warning-activation tire pressure | 174 kPa or less (recommended pressure: 220 kPa) |
| Frequency of radio signals | 433.92 MHz |
| Data transmission interval | When vehicle is running: every minute<br>When vehicle is not running: every hour |

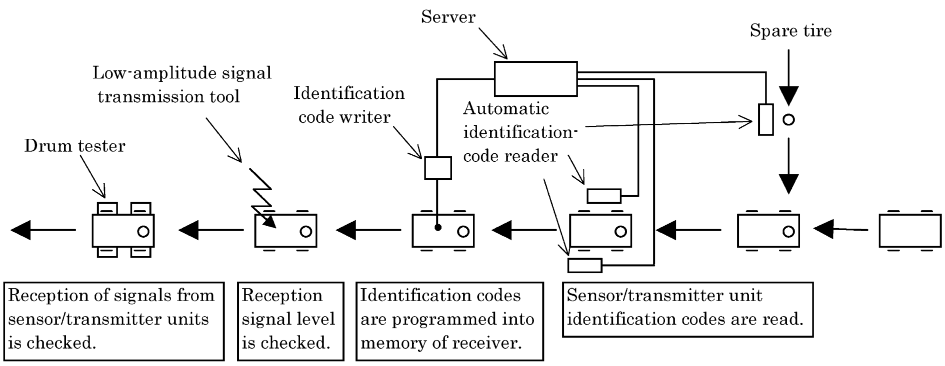


Fig. 3 Production process

Each sensor/transmitter unit forms an integral part of the tire's air valve and is located in the valve hole of the wheel. The wheels on the ENDEAVOR are specially designed to accommodate the sensor/transmitter units (including enough space for their installation and removal). **Fig. 2** shows a sensor/transmitter unit as installed on a wheel.

## 3. Specifications

The main specifications of the ENDEAVOR's tire-pressure monitoring system are presented in **Table 1**.

The system operates not only while the vehicle is being driven but also while the vehicle is parked (with the ignition switch off). If the receiver detects an excessive decrease in any tire pressure when the engine is not running, it activates the warning lamp immediately after the ignition switch is next turned on.

## 4. Production-line processes

As mentioned, the receiver must have in its memory the identification codes of the corresponding sensor/transmitter units before it can discriminate between tire-pressure signals from its own sensor/transmitter units and tire-pressure signals from sensor/transmitter units on other vehicles. On the ENDEAVOR assembly line, therefore, the identification codes are efficiently programmed into the receiver as follows: Each sensor/transmitter unit is subjected to a special radio signal that causes it to emit its identification code. A code reader automatically reads the identification code and programs it into the receiver via the vehicle's diagnosis connector (**Figs. 3** and **4**). (When identification-code

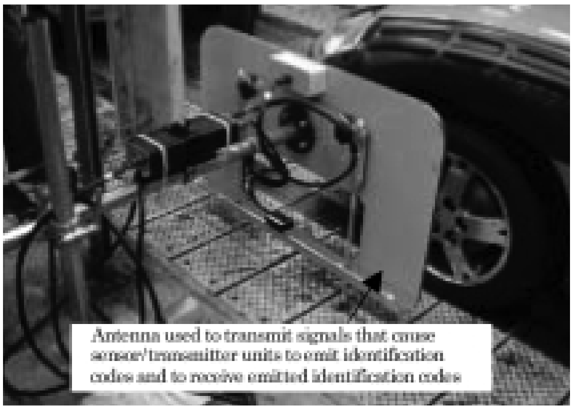


Fig. 4 Automatic identification-code reader

programming is necessitated by part replacement or other work performed in a service workshop, a separate method involving a diagnosis tool is used).

In the inspection process performed on the production line, special low-amplitude radio signals are emitted by a transmission tool held near the antenna and the strength of the signals detected by the receiver is monitored to enable confirmation that the antenna and receiver are correctly connected. For verification of the system's communication quality, a check is made for correct reception of radio signals from the sensor/transmitter units while the vehicle is running on a drum tester.

## 5. Conclusion

MMC plans to equip more vehicle models with the tire-pressure monitoring system that it developed for the ENDEAVOR. We look forward to developing other new products that enable us to meet our customers' needs in a timely manner.


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# Technological Trends in North American Markets

Hideki HADA*

## 1. The significance of North American markets

North America has massive automobile markets in which nearly 20 million new vehicles are sold every year. The vastness of the continent and the diversity of its inhabitants give the North American automobile markets unique characteristics that set them apart from the Japanese and European markets (**Table 1**). Further, the Canadian market strongly resembles the United States (US) market but is steadily developing its own distinct characteristics. This paper gives an overview of current automobile-related technological trends in the US and Canadian markets.

**Table 1 NAFTA automotive markets (2001 data)**

| | United States | Canada | Mexico |
|---|---|---|---|
| Vehicle production (million units) | 11.4 | 2.5 | 1.9 |
| New vehicle sales (million units) | 17.1 | 1.6 | 0.7 |
| Registered drivers (million persons) | 221.5 | 17 | – |
| Traffic fatalities (persons) | 42,116 | 2,778 | – |

## 2. Traffic safety measures taken by the US Department of Transportation

The US Department of Transportation (DOT) receives an annual budget in accordance with federal law. This budget is used to fund activities that include automotive safety research performed by the DOT and highway maintenance and construction performed by state governments under the auspices of the DOT. The federal government was implementing surface-transportation-related plans based on the Transportation Equity Act for the 21st Century (TEA-21) since 1998. This piece of federal legislation expired in September 2003, until when the federal government and the Congress had since 2002 been debating the content of legislation to succeed it. Thus far, the DOT has submitted the Safe, Accountable, Flexible, and Efficient Transportation Equity Act (SAFETEA), which calls for a total budget of $247.4 billion over a six-year period from 2004 to 2009.

The budget allocated for research by the National Highway Traffic Safety Administration (NHTSA), which is responsible for issues pertaining to vehicle safety, was approximately $80 million in fiscal 2003. The NHTSA's main activities include research into collision safety, collision prevention, and injury mechanisms and studies pertaining to intelligent transport systems (ITS) (**Table 2**).

Since 1978, the NHTSA has been assessing vehicles' safety performance through the New Car Assessment Program (NCAP). This program is currently being revised in terms of assessment objects and assessment criteria to accommodate changes in types of vehicle accidents occurring in the US and as a reflection of developments in similar assessment programs in other countries. Until recently, the only major revisions made to the program were the addition of static rollover crash indices and the addition of side impact tests. Encouraged by the Transportation Recall Enhancement, Accountability, and Documentation (TREAD) Act enacted in November 2000, however, the NHTSA is planning to apply more stringent assessment standards to a wider variety of test items: From 2003, dynamic rollover crash tests are to be incorporated into the program and the results of these tests are to be announced to the public. An assessment of the usability of child seats is to be mandatory. Plus, the number of assessment items for side impact tests is to be increased and an assessment of braking performance is to be added to the program.

## 3. Traffic safety measures taken by Transport Canada

Transport Canada is currently running a program called Road Safety Vision 2010 with a view to achieving the highest level of road safety among Organisation for Economic Co-operation and Development member nations by 2010. The main objective of this program is to keep the total number of automobile-related deaths and injuries in the 2008 – 2010 period 30 % lower than the total recorded in the 1996 – 2001 period. If the program is successful, the number of automobile-related deaths in 2010 will be lower than 2100. Concrete numerical targets set by Transport Canada include raising the rate of seatbelt usage among vehicle occupants to at least 95 %, reducing the number of deaths and injuries resulting from drunk driving and non-fastening of seatbelts by 40 %, and reducing the number of deaths and injuries involving speeding, road intersections, and beginner drivers by 20 %.

