

Honda R&D

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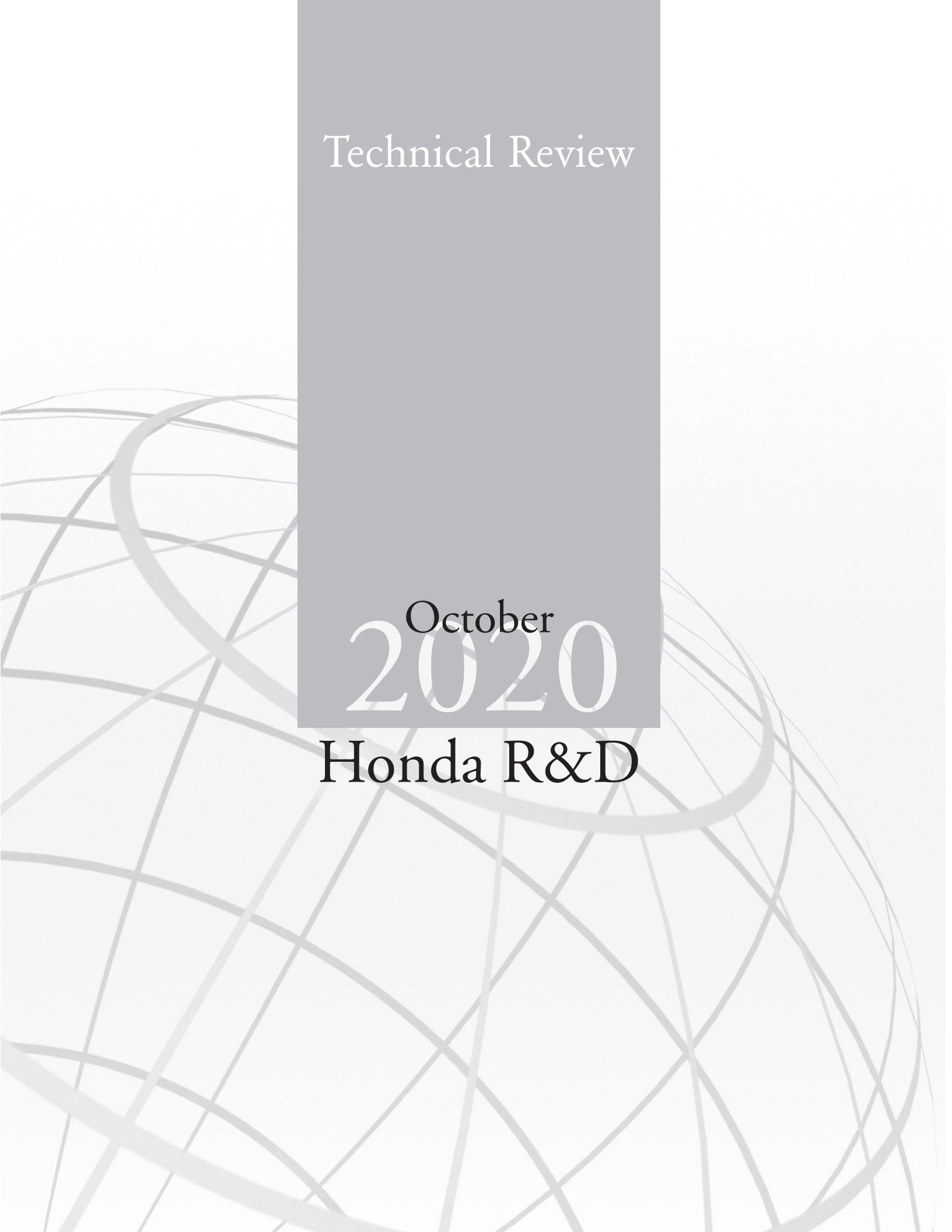
Comment on the Cover

For this cover image, we isolated the slit elements of the interior fittings of the N-VAN, and created an abstract spatial composition.

The use of numerous slits in the design of the N-VAN's panels makes scratches and other blemishes less noticeable even under hard use, and also has the effect of dramatically expanding interior space. The realization of both functional value and the value created by sculptural molding that is visually appealing is an important element in product design, and I believe that this product, which also incorporates the imagination of our engineers, can legitimately be called a masterpiece.