## 4. An examination of data on traffic problems in the US

A project on which the NHTSA has placed the high-

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**Table 2 Main NHTSA projects**

| Collision safety | Collision prevention | Injury mechanism analysis | ITS |
|---|---|---|---|
| Alleviation of injury and damage in frontal collisions<br>Occupant protection in rollovers<br>Reduction of occupants thrown out of vehicles<br>Improvement of occupant protection performance in side impacts<br>Development of advanced occupant protection devices<br>Assessment of airbag-inflicted injuries<br>Pedestrian protection<br>Accumulation and assessment of pre-impact data | Reduction of accidents involving rollovers<br>Quantification of rollover performance<br>Verification of effectiveness of antilock braking systems<br>Reduction of driver distraction<br>Clarification of anti-glare measures<br>Examination of effects of aging on driving | Clarification of measures for reducing injuries and damage<br>Clarification of injury and damage mechanisms<br>Verification through simulations<br>Establishment of method for estimating extents of injury and damage<br>Establishment of assessment procedures for airbags | Operational testing of collision warning systems<br>Accumulation of data on driving under normal conditions<br>Operational testing of driver monitors<br>Analysis of accidents occurring at intersections<br>Examination of equipment for preventing drivers from ignoring traffic lights<br>Development of high-accuracy digital maps<br>Assessment of workload quantification methods |

**Table 3 Data on Mitsubishi vehicles mentioned in NHTSA accident databases**

| Database | Content | Data on Mitsubishi vehicles (number of items) |
|---|---|---|
| **FARS**: Fatality Analysis Reporting System | Data on all fatal automobile accidents (approx. 40,000 cases/year) | 2,552 |
| **NASS-CDS**: National Automotive Sampling System – Crashworthiness Data System | Samples of accidents involving property damage or worse damage (5,000 cases/year) | 513 |
| **SCI**: Special Crash Investigation | Airbag-inflicted injuries and other special accident types (200 cases/year) | 16 |
| **CIREN**: Crash Injury Research & Engineering Network | Correlation between accidents and occupant injuries | 2 |

est priority is the construction of accident databases. These databases are significant not only because they are used by the DOT for planning of programs and evaluation of program results but also because they are available to the public and are thus treated by a large number of traffic-safety-related parties as a common source of reliable information. The NHTSA is working to create a system that allows website-based access to various data such as total numbers of deaths caused by automobile accidents, sample data on accidents involving material (or worse) damage, investigation results for accidents classified by specific items such as airbag-inflicted injuries, and data on occupant injury mechanisms in accidents. **Table 3** shows the NHTSA accident database types and the numbers of database content items that correspond to Mitsubishi vehicles.

In 2002, there were 38,356 fatal automobile accidents in the United States; 42,850 victims died within 30 days of their respective accidents. The NHTSA estimates that, behind these figures, there were 1.93 million accidents resulting in personal injury, 4.31 million accidents involving property damage, and 8.90 million unreported accidents, making a total of 15.20 million accidents. This means that at least one in every 15 people with driving licenses was involved in an accident of some kind. Automobile accidents are currently the leading cause of death of people in the 1 – 34 age group.

Rollover accidents are a particularly serious concern. According to NHTSA figures, they represent only 8 % of all automobile accidents but account for 31 % of all deaths caused by automobile accidents. Notably, about 60 % of fatal accidents involving sport utility vehicles (SUVs) are rollover accidents. Of all fatal accidents involving SUVs, rollover crashes account for approximately 60 %. The occupant death rate in rollover accidents is also alarmingly high at a little less than 50 %. Further, rollover accidents often cause people to be thrown out of their vehicles. It is known that 90 % of people thrown out of their vehicles in rollover accidents were not wearing their seatbelts.

## 5. Driver distraction

Driver distraction (reduction of attention and decision-making ability) caused by the use of cellphones and navigation systems in vehicles has been a matter of growing concern in the last few years. Since cellphone usage during driving is banned only in limited areas such as New York state and Miami, Florida, it is not rare in the United States to see people using cellphones while driving. Navigation systems are not yet as widespread in the US market as they are in the Japanese market, but they are growing in popularity; 18 % of all vehicle models sold in the US market in 2002 were compatible with navigation systems, and the rate of original-equipment-manufacturer installation of navigation systems on new vehicles in California currently exceeds 3 %. Further, the number of subscribers to telematics services that provide motorists with information via cellphone networks already exceeds 2.3 million and the types and quantity of information available from such services are growing rapidly. Government and industry bodies recognize the importance of providing in-vehicle data terminals with interfaces that drivers can use safely and easily and are thus working to create interface standards and guidelines and to establish methods for assessing the safety of in-vehicle data terminals.

To enable quantitative assessment of the danger of driver distraction, 17 US states have since 2002 required every accident report to indicate whether the driver was using a cellphone, fax machine, computer, navigation system, two-way radio, and/or head-up display at the time of the accident. According to the accumulated data, 949 accidents occurred during cellphone usage in 2002 alone.

The Alliance of Automobile Manufacturers (AAM) created voluntary guidelines concerning the interfaces of navigation systems and other in-vehicle information devices and submitted them to the NHTSA and Transport Canada in April 2002. Although these guidelines are broadly consistent with Japanese and European guidelines, certain aspects are specific to the United States. (For example, the AAM guidelines specify operations permitted during driving with reference to actual measurements of the time required for the driver to see and operate relevant devices.) All AAM member companies are required to design the interfaces of their in-vehicle information devices in accordance with these guidelines. The AAM revised the 2002 guidelines through the summer of 2003, by which it finalized the guidelines for additional items. Nevertheless, the AAM is continuing to develop guidelines as there are many items remaining unaddressed including voice interfaces.

The NHTSA acknowledges the AAM's contributions to vehicle safety but is reluctant to officially adopt the AAM's guidelines, instead showing a readiness to create its own regulations. Indeed, the NHTSA has officially announced that it plans to conduct an investigation from 2005 into the feasibility of establishing new regulations. It plans to publish the results in 2006. The investigation will focus on three main areas: standards on operations that are permissible during driving; standards related to workload manager technologies that automatically optimize the information processing workload borne by drivers; and standards related to operation of devices carried into vehicles from outside.

By contrast, Transport Canada, rather than legislating for safer use of in-vehicle telematics devices, advocates exercising administrative control over the development of telematics devices to ensure that such devices are designed in a way that prevents unsafe operation during driving. It is presently discussing this issue in detail with the Canadian Vehicle Manufacturers' Association and other relevant organizations. Since the beginning of 2003, Transport Canada has taken a further step in line with its policy by clearly showing its intent to ban reconfigurable interfaces and open-architecture designs that allow plug-and-play usage of devices. In addition, Transport Canada indicated to automobile manufacturers its readiness to establish an ISO9000-type process standard compelling all automobile manufacturers to provide reports showing that the safety of telematics devices is adequately verified at each stage of development.

The Safety and Human Factors Committee of the Society of Automotive Engineers (SAE) has, over the years, been developing a standard specifying the types of operation of navigation systems that are permitted during driving. The draft standard will be proposed to the ISO/TC22/SC13/WG8 upon approval by the committee. Like the moves of the US and Canadian governments, it is attracting much attention in the automotive industry.

## 6. Standardization of data recorders

When a vehicle crashes, its airbag controller records data on the impact and data on the vehicle. Provided these data are properly managed and are made conveniently retrievable, they are potentially useful in efforts to clarify accident mechanisms and in efforts to devise measures to minimize occupant injuries. The NHTSA has long stressed the importance of on-board data recorders as a means of improving the efficiency and reliability with which accident data are obtained and has issued a report on types and formats of recorded data.

General Motors and Ford have publicly acknowledged that every one of their production models carries a data recorder from which accident data can be downloaded using commercially available diagnostic tools. A number of other automobile manufacturers are expected to follow suit, so it has become necessary to create standards for data types and recording formats. As a continuation of the NHTSA's work on data recorders, the Institute of Electrical and Electronics Engineers (IEEE) has been working to create standards since January 2002. The IEEE's standardization activities encompass all types of vehicle platform (from passenger cars to heavy-duty trucks) and all types of accident. In parallel with these activities, the SAE began its own standardization project in February 2003. The SAE's project was limited to frontal impacts suffered by passenger cars and was completed in July 2003. The SAE committee responsible for the project has since announced plans to expand the project to include side-impact accidents, multiple-impact accidents, pre-impact driving records (obtained from drive recorders), and real-time data transmission (achieved by means of remote diagnosis devices).

## 7. The present state of ITS projects

ITS research and development in the United States began in earnest in the early 1990s and has been progressing even more rapidly since the beginning of the new century. The federal ITS budget for the next six years will be defined in detail in the new federal law that defines the surface transportation budgets for fiscal 2004 and onward. Over the next six years, the DOT is expected to be able to spend $121 million per year on ITS research and development and state governments are expected to be able to spend $135 million per year on the development of ITS infrastructure.

Under a vehicle-directed ITS program called the Intelligent Vehicle Initiative (IVI), the DOT has, since 1999, been equipping heavy-duty trucks and other vehicles with ITS technologies and using them to accumulate huge amounts of real-world road data (**Table 4**). In the next step of the program, the DOT will conduct ergonomic tests in passenger cars in order to gather a

**Table 4 R&D missions for IVI program**

| Content | Participating companies |
|---|---|
| Development of human-machine interface (employing head-up display) for rear-impact warning | Ford, GM |
| Assessment of driver workload quantification methods | Ford, GM, Nissan, Toyota |
| Development of high-accuracy digital map database | DaimlerChrysler, Ford, GM, Navigation Technologies, Toyota |
| Establishment of optimum parameters for adaptive cruise control (ACC) and rear-impact warnings | GM, Delphi |
| Assessment of human-machine interface of lane departure warning systems | Visteon, AssistWare |
| Accumulation of data on driving under normal conditions | Virginia Tech University |

large amount of data on drivers' responses to various types of ITS equipment. Related interface-evaluation tests will involve over 100 drivers and are expected to yield information that is unprecedented in terms of volume and potential usefulness. Another IVI mission is the Naturalistic Driving Data project led by Virginia Polytechnic Institute and State University, which focuses on the collection of data on normal driving. Here, vehicles carrying measuring equipment will be lent to 100 average drivers and used to gather a large amount of data on accident-free driving in normal circumstances. Comparison of the resulting data with data corresponding to crashes and near misses will, it is hoped, enable methods for detecting potentially dangerous driving to be devised.

The DOT is also active in efforts to realize ITS technologies that can be incorporated into the existing transportation infrastructure; the NHTSA and Federal Highway Administration (FHWA) have relevant programs under way. The NHTSA's program is called Vehicle Safety Communication (VSC) and is designed for technical verification of dedicated short-range communication (DSRC) systems and other technologies that enhance traffic safety by means of communication between vehicles and between vehicles and roadside devices. (The VSC program includes work on definitions of message sets transmitted between vehicles.) The FHWA's program is called Vehicle-Infrastructure Integration (VII). Under this program, state transportation agencies and several automobile manufacturers are pursuing the technical verification necessary to realize an intelligent transportation system through the use of various forms of communication between vehicles and roadside devices. The VII program encompasses not only technological issues but also organizational issues such as determination of the framework within which the common communications protocol for real-time transmission of traffic information to vehicles should be developed. A specific example of VII work is research on devices that work within the existing transportation infrastructure to prevent accidents on intersections (**Photo 1**). At the time of writing, an FHWA facility is testing a system that uses infrastructure-side

**Photo 1 FHWA's intersection accident prevention system**

equipment to detect vehicles entering an intersection and, when it determines that a vehicle is likely to suffer a frontal collision, issues a warning message outside the vehicle (by means of a roadside sign) and inside the vehicle (by means of DSRC).

The ITS industry is also playing an active role in the development of infrastructure-compatible intelligent transportation systems, using DSRC as a key to bring together vehicle-safety devices, telematics devices, transportation-infrastructure equipment, telecommunication-infrastructure equipment, and other elements whose development paths were previously quite separate. Whereas Japanese and European ITS efforts are showing signs of leveling off, ITS efforts in North America have, provided the public and private sectors continue to strengthen their cooperation, the potential to realize massive progress in the years ahead.

## 8. Conclusion

Although this paper gives only a limited view of technological trends in the North American automobile markets, it gives a sense of the diversity and multiplicity of automobile-related activities under way in the United States and Canada. The Mitsubishi Motors R&D of America Technical Information Group will work to continue functioning as a source of timely information not only on technological trends in the areas discussed in this paper but also on technological trends in other important fields such as environmental protection (a field where on-board diagnosis systems are a key focus). One of our offerings is the *NAFTA Technical Report*, which we publish twice a year (at March-end and September-end) as a source of up-to-date information on North American technological trends. We hope our work will continue to be of value.

Hideki HADA

# Euro NCAP and Improvement of Vehicle Safety Performance

Herbert Wagner*

## Introduction

According to the European Commission, automobile accidents account for about 170,000 deaths and 5,000,000 injuries in Europe each year. The magnitude of these figures has made the improvement of vehicle safety performance one of the top concerns for automakers.

The European New Vehicle Assessment Program (Euro NCAP) helps to tackle the issue of vehicle safety performance by providing independent assessments of the safety performance of individual vehicle models. Backed by a group of government agencies, crash-testing organizations, and consumer organizations, it evaluates vehicles' safety performance based on crash-test results, assigns ratings (expressed as numbers of stars from one to five) to vehicles accordingly, and periodically announces the results to the public. By providing consumers with this type of information, Euro NCAP gives automakers a powerful incentive to improve their vehicles' safety performance.

This report describes how Euro NCAP has driven improvements in vehicle safety thus far, describes the Euro NCAP performance of Mitsubishi vehicles, and discusses likely future Euro NCAP measures.

## 1. Euro NCAP testing and assessment procedures

Euro NCAP's testing and assessment procedures have undergone numerous changes, which are reviewed in section 2 of this report. First, let us take a look at the testing and assessment procedures presently employed by Euro NCAP.

The program is conducted at a pace of one phase per half-year. Vehicle models are chosen for each phase in accordance with their respective market categories, sales volumes, and other attributes.

Each selected vehicle is subjected to a 40 % offset frontal impact test (at 64 km/h) and a side impact test (at 50 km/h) at an official testing facility. If the vehicle has head-protecting side airbags, the manufacturer has the option of accepting a side impact pole test (at 29 km/h), through which it can earn bonus points. The data such as head, chest, and leg loading suffered by an anthropometric dummy is measured in each test, and they are used for assessment of the occupant protection provided by the vehicle. Further, points are deducted in accordance with the check points such as the extent of deformation suffered by certain parts of the vehicle in each test. The vehicle's safety performance reflects the sum of points earned and points deducted.

A vehicle can obtain up to 16 points in the offset frontal impact test and up to 16 points in the side impact test. It can earn a further two points in the side impact pole test and up to three points for having a seatbelt reminder system, making a maximum possible score of 37 points. The points are translated into stars (☆ to ☆☆☆☆☆) as follows :

- 1 to 8 points : ☆
- 9 to 16 points : ☆☆
- 17 to 24 points : ☆☆☆
- 25 to 32 points : ☆☆☆
- 33 or more points: ☆☆☆☆☆

Tests are also conducted for evaluation of the vehicle's pedestrian protection performance. A rating of one to four stars is given for pedestrian protection.

## 2. Upgrading of testing and evaluation methods, and improvement of vehicles

Euro NCAP started its first phase in the autumn of 1996 and has since advanced to its 12th phase (as of Sept. 2003). During this period, the methods employed in the Euro NCAP tests and assessments have undergone a number of changes, becoming increasingly stringent. An overview of these changes is presented in **Table 1**. New criteria for negative evaluation have been added in successive phases as indicated below, making it increasingly difficult for vehicles to earn points.

- Phase 8 : Airbag bottoming out modifier
- Phase 9 : Door opening modifier
  All pedals deformation modifier
- Phase 10: Dummy's back plate load modifier
- Phase 12: Pedal blocking modifier

Euro NCAP's safety enhancement policy reflects a carrot-and-stick approach. The stick is the increase in criteria for negative evaluation. Automakers have responded by making structural improvements to their vehicles. They have also responded by adopting as standard equipment safety technologies that were not standard at the beginning of the program. (Such technologies include front passenger's airbags, side airbags, and pretensioner-equipped seatbelts.) The carrot is the possibility of bonus points for vehicles that incorporate innovative safety measures. When Renault installed head-protecting airbags in the Megane I during Euro NCAP phase 7, for example, the Euro NCAP rules were modified to enable the introduction of a new pole impact test by means of which Renault could obtain bonus points. And in phase 10, bonus points

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**Table 1 Assessment methods and newly covered technologies by Euro NCAP phase**

| Phase | New assessment item | New technology | Remarks |
|---|---|---|---|
| 1 | • Test and assessment of front impact, side impact and pedestrian protection | • Driver airbag<br>• Passenger airbag<br>• Side airbag<br>• Seat belt pre-tensioner | • These technologies were soon widely adopted as standard equipment. |
| 2 | | | • Emergence of first four-star vehicle [Volvo S40] |
| 5 | • Footwell intrusion assessment | | |
| 6 | • New pedestrian protection assessment | | |
| 7 | ○ Pole impact test and assessment | • Head airbag system [Renault Megane I] | |
| 8 | ● Airbag bottoming out modifier<br>• Lateral steering wheel assessment | | |
| 9 | ● All pedals deformation modifier<br>● Door opening modifier | | • Emergence of first five-star vehicle [Renault Laguna] |
| 10 | ○ Seat belt reminder (SBR) assessment<br>● Back plate load modifier<br>• New pedestrian protection assessment<br>• Side impact assessment with new dummy | • Seat belt reminder system [Mercedes C-class] | |
| 11 | • Points balance assessment | | |
| 12 | ● Pedal blocking modifier<br>• Side impact assessment with new dummy and new barrier | • Driver knee airbag [Toyota Avensis] | |

○: Points awarded ●: Points deducted

were awarded to the Mercedes-Benz C-class owing to its incorporation of a seatbelt reminder system (a system that uses a buzzer and a warning lamp to remind occupants to fasten their seatbelts). Since phase 11, bonus points have enabled a number of vehicles to earn a five-star rating. Other changes made to the Euro NCAP testing and assessment procedures include improvement in phases 10 and 12 of the barriers and dummies used in crash tests and improvement in phase 11 of the rating system for a better balance between frontal and side impacts.