Design Center
Atsushi SASAKI

The background features a light gray wireframe sphere on the left side, composed of intersecting curved lines. A solid gray vertical bar runs down the center of the page, serving as a backdrop for the main text.

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CONTENTS

Introduction of new technologies

“N for Work” N-VAN Design Enriches Possibilities for Life with Loading and Carrying Maki YAMAGUCHI, Chiaki KATO Yoshihisa YANAGIMOTO, Noriyuki ISHIDA	1
Development of 2020 CRF1100L Africa Twin	Kenji MORITA, Nozomi OKADA Hiroshi OKAMURA, Shota SUZUKI
Development of Electronically-controlled Suspension System for 2020 CRF1100L Africa Twin Adventure Sports ES Hiroshi OKAMURA, Tsuyoshi TSUDA, Atsushi OGAHARA	27
Cornering Lights of 2020 CRF1100L Africa Twin Adventure Sports Using Additional Light Source Tokujiro KIZAKI, Hirotaka SATO	35
Experimental Environment for Verification of Speech-based News Delivery System Hiroshi HONDA, Hiroaki TAKATSU Yoichi MATSUYAMA, Tetsunori KOBAYASHI	42
Guide Robot Management System	Kenji NISHIMIYA, Shinya KANEKO
Development of Deviceless Tumble Enhancement Method for Small Motorcycles Makoto FUJIKUBO, Yohei NAKAMURA, Yosuke INOUE Keigo KAMEDA, Hazuki HIDAHA, Hironobu OIKAWA	56
Development of High-efficiency CVT for 2020 Model Year CITY Soichiro SUMIDA, Yoshifumi MURAKAMI, Makito NAKASONE	70
Small Size Power Control Unit for 2020 Model Year FIT Hitoshi NISHIO, Yasuhiko KONDO, Yuichiro UENO Kenichi NONAKA, Yukiya KASHIMURA, Kenichi TAKEBAYASHI	78
Development of One-piece Reverse Rim Aluminum Alloy Wheel Using Flowforming Process Masayoshi OHASHI, Muneyoshi SAWAI, Tomonori SAKAI Erina KOBAYASHI, Hideyuki SUZUKI, Minoru KAWAKAMI	84
Modeling and Utilizing Expert’s Knowledge, Experience, and Thinking in Automobile Development Shigeto YASUHARA, Takeshi YOSHIMOTO, Hideyuki OKADA	91
Search for Alloy Catalyst for Automobile Exhaust Gas by Means of Integrated Flow of Experiments, First-principles Calculation, and Materials Informatics Satoshi HIROSE, Hitoshi MIKAMI, Masafumi SAKOTA Hiroki TAKEORI, Tatsuya OKAYAMA	99
Material Database for Efficient Development Using Materials Informatics Tsuyoshi ITO, Satoko ISHII, Hiroshi HONDA Nao SUGIMOTO, Yoichi TOYOOKA, Toru FURUSAWA	110

Technical papers

3D-structured Cathode Electrode for High Capacity Lithium-ion Battery Kiyoshi TANAAMI, Yuji ISOGAI, Shintaro AOYAGI Kazuki OKUNO, Hiroshi TAKEBAYASHI, Kikuo SENOO, Akihisa HOSOE	118
Low Relative Permittivity of Magnet Wire Insulation Coating for HEV Motor Ryotaro KANEKO, Tadao NISHIYAMA, Keisuke AZUSAWA	129
Analysis of Subjective Values of Car Users in Japan and U.S. Using Free Description Keyword Method Kaoru KUSAKA, Toshiya KANDA, Takeaki NAKAJIMA Tetsuya KAYUMI, Ayako MASUDA	137
Traversability Analysis for Mobile Robot Navigation in Rough Terrain.	Shintaro HIDAKA, Norio NEKI 146

“N for Work”

N-VAN Design Enriches Possibilities for Life with Loading and Carrying

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ABSTRACT

The N-VAN is a microvan that as successor to the ACTY VAN represents the first full model change in 19 years. Since the time of its founding, Honda has pursued experiential value that would help enrich customers' lives.