## 3. Improvement of vehicle safety performance

Euro NCAP's carrot-and-stick approach has driven significant improvements in vehicle safety performance as reflected in **Table 2**.

A total of 165 vehicles have been tested and assessed in the seven-year period between the autumn of 1996 (when Euro NCAP phase 1 began) and the time of writing (when phase 12 is taking place). In phase 1, the highest rating achieved by any vehicle was three stars. In phase 2, only a half-year later, the Volvo S40 became the first vehicle to earn four stars. And in phase 9, which occurred in 2001, the Renault Laguna became the first vehicle to earn five stars.

Except for the Kia Carnival, which was given two stars in phase 12, there have not been any one-star-rated or two-star-rated vehicles since phase 8. The general trend is as follows:

- Phases 1 to 3 (1996 to 1997): average rating of two stars
- Phases 4 to 7 (1998 to 1999): average rating of three stars
- Phases 8 to 12 (2000 to 2003): average rating of four stars

The introduction of the point-deduction system has made Euro NCAP's evaluation procedure more demanding, meaning, for example, that a three-star rating earned today reflects a much higher level of safety performance than a three-star rating earned at the beginning of the program. It is reasonable to say that the general and actual level of vehicle safety performance has increased significantly in the past several years.

## 4. Safety performance of Mitsubishi vehicles

All Mitsubishi vehicles that have been tested in the Euro NCAP program are indicated in **Table 2**. As shown, a total of five Mitsubishi models have been tested thus far (a rate of one model every one to two years).

All Euro NCAP-assessed Mitsubishi vehicles except the LANCER (the first Mitsubishi vehicle to be assessed) have earned three stars. Among them, the CARISMA (tested in phase 9a) and PAJERO JUNIOR (tested in phase 11) were each only one point away from achieving a four-star rating, reflecting a strong improvement in the safety performance of Mitsubishi vehicles in real terms.

Mitsubishi Motors Corporation (MMC) is developing new vehicles with a view to ensuring that the next Euro NCAP-assessed Mitsubishi vehicle earns a four-star rating at least. One related initiative is the Production Vehicle Crash Safety Performance Verification Program (PCVP), which is designed to enable the safety performance quality of line-produced vehicles to be checked and maintained. Under the PCVP, vehicles sampled from the production line are sent to an official facility in

**Table 2 Euro NCAP assessment results**

| Phase | Period | Evaluation results | Tested Mitsubishi vehicle results |
|---|---|---|---|
| 1 | 96/09 ~ 97/03 | | |
| 2 | 97/01 ~ 97/07 | | |
| 3 | 97/11 ~ 98/05 | | LANCER |
| 4 | 98/03 ~ 98/09 | | |
| 5 | 98/05 ~ 99/01 | | |
| 6 | 98/08 ~ 99/06 | | SPACE WAGON |
| 7a | 99/04 ~ 00/02 | | |
| 7 | 99/08 ~ 00/03 | | |
| 7b | 00/07 ~ 00/11 | | |
| 8 | 00/05 ~ 01/03 | | SPACE STAR |
| 9a | 00/10 ~ 01/06 | | CARISMA |
| 9b | 00/10 ~ 01/11 | | |
| 10 | 01/10 ~ 02/06 | | |
| 11 | 02/05 ~ 02/11 | | |
| 11+ | 02/05 ~ 03/02 | | PAJERO PININ |
| 12 | 02/10 ~ 03/06 | | |

● : Mitsubishi vehicle : ☆ : ☆☆ : ☆☆☆ : ☆☆☆☆ : ☆☆☆☆☆

Europe, where they are subjected to crash tests. At the time of writing, the results of crash tests conducted on the Mitsubishi OUTLANDER in July 2003 at TNO testing facility in Netherlands are under review and preparations are being made for October 2003 testing of the LANCER STATION WAGON. All Europe-specification Mitsubishi vehicles will eventually be tested in this way. Whereas MMC previously conducted crash tests only during the development of vehicles, it can now, thanks to the PCVP, ascertain the true safety performance of production vehicles and can thus not only maintain and improve the safety performance quality of production vehicles but also increase the possibility of success in Euro NCAP tests.

## 5. Activities at Mitsubishi Motors R&D Europe

Mitsubishi Motors R&D Europe (MRDE) undertakes various activities related to Euro NCAP.

On a daily basis, MRDE communicates with the Euro NCAP office and gathers information on updates and other revisions made to testing and assessment methods. It also conducts research on the activities of other automobile manufacturers.

When a Mitsubishi vehicle is chosen for Euro NCAP testing, MRDE is responsible for the following tasks:

- negotiating with the Euro NCAP office on the selection of the model version to be tested and on the specifications (including replaceability of parts) of the vehicle;
- preparing for the tests (including preparation of replacement parts and service parts);
- witnessing the tests; and
- negotiating with the Euro NCAP office on the results of its evaluation (with a view to earning the highest possible number of points).

MRDE also deals with factory surveillance conducted by the Euro NCAP office in the event of an accident or other exceptional incident. Further, MRDE undertakes PCVP-related jobs for MMC's Quality Management Office.

## 6. Likely future Euro NCAP measures

The Euro NCAP organization has many internal Technical Working Groups that discuss a wide variety of goals and other issues related to future Euro NCAP work. Goals that are likely to be achieved in the near future include

- assessment of child safety performance (including assessment of safety performance of child seats);
- evaluation and point-deduction systems for excessive loading applied to certain parts of the spine (for example, the lumbar area);
- whiplash injury testing and assessment; and
- lower-leg injury assessment by means of component testing.

Assessment of child safety performance is a particularly high priority. Although child safety performance is currently handled as part of the overall safety assessment, child safety performance will be given a star rating of its own under the title of Child Protection Rating.

Items being discussed for longer-term handling include:

- in-cabin head impact test methods;
- full-lap frontal impact test methods;
- rollover test methods; and
- vehicle-to-vehicle compatibility crash test methods.

Further, studies have been started for the establishment of a Primary Safety New Vehicle Assessment Program, which relates to the effectiveness with which vehicles prevent or minimize the likelihood of accidents by means of sensing systems and other advanced technologies rather than to the effectiveness with which vehicles protect people during and after collisions.

## 7. Conclusion

Approximately seven years have passed since Euro NCAP was established in the autumn of 1996. There has been a huge increase in vehicle safety performance in this period, and Euro NCAP has undeniably played a major role in bringing it about. Plus, new Euro NCAP initiatives aimed at promoting vehicle safety performance will provide automobile manufacturers with ongoing incentives to pursue further improvements in safety technologies. Unfortunately, many drivers in Europe drive dangerously, some treating the autobahn like a Formula One circuit, perhaps partly because they place too much confidence in their vehicles' safety performance. To achieve the goal of halving the number of annual deaths and injuries in automobile accidents by 2010, it is necessary not only to improve automobile safety technologies but also to find ways to improve the driving manner of the people who use them.

Herbert Wagner

# New GRANDIS



The three-row-seating minivan was pioneered in Japan by Mitsubishi Motors Corporation (MMC) with the first-generation CHARIOT in 1983. It has since become the vehicle type of choice for a huge proportion of motorists. MMC's fourth-generation vehicle in this category appeared in the market in May 2003. Named the GRANDIS, it's a future-oriented minivan that offers a new array of standard-setting features to complement users' lifestyles.

## 1. Targets

Since the beginning of the 21st century, consumers have shifted their priorities toward products whose attraction lies in painstaking attention to detail. In developing the GRANDIS, MMC sought to accommodate the customer priorities of today and tomorrow with a comfortable, sporty, three-row-seating minivan offering emotionally appealing design, smart performance, and freedom of personal coordination.

## 2. Features

- Emotionally appealing design

(1) Flowing exterior lines and surfaces

A three-diamond emblem in the center of the front grille defines the new MMC design identity and forms the locus from which lines and surfaces manifesting emotionally appealing next-generation minivan styling flow all the way back to the tail. The body contours express Japanese aesthetic sensibilities by creating a look that changes subtly with the light or angle of view.

The unique visual characteristics of light-emitting diodes are exploited in the rear combination lamps, high-mount stop lamp, and door-mirror-integrated turn-signal lamps, making the GRANDIS immediately recognizable even at night.

Further, a choice of two exterior styling packages (Elegance, which conveys a relatively refined personality, and Sports, which creates a more purposeful, dynamic image) accommodates customers' individual tastes. Each exterior styling package creates the desired visual effect by means of exclusive designs for the bumpers, side-sill garnishes, front grille, and other exterior items.

(2) A cabin embodying Japanese aesthetic sensibilities

The interior environment sets new standards that transcend the conventional perception of luxury.

A gently undulating wave-type form for the instrument panel helps to create a sense of roominess and relaxation in the cabin, and the instrument panel is finished with a special coating whose hue changes subtly with the angle of view, giving expression to the traditional Japanese aesthetic values attached to the beauty to be found in the transition of light through different shades. The form, color, and luster of the wood-grain or metallic materials used on the center panel are synergized to bring out the essential feel of the materials. And the Japanese aesthetic of transition is reflected in the seat upholstery, which is interwoven with a lustrous fiber that generates a rich variety of visual expression as the light falling on it changes.

Further, a choice of two interior styling packages (Elegance and Sports, each of which conveys a distinct personality through its own meter coloring, center-panel finish, and seat fabrics) accommodates customers' individual tastes.

- Smart performance

(1) Efficient packaging permitting superior maneuverability

The GRANDIS has a greater overall length than its predecessor, so it has 100 mm more usable interior length, which helps to realize the generous cabin roominess and luggage-area capacity that minivan users expect. Although the body is larger than that of the GRANDIS's predecessor, the GRANDIS maintains its predecessor's acclaimed maneuverability and has a class-leading minimum turning radius of 5.5 m.

(2) New platform realizing superior collision safety

A newly developed platform realizes class-highest levels of collision safety, structural stiffness, and vibration and noise suppression. Reflecting MMC's Refined Impact Safety Evolution concept, it's structurally designed to effectively absorb and disperse impact energy while minimizing cabin deformation.

Further, the cabin has a six-way airbag system including curtain airbags that extend beyond the second row of seats. And for child safety, the second-row

seats each incorporate retaining bars and a top-tether anchor for an ISOFIX child seat.

(3) Newly developed 2.4-litre MIVEC engine

A newly developed 2.4-litre engine gives the GRANDIS outstanding running performance and environmental performance. A Mitsubishi Innovative Value lift and timing Control (MIVEC) system on the engine ensures optimal driveability and performance across the entire rev range by switching between low- and high-speed cam profiles for the two intake valves on each cylinder. At the same time, the engine is exceptionally fuel-efficient and has exhaust emissions so low that the GRANDIS is certified as an ultra-low-emission vehicle.

(4) Superior ride quality and Multi-Select 4WD System

A suspension system that's optimally tuned for a minivan delivers taut, precise handling together with a flat but forgiving ride for all occupants.

Four-wheel-drive (4WD) versions of the GRANDIS are equipped with MMC's new Multi-Select 4WD system, which delivers all-surface traction and control similar to those of other 4WD systems but is lighter and permits superior fuel economy. Exploiting the benefits of electronic control, it offers three operating modes (4WD mode, 2WD mode, and LOCK mode) to accommodate diverse driving conditions.

(5) New-concept seating flexibility

The seats in the GRANDIS incorporate newly conceived features that accommodate the full spectrum of user needs: The first-row passenger seat has MMC's acclaimed Useful Seat design, which allows secure retention of shopping bags or briefcases. The second-row seats each have a Relax Mode function that allows the user to position the squab at any of three angles for comfort and relaxation. And the third-row seats can be individually stowed under the floor with minimal physical effort for flexible accommodation of various passenger- and luggage-carrying needs.

The underfloor stowability of the third-row seats and a tip-and-tilt function in the second-row seats can be combined with the luggage area to create exceptionally spacious, flexible accommodation for luggage items of diverse shapes and sizes.

(6) Confidence-inspiring security measures and user-friendly appointments

For protection from thieves, every GRANDIS version is equipped with an advanced security system consisting of an immobilizer and a security alarm. And to promote driving safety, a newly developed Dual Around Monitor system supplements the driver's lateral field of view with images from a nose-view camera.

Navigation assistance is provided by a version of the Mitsubishi Multi-Communications System that supports Digital Versatile Disc navigation functions. Combined with this system are an AM/FM radio, a MiniDisc player, and a six-disc CD changer. The control panel for these items is designed to neatly complement the wave-form dashboard. Rear-seat passengers are provided with a seven-inch overhead liquid-crystal display. Audio and video played for rear-seat passengers can be different from those for first-row occupants.

A number of other features makes the GRANDIS experience even more enjoyable. One such feature is a cabin material that absorbs and harmlessly breaks down odors and chemical substances. Another is solar-control glass that protects occupants from ultraviolet and thermal radiation.

- Freedom of personal coordination

The Customer Free Choice system, which has already earned high praise from COLT owners, gives GRANDIS customers the freedom to tailor their vehicles to suit their personal tastes. In terms of styling and color alone, there are 160 selectable combinations.

## 3. Major specifications

The major specifications of the GRANDIS are shown in the following table.

| Specifications / Model code | | | Mitsubishi UA-NA4W | |
|---|---|---|---|---|
| | | | 2WD | 4WD |
| Overall length | | (mm) | 4,755 | |
| Overall width | | (mm) | 1,795 | |
| Overall height | | (mm) | 1,655 | |
| Weight | | (kg) | 1,620 | 1,700 |
| Min. turning radius | | (m) | 5.5 (with 16-inch wheels); 5.8 (with 17-inch wheels) | |
| 10·15-mode fuel consumption | | (km/L) | 11.4 | 11.0 |
| Engine type | | | 4G69 MIVEC | |
| No. of cylinders; valvetrain | | | 4 in line; 16-valve SOHC | |
| Max. output | | {kW (PS)/rpm} | 121(165)/6,000 | |
| Max. torque | | {Nm (kg·m)/rpm} | 217(22.1)/4,000 | |
| Transmission type | | | INVECS-II with Sport Mode 4-speed automatic transmission | |
| Suspension | Front | | MacPherson struts with coil springs | |
| | Rear | | Semi-trailing arms with coil springs | |
| Tires | | | 215/60R16; 215/55R17 | |

(RV Product Development Project, Research & Development Office: Kuzuoka, Kishi, Miyanaga)
(New Product Project, Product Planning & Program Management Office: Ito)

# New ENDEAVOR



The new ENDEAVOR is a crossover Sport Utility Vehicle (SUV) developed by Mitsubishi Motors Corporation (MMC) to compete in the United States market for mid-size SUVs. (There is consistently high demand for vehicles in this category in the United States.) Based on a passenger-car platform and launched in March 2003, it is a core model in the MMC lineup for the United States.

## 1. Targets

In developing the new ENDEAVOR on a passenger-car platform, MMC sought to create a next-generation SUV combining the merits of a conventional SUV with the merits of a passenger car. MMC focused on distinctive styling, on packaging that realizes superior comfort, space utility, and visibility, and on performance that enables users to drive in comfort and with peace of mind. Further, MMC based every aspect of the new ENDEAVOR's creation (from design and development through production) in the United States to ensure an optimal match with customer's needs.

## 2. Features

(1) Next-generation platform

The new ENDEAVOR is built on a next-generation platform that was newly developed by MMC for production in the United States.

Superior passive safety is realized by a body structure that combines highly energy-absorbent front and rear zones with a highly rigid cabin and has straight frame members, a large, octagonal cross-section for the front side members, and reinforced joints.

MacPherson-strut suspension (the type of suspension most commonly used on passenger cars) with a light, highly rigid, flat crossmember is used at the front. Low-mount multi-link independent suspension is used at the rear. Its crossmember is elastically supported and is hydroformed for lightness and superior precision.

(2) Styling

The new ENDEAVOR's styling is a distinctive look with elements of SUV toughness combined with a unique front design, bold character lines and with wide, low proportions that convey a sense of stability.

(3) Packaging

The new ENDEAVOR's packaging provides front-seat occupants with a high eye point (this enables good visibility and is a key characteristic of an SUV) and with a seating height that realizes superior ease of ingress and egress.

The packaging also realizes minimum ground clearance of eight inches (plenty of ground clearance is a key requirement with an SUV) together with a modest overall height that helps to realize a low center of gravity and thus contributes to stability.

To enable users to ride in comfort, plenty of headroom and legroom is realized not only for the driver and front passenger but also for rear passengers.

The luggage area has a flat surface, ample capacity,

and a large tailgate opening to meet the lifestyle requirements of users in the target market. For further user-friendliness, the tailgate window can be opened as a hatch for access to the luggage area.

Also incorporated into the new ENDEAVOR's packaging is a large, 81-liter fuel tank, which accommodates the long distances that are often driven in the target market.

(4) Interior

The instrument panel is distinguished by a uniquely styled central section that incorporates the audio and climate-control switches. The switches are large and optimally positioned, and an easy-to-read liquid crystal display is located above them. Further, blue light-emitting diodes are used to give the meters and switches ice-blue backlighting, which helps to create a uniquely cool feeling in the cabin.