Honda Design refers to this as experience design and engages in vehicle design that ponders ever more deeply about the customer's experiential value. N-VAN development was also based on this kind of thinking, and in order to reach a deeper understanding of the customer, research was done into the actual circumstances of people who work and people who engage in loading and carrying cargo. The designers themselves worked with package models and went through repeated trial and error to experience directly how different cargo would be loaded, what kinds of issues would be encountered when loading, what points people would have challenging with, and so on. As a result, it was decided that customers are of two types, those who emphasize functionality and those who also like to emphasize style in addition to functionality. First, for customers who emphasize functionality, the concept of “a tool for a life that involves loading and carrying things” was determined, with the idea that the vehicle would become like a familiar tool that is easy to work with. The base G and L grades were designed around the keywords of “a feeling of flexible usability,” “a feeling of unstressed security,” “a feeling of solid stability,” and “beautility.” With these G and L grades as a foundation, another grade called +STYLE was configured to support a world view of each customer who places importance on style in addition to functionality. With these two grades, a new standard was created for a new microvan that becomes an important tool for everyday lives that involve loading and carrying things.

1. Introduction

The N-VAN is a microvan that represents a full model change in the ACTY VAN, which has been a customer favorite for as long as 19 years. The N series of mini compact vehicles (K-cars) is intended to offer models suited to customer uses in every direction of the mini compact category, with the N-BOX for family use, the N-WGN for personal use, and the N-ONE for couples. The N-VAN is the sixth in this series and was developed as a microvan aimed at commercial users and hobbyists.

Marketing research on microvans done when starting development showed that circumstances had changed considerably since 19 years before. Business using microvans had changed greatly as well, as in the small-lot distribution services that had increased as internet sales became widespread, there was a new style of mobile business using vehicles as business establishments, there was an expansion of businesses providing locations to mobile business, and so on. In conjunction with these changes, it was found

that where the former user group had been envisioned as mostly middle-aged and older men, now there were growing numbers of women and elderly people as well as younger people starting up businesses as private individuals.

What people look for in microvans has also changed. It is no longer just a commercial vehicle. They said that they want to work in a fashionable way, they want to work in a way that is considerate of their bodies, they want to drive comfortably, they want to avoid intimidating pedestrians even in narrow back-streets, and so on. It is also necessary to respond to customers' heightened safety orientation as a societal requirement for motor vehicles. The designers felt and understood these things from repeated efforts to go out and do research on foot, conduct group interviews, and so on. The main issue 19 years ago was how to load more cargo into the vehicle, but they understand that in today's workplace, consideration and kindness to people is important, because people want to work more efficiently while enhancing loading capability, to work in a way that is considerate of their bodies, to have greater safety, and so on.

¹ Design Center

Based on research of this kind, the base concept for the N-VAN, as shown in Fig. 1, was declared to be, “providing for people in Japan whose lives involve loading and carrying things.” In addition to people who put the emphasis on functionality in their work, there are also people who are

concerned with style in the way they work. The aim here was to enrich these people’s lives and make this a new standard for the next-generation microvan by pursuing the three key themes of space that is made totally usable, smooth driving and fuel economy, and consideration for people.



Fig. 1 Base concept

2. Concept of a Tool for a Life that Involves Loading and Carrying Things

Honda has implemented designs that pursue experiential value to help enrich customers’ lives. At Honda, experiential value design that understands customer expectations and provides them with a real feeling of value in their actions and experiences is called experience design. The aim here is to advance this experience design beyond where it was before and further heighten the value provided to the customer.

Design development ordinarily proceeds with separate designs for the package, interior, and exterior. For the N-VAN, however, this experience design approach was taken as the

foundation and a total design that considered the customer’s experiential value more deeply was carried out. The vehicle becomes like a familiar, important tool that is easy to work with in an everyday life that involves loading and carrying things. Providing that kind of experiential value was determined as the aim, and “a tool for a life that involves loading and carrying things” was taken as the common concept.

The package design, which creates the framework for the vehicle, and the interior design were carried out first. As indicated in Fig. 2, the aim was to express “a tool for a life that involves loading and carrying things” through the three elements of “a feeling of flexible usability,” “a feeling of unstressed security,” and “a feeling of solid stability.”