Convenience is enhanced by numerous storage spaces and utility hooks and by four accessory sockets, which are located near the front seats, near the rear seat, and in the luggage area (four locations in total). Sunvisor extensions, a sunglasses holder, and cupholders are also provided. Each of these items is specially designed to meet the needs of users in the target market.

(5) Running performance

MMC's product concept for the new ENDEAVOR prioritizes the basic performance elements of running, turning, and stopping.

Class-leading running performance is realized by a powertrain in which a 3.8-liter V6 engine that's tuned with an emphasis on torque at low and mid-range speeds is mated to a four-speed automatic transmission with sports mode.

Further, the passenger-car platform permits passenger-car levels of handling stability and ride comfort. Plus, a high-capacity brake booster is combined with four-wheel disc brakes for reassuring braking performance.

(6) Major equipment

Notable items of available equipment include a tire pressure monitoring system (this promotes active safety), a function customizer (this allows the user to customize various timer and alarm functions by means of the center display), and a rear-seat entertainment system (this employs a display with a built-in DVD player).

## 3. Major specifications

Major specifications of the new ENDEAVOR are shown in the following table.

| Specifications \ Vehicle model and type | | | | ENDEAVOR | | |
|---|---|---|---|---|---|---|
| | | | | LS | XLS | LIMITED |
| | | | | 2WD/full-time 4WD | | |
| | | | | Sports-mode 4 A/T | | |
| Seating capacity | | | (persons) | 5 | | |
| Dimensions | Overall length | | (mm) | 4,830 | | |
| | Overall width | | (mm) | 1,870 | | |
| | Overall height | | (mm) | 1,769 | 1,784 | |
| | Wheelbase | | (mm) | 2,750 | | |
| | Tread | Front | (mm) | 1,600 | | |
| | | Rear | (mm) | 1,600 | | |
| | Min. ground clearance | | (mm) | 211 | | |
| Engine | Model | | | 6G75 | | |
| | Displacement | | (cc) | 3,828 | | |
| | Valve mechanism; number of cylinders | | | SOHC 24-valve; 6 cylinders | | |
| | Max. output | | (HP/rpm) | 215/5,000 | | |
| | Max. torque | | (lbs-ft/rpm) | 250/3,750 | | |
| | Fuel supply system | | | ECI-MULTI (electronically controlled fuel injection) | | |
| Chassis | Steering | | | Rack and pinion (with power assistance) | | |
| | Suspension | Front | | MacPherson-strut | | |
| | | Rear | | Low-mount multi-link | | |
| | Brakes | Front | | Ventilated disc (16-inch) | | |
| | | Rear | | Drum-in-disc (16-inch) | | |
| | Tires | | | 235/65R17 | | |

(C&D Product Development Project, Research & Development Office: Nomura, Matsumoto, Nakata)

# eK·CLASSY

The eK series debuted as a new minicar standard in October 2001. The initially launched model, the eK·WAGON, was joined in September 2002 by a sportier model, the eK·SPORT. The third model in the series, the eK·CLASSY, was launched on May 26, 2003. Developed in line with a 'chic and modern' theme, it offers levels of refinement that satisfy the most discerning and mature customers.

## 1. Targets

In developing the eK·CLASSY, Mitsubishi Motors Corporation (MMC) sought to realize a minicar with unprecedented quality that would appeal to married men and women in the 30 – 50 age group and to younger single women. By introducing the eK·CLASSY, MMC widened the appeal of the eK series to the entire spectrum of minicar users and gave the series even greater potential for long-term commercial success.

## 2. Features

(1) Refined performance

The eK·CLASSY's powertrain combines the 3G83 inline-three-cylinder, naturally aspirated engine that MMC initially used in the eK·WAGON with the four-speed automatic transmission that MMC initially used in the eK·SPORT. Improvements to these components (for example, a steel crankshaft and liquid-filled engine mounts) realize a superior combination of performance and quietness.

With regard to environmental performance, the eK·CLASSY qualifies for certification as an ultra-low-emission vehicle by having exhaust-emission levels 75 % lower than those permitted by Japan's 2001 regulations. Also, two-wheel-drive and four-wheel-drive versions of the eK·CLASSY both offer 10·15-mode fuel economy that satisfies Japan's 2010 fuel-economy regulations. (The eK·CLASSY is the first model in the class to satisfy these fuel-economy regulations.) The eK·CLASSY's environmental credentials enable purchasers to benefit from Japan's 2003 system of 'green' tax exemptions.

The body has an enhanced-rigidity structure that MMC first adopted with the eK·SPORT, and it is complemented at the front by special high-responsiveness shock absorbers in the suspension system. As a result, users enjoy a superior combination of handling stability and ride smoothness.

(2) Refined interior

In the eK·CLASSY's cabin, a beige keynote color contributes to a bright, refined environment that gives a feeling of openness. Visual interest and a sense of newness are created by treatments that include the use of black coloring on the top of the instrument panel.

The center panel has a newly conceived design that accommodates an automatic air conditioner, provides the heater controls with their own distinct section for easier operation, and helps to realize a look of consistency across the instrument panel. The steering wheel is leather-wrapped for a sense of refinement. Plus, specially designed center meters and a specially designed nameplate in front of the driver help to create visual harmony with the rest of the cabin.

The seat upholstery fits into the beige color scheme to help create a visually consistent, refined-feeling interior environment. Soft-touch suede-look fabric on each seat is complemented by a knitted fabric for the seat squab and by brown stitching that is color-keyed to the base fabric to create an attractive visual accent.

(3) Refined exterior

The eK·CLASSY is distinguished by a exclusive front mask in which elegant contours flow from the A-pillars to the hood and front bumper. Dark-gray coloring for the bottom half of each bumper and for the side-sill garnishes lowers the body's visual center of gravity and enhances the overall look of stable refinement.

Alloy wheels that are cut-machined for a brilliant surface effect form a further expression of quality. And the body's rear emblem is formed from a soft-touch material and has a deeply contoured shape and a chic glossy finish.

A range of six body colors was available at the time of the eK·CLASSY's launch. Three of these colors are exclusive to the eK·CLASSY. The main color in the range is the newly created Light Orange Metallic, which conveys a sense of freshness and refinement.

(4) Superior user-friendliness

The eK·CLASSY is MMC's first minicar to incorporate an automatic air conditioner. The automatic air conditioner was developed by MMC specially for this model. It offers 16 levels of blower-speed control during automatic operation (eight levels during manual operation) and combines precise temperature regulation with outstanding quietness. Further, a button-type control for selection of outside air or interior-air recirculation realizes superior ease of use and a sense of quality.

The windshield is the first on a minicar to be made of solar-control glass that shuts out skin-burning ultraviolet radiation and limits the transmission of infrared radiation, thereby preventing unpleasant hotness in the cabin when the vehicle is exposed to bright sunshine.

A 2-DIN audio unit containing an electronically tuned AM/FM radio and a CD/MD player is standard equipment. It plays through four speakers (located in the instrument panel and rear doors) to create a pleasant listening environment.

The Electronic Time & Alarm Control System, a highly praised feature of the other models in the eK series, is employed also in the eK·CLASSY. This system promotes user-friendliness by supporting a function that allows easy confirmation of keyless locking and unlocking, a function that automatically switches the headlights off, a function that automatically dims the interior lamps, and a function that allows electrical equipment to be used for certain period after the ignition switch has been turned to the 'OFF' position. It also promotes child safety by supporting an anti-pinch function for all four windows; if the system detects an obstruction (for example, a hand or arm) during closure of any window, it immediately stops and reverses the window to prevent entrapment.

Crashworthiness is comparable with that of the eK·WAGON, which has earned a Japan New Car Assessment Program (JNCAP) four-star rating for driver protection and a JNCAP five-star rating for front-passenger protection. Elements contributing to passive safety include a Reinforced Impact Safety Evolution body structure (the same as that of the other models in the series), driver and front-passenger airbags, and three-point front seatbelts that each have a pretensioner and a variable force limiter.

Further, the eK·CLASSY offers the highest level of active-safety performance in the class thanks to technologies that include a standard-equipment antilock braking system with electronic brake-force distribution.

## 3. Major specifications

Major specifications of the eK·CLASSY are shown in the following table.

| Specifications | | | Vehicle model | eK·CLASSY | |
|---|---|---|---|---|---|
| | | | | L | |
| | | | | 2WD | 4WD |
| | | | | 4 A/T | |
| Dimensions | Overall length | | (mm) | 3,395 | |
| | Overall width | | (mm) | 1,475 | |
| | Overall height | | (mm) | 1,550 | |
| | Wheelbase | | (mm) | 2,340 | |
| | Tread | Front | (mm) | 1,295 | |
| | | Rear | (mm) | 1,295 | |
| | Interior length | | (mm) | 1,830 | |
| | Interior width | | (mm) | 1,220 | |
| | Interior height | | (mm) | 1,280 | |
| | Gross vehicle weight | | (kg) | 820 | 870 |
| | Min. turning radius | | (m) | 4.4 | |
| Engine | Model | | | 3G83 | |
| | Displacement | | (cc) | 657 | |
| | Valve mechanism; number of cylinders | | | SOHC 12-valve; 3 cylinders | |
| | Max. output | | {kW (PS)/min$^{-1}$ net} | 37 (50)/6,500 | |
| | Max. torque | | {Nm (kgf·m)/min$^{-1}$ net} | 62 (6.3)/4,000 | |
| | Fuel supply system | | | ECI-MULTI (electronically controlled fuel injection) | |
| Chassis | Steering | | | Rack and pinion (with power assistance) | |
| | Suspension | Front | | MacPherson-strut | |
| | | Rear | | Torque-arm (3-link) | |
| | Brakes | Front | | Disc (13-inch) | |
| | | Rear | | Leading/trailing drum (7-inch) | |
| | Tires | | | 155/65R13 | |

(A&B Product Development Project, Research & Development Office: Morii, Nishino, Sasakura)

# CANTER “Ultra-Low-PM Model”

The Mitsubishi Fuso CANTER series of light-duty trucks underwent a full model change (its first in eight years and seven months) in June 2002 and has since earned high praise for its user-friendly features (these include an instrument-panel-mounted shift lever, superior interior comfort and driving performance.). Mitsubishi Fuso Truck and Bus Corporation (MFTBC) made the new CANTER series even more attractive in February 2004 by launching an environment-focused model equipped with cutting-edge technologies that realize ultra-low emissions of particulate matter (PM). This ultra-low-PM model complies with Japan’s new short-term emissions regulations (JP03). It also qualifies for additional certification as a diesel vehicle whose PM emissions are at least 75 % lower than those permitted by JP03.

## 1. Targets

In developing the CANTER ultra-low-PM model, MFTBC sought to realize a vehicle that complies with JP03 and with the certification requirements for diesel vehicles whose PM emissions are at least 75 % lower than those permitted by JP03. More specifically, it sought to achieve unparalleled emissions performance together with uncompromised levels of power, fuel economy, and reliability by means of a new ‘environment engine’ and a ‘continuous-regenerative diesel-particulate filter (DPF)’.

## 2. Features

(1) New ‘environment engine’

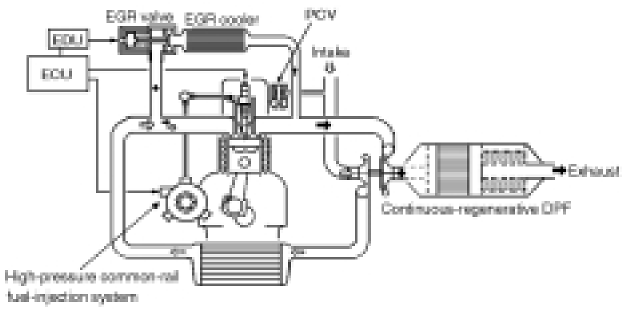
The 4M50T is a new ‘environment engine’ with a turbocharger and an intercooler. A number of newly adopted technologies minimize the engine’s exhaust emissions. To suppress emissions of nitrogen oxides ($NO_x$) and PM, a high-pressure common-rail fuel-injection system, which permits a high degree of control over injection characteristics and thus realizes superior atomization and combustion of the spray, is combined with an optimized combustion chamber and an optimized swirl ratio. The engine’s $NO_x$ emissions are further suppressed by a cooled exhaust-gas recirculation (EGR) system whose EGR valve operates under optimized electronic control. A positive crankcase ventilation (PCV) system further reduces emissions by preventing blowby gases from escaping into the atmosphere. Plus, an onboard diagnostics system monitors the operating status of the EGR system and other emission-control equipment and alerts the driver by means of a warning lamp in the event of an electrical open-circuit or other fault.

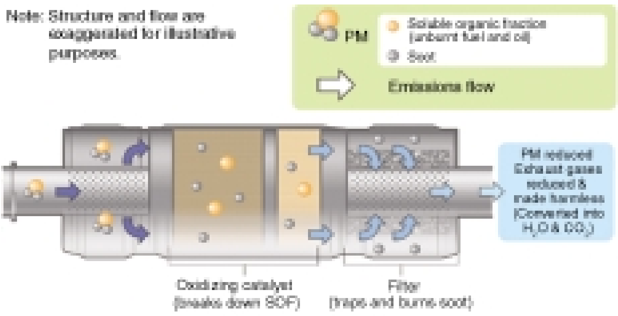
(2) New ‘continuous-regenerative DPF’

The newly developed ‘continuous-regenerative DPF’ is an aftertreatment device whose adoption was made possible by the use of low-sulfur diesel fuel. It consists of a powerful, high-capacity oxidizing catalyst, which breaks down PM, and a filter, which continuously captures and burns the resulting particles. Partly because the engine’s PM emissions are extremely low and partly because the oxidizing catalyst is highly effective, only small amounts of particles accumulate in the filter. Even during urban operation, which involves frequent driving at low speeds, therefore, active regeneration (which would increase fuel consumption) is unnecessary. Further, the size of the filter mesh is optimized to prevent accumulation in the filter of ash (a product of combustion in the engine). This arrangement obviates the need for regular maintenance of the filter and promotes both fuel economy and filter reliability.

(3) Low noise

To limit the increase in noise resulting from the






adoption of a high fuel-injection pressure in the engine, the rigidity of the crankcase was increased. Also, a compact fuel-supply pump was adopted to reduce gear noise, a large, double-layer cover was adopted to reduce valve noise, and pilot injection and other combustion-optimizing measures were applied to limit combustion noise, making the engine exceptionally quiet under all operating conditions. Also, the ribs on the transmission case were optimized to reduce overall noise even further.

(4) Superior reliability

To accommodate the engine's relatively high torque, the crankcase was changed from a Siamese type to a full-jacket type (resulting in superior liner cooling performance) and the engine's pistons were produced from fiber-reinforced metal and provided with chrome plating on their rings. The high engine torque is further accommodated by an uprated clutch in vehicle variants with payloads of three tons or more, and by reinforced gears, bearings, and other parts in the transmission. Reliability is concomitantly superior.

(5) Compliance with regulations

As mentioned, the ultra-low-PM CANTER model complies with JP03 and with Japan's certification requirements for diesel vehicles with ultra-low PM emissions. In addition, it is recognized as a low-emission vehicle under the 8-Tokenshi and LEV-6 certification systems operated by prefectural authorities in the Kanto and Kansai regions, respectively, and complies with Japan's Automobile $NO_x$ and PM Control Law. Purchasers in Japan thus enjoy a preferential rate of vehicle purchase tax, are eligible for government grants, and can make unrestricted use of the ultra-low-PM model throughout Japan.

(6) Model variations

In addition to model variants equipped with the 4M50T engine, MFTBC plans to introduce variants equipped with the newly developed 4M42T engine and with equipment such as the Intelligent & inNOvative Mechanical Automatic Transmission (INOMAT), which permits easy driving by fully automating transmission functions that are conventionally manual.

## 3. Major specifications

Major specifications of key vehicle variants are shown in the following table.

| Specifications | | | Model | FE70DB13 | FE72DE63 |
|---|---|---|---|---|---|
| | | | | Standard cab | |
| | | | | 2-ton payload; low deck | 3-ton payload; high deck |
| Dimensions | Overall length | | (mm) | 4,690 | 5,985 |
| | Overall width | | (mm) | 1,695 | 1,890 |
| | Overall height | | (mm) | 1,975 | 2,160 |
| | Wheelbase | | (mm) | 2,500 | 3,350 |
| | Tread | Front/rear | (mm) | 1,390/1,235 | 1,390/1,435 |
| | Bed interior length | | (mm) | 3,120 | 4,350 |
| | Deck height above ground | | (mm) | 825 | 1,035 |
| Weights | Max. payload | | (kg) | 2,000 | 3,000 |
| | Gross vehicle weight | | (kg) | 4,535 | 5,865 |
| Engine | Model | | | 4M50T (3) | |
| | Displacement | | (cc) | 4,899 | |
| | Max. output | | {kW (PS)/min$^{-1}$ net} | 103 (140)/2,700 | |
| | Max. torque | | {Nm (kgf·m)/min$^{-1}$ net} | 412 (42.0)/1,600 | |
| Chassis | Transmission | | | 5 M/T | |
| | Suspension | Front/rear | | Independent/rigid axle | |
| | Brakes | Front/rear | | Disc/drum | |
| | Tires | | | 205/70R16 | 205/85R16 |