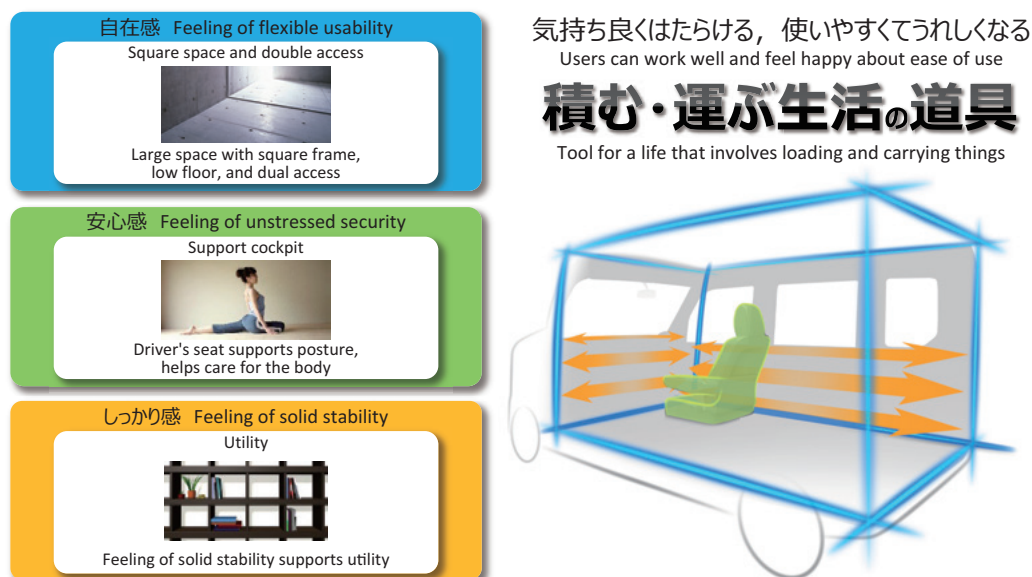


Fig. 2 Experience of N-VAN design concept

2.1. A Feeling of Flexible Usability

In order to support customers’ feeling of wanting to get loading done and raise efficiency, the squared-off high-volume space shown in Fig. 3 was realized. It has a large space with a low floor, is pillar-less on the front passenger-

seat side, and has a dive-down front passenger seat. Thought was given to lines of flow extending outside the vehicle, so the large openings on the front passenger side and at the rear create a space that feels open to flexible use in a variety of potential ways.

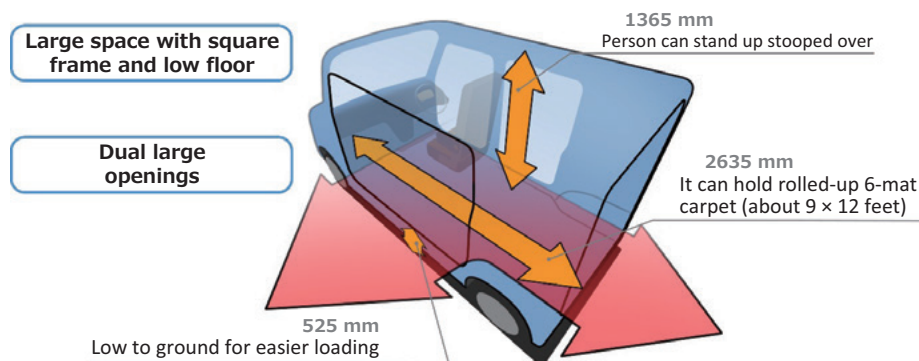


Fig. 3 Space that gives feeling of flexible usability

As shown in Fig. 4, the front-engine front-drive (FF) layout allows for larger vertical space in the cargo area than the midship rear-drive (MR) engine layout of the ACTY VAN, where the floor surface tends to be higher above the

ground. The N-BOX FF platform was therefore adopted. A further thought was that, by providing suggestions for style that go beyond the commercial image, the potential for microvan usability could be greatly expanded.

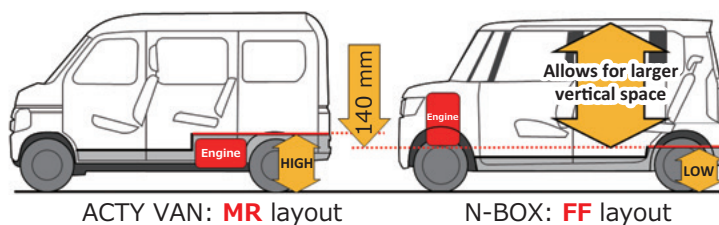


Fig. 4 FF layout

The next-generation loading and carrying space that goes beyond the loading and carrying done before was then examined. Team members carried on three-dimensional Y-gaya discussions, as shown in Fig. 5, to verify by their own experience of whether the space really was usable, how to use it, and so on, using the package model. Honda has a conceptual

approach called the Three Realities Principle that says to seek solutions to issues not by theoretical speculation but by going to the actual place, finding the actual source of the issue at hand, and basing your actual decision on reality. By working from this Three Realities Principle, the result of a large space with square frame and low floor was successfully realized.



Fig. 5 Package models used in 3D Y-gaya discussions to find ways of “using space completely”

These Y-gaya discussions also produced the idea of making the front passenger seat dive-down, which overturned the conventional view that the area behind the front passenger position was the cargo area. As shown in

Fig. 6, making the floor on the front passenger side flat made it possible to realize a flat cargo area that can hold long objects up to 2635 mm in length between the foot of the front passenger seat and the tailgate.

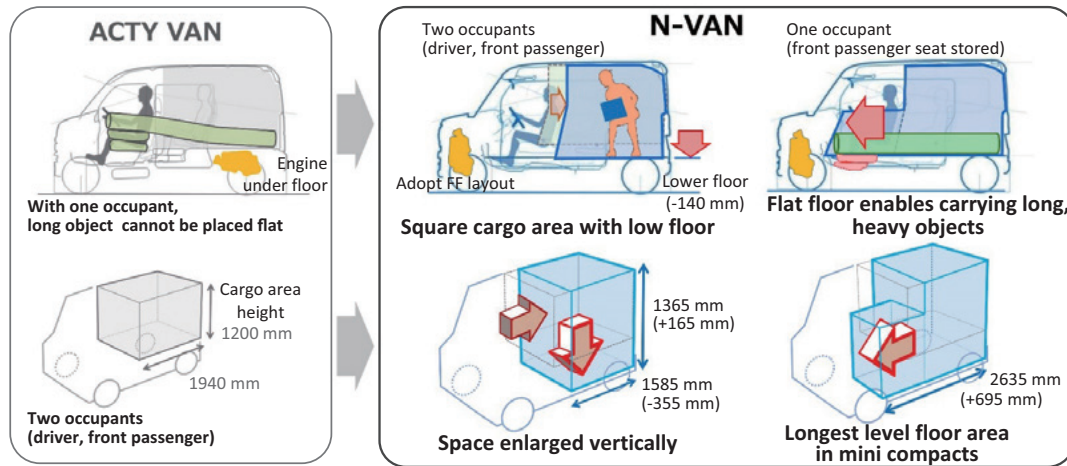


Fig. 6 Different ways to use space

In addition, the pillar on the front passenger-seat side was moved to the door side to make a framework with a large side opening. As shown in Fig. 7, this added a new line of loading and carrying flow from the front passenger-seat side, where previously the line of flow was at the rear. Realizing two lines of flow that allow simultaneous access

creates an entirely new, flexible openness of usability that can accommodate a variety of scenarios. These include safe loading and unloading from the sidewalk side, use as counter space for a mobile shop, allowing access to the vehicle interior and exterior at parking spaces that are too tight for the tailgate to be opened, and so on.



Fig. 7 Conceptual images of uses for new lines of flow and dual large openings

Also, as shown in Fig. 8, the area has a flat steel panel placed vertically with numerous "utility nuts" built-in to accommodate bolts to support boards to make shelves and so on. A pedal-hampering prevention board was added to keep objects from intruding into the driver foot space when the front passenger seat is in dive-down. In order to make

working at night safer, the ceiling light is positioned so that its illumination can extend outside the large opening on the front passenger-seat side. Additional comprehensive steps were taken to enhance