(LDT/LDE Project: Saito, Chassis Design Department, Research & Development Office: Onda)

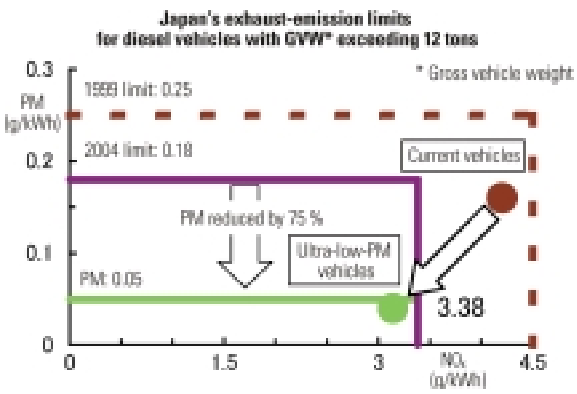
# SUPER GREAT "Ultra-Low-PM Model"

NEW PRODUCTS

FUSO

While heavy-duty trucks play an increasingly crucial role in the distribution of goods, their manufacturers face increasingly stringent requirements with regard to environmental performance. The 2003 SUPER GREAT series (launched in April 2003) reflects Mitsubishi Fuso Truck & Bus Corporation's (MFTBC's) response. It maintains a competitive edge over competitors in Japan by combining quietness (it satisfies Japan's 2001 noise regulations) with functionality that meets evolving market needs. Further, most SUPER GREAT-series models (including special-purpose models such as dump trucks and mixer trucks) are powered by 6M70T six-cylinder, turbocharged, intercooled engines, which not only offer high power and fuel economy but also achieve early compliance with Japan's 2004 limit (0.18 g/kWh) on particulate-matter (PM) emissions.

Notwithstanding the excellent environmental credentials of the SUPER GREAT models launched in April 2003, MFTBC subsequently created, in line with its constant goal of developing environment-friendly diesel vehicles, an ultra-low-PM model that realizes even better compliance with exhaust-emission regulations by means of an 'environment' engine whose emissions of PM (an exhaust-emission component that is particularly harmful to human health) are comprehensively minimized. This ultra-low-PM model was the first heavy-duty truck in Japan to qualify as a low-emission vehicle. It was launched in August 2003 (more than a year before the fall-2004 enforcement of Japan's new short-term emissions regulations).




## 1. Targets

In developing the SUPER GREAT ultra-low-PM model, MFTBC sought to realize an ultra-low-PM vehicle whose PM emissions are 75 % lower than those permitted by Japan's 2004 exhaust-emission regulations. More specifically, it sought to achieve the cleanest operation among heavy-duty trucks in Japan together with uncompromised levels of power, quietness, fuel economy, and reliability by means of a new 'environment' engine (a conglomeration of state-of-the-art MFTBC technologies) and a new continuous-regenerative diesel-particulate filter (DPF).

## 2. Features

(1) New 'environment' engine with low exhaust emissions and low fuel consumption

MFTBC created a new 'environment' engine based on each of three engine variants (320PS, 350PS, and 380PS) in the five-variant 6M70T series.

To realize ultra-low emissions with no sacrifice in the class-leading power, fuel economy, and quietness of the original design, new technologies were employed in addition to the already-employed Mitsubishi Innovative Quiescent Combustion System and high-pressure common-rail fuel-injection system. These new technologies include an exhaust-gas-recirculation (EGR) system that operates under electronic control and incorporates a water-cooled gas cooler; a positive crankcase ventilation system that recirculates blowby gases into the intake system; and an onboard-diagnostics system that monitors the operating status of the EGR system and other emission-control equipment and makes an appropriate response in the event of an electrical open-circuit or other fault. In addition, a powerful Powertard compression-release brake (previously used with the 350PS and 380PS base engines) was adopted not only with the 6M70T2 (350PS) and 6M70T3 (380PS) but also with the relatively light 6M70T1 (320PS).

(2) New continuous-regenerative DPF

The newly developed continuous-regenerative DPF is an aftertreatment device that requires no filter-cleaning nor any other kind of regular maintenance. It consists of a powerful oxidizing catalyst, which breaks down unburned fuel and oil, and a filter, which captures and burns soot. Its design precludes maintenance costs by ensuring that the filter does not become clogged during low-speed vehicle operation and by obviating the need for active regeneration (which would increase fuel consumption). Further, the continuous-regenerative DPF is approximately the same size as a conventional exhaust muffler and can thus be used in already-existing vehicle layouts. Plus, it permits the tailpipe to be shorter (and concomitantly lighter) than that used with a conventional muffler. Since the tailpipe opening can be located under the center of the vehicle (rather than at the tail), more space within the wheelbase can be used for vehicle-mounted equipment (for example, refrigeration equipment). And the side guards do not need heat-resistant paint since they are not directly exposed to exhaust gases. Thus, equipment-layout freedom is enhanced and costs are reduced.

(3) Preferential government treatment

- Reduced vehicle purchase tax

By not only satisfying Japan's 2004 exhaust-emission regulations but also achieving PM emissions that are 75 % lower than the permitted level, the ultra-low-PM model meets the requirements of Japan's certification system for ultra-low-PM-emission diesel vehicles (the most stringent certification system of its kind). Customers in Japan thus enjoy a 1.5 % reduction in vehicle purchase tax until the end of March 2005.

- Subsidies

Customers in Japan purchasing the ultra-low-PM model in 2003 receive subsidies provided by the national government, local authorities, and other public bodies.

- Other benefits

The ultra-low-PM model is recognized as a low-emission vehicle under the 8-Tokenshi and LEV-6 certification systems operated by prefectural authorities in the Kanto and Kansai regions, respectively, and is eligible to be counted toward the proportion of low-emission vehicles that local authorities in the Tokyo metropolitan area require truck operators to own. Purchasers can thus make unrestricted use of the ultra-low-PM model throughout Japan.

(4) Vehicle lineup

The ultra-low-PM model is currently available in the FT, FU, and FS series of long-body cargo trucks, which are used mainly on fixed distribution routes. With the FU series and FS series, it is offered with rear-axle air suspension (heavy-duty trucks with rear-axle air suspension are selling in rapidly growing volumes) and with all-axle air suspension (a choice for customers seeking even higher transportation quality, better ease of loading and unloading, and a low cargo deck). The range of vehicle and component choices is further expanded by incorporation of MFTBC's increasingly popular Intelligent and Innovative Mechanical Automatic Transmission (INOMAT) in order to reduce driver fatigue and fuel economy in FU- and FS-series vehicles that have the 380PS engine variant and a GVW of 25 tons.

## 3. Major specifications

Major specifications of key vehicle variants are shown in the following table.

| Specifications \ Model | | | 6 x 2 (dual front axle) leaf-spring-suspension cargo truck | 6 x 2 (dual rear axle) Air-suspension cargo truck | 8 x 4 low-deck | |
|---|---|---|---|---|---|---|
| | | | | | Air-suspension cargo truck | All-axle-air-suspension cargo truck |
| | | | FT50JVX2X | FU54JUZ3X | FS54JVZ3X | FS55JVZ3X |
| Dimensions | Overall length (mm) | | 11,990 | | | |
| | Overall width (mm) | | 2,490 | | | |
| | Overall height (mm) | | 2,920 | 2,900 | 2,960 | 2,930 |
| | Wheelbase (mm) | | 7,550 | 7,220 | 7,480 | |
| | Tread | Front (mm) | 2,050 | | 2,060 | |
| | | Rear (mm) | 1,845 | | 1,855 | |
| Weights | Vehicle weight (kg) | | 7,990 | 8,540 | 8,660 | 8,830 |
| | Max. payload (kg) | | 11,800 | 16,200 | 16,100 | 15,900 |
| | Gross vehicle weight (kg) | | 19,900 | 24,850 | 24,870 | 24,840 |
| Engine | Model | | 6M70T2 | 6M70T3 | | |
| | Displacement (L) | | 12,882 | | | |
| | Max. output {kW (PS)/min$^{-1}$} | | 257 (350)/2,200 | 279 (380)/2,200 | | |
| | Max. torque {Nm (kgf·m)/min$^{-1}$} | | 1,520 (155)/1,200 | 1,618 (165)/1,200 | | |
| Chassis | Suspension | Front | Long-taper leaf springs | | | Air springs |
| | | Rear | Long-taper leaf springs | Air springs | | |
| | Brakes | | Wedge-type full air brakes | | | |
| | Tires | Front | 11R22.5-14PR | 295/80R22.5 | 245/70R19.5 | |
| | | Rear | 11R22.5-14PR | | 245/70R19.5 | |

(HDT/MDT Project: Noguchi)

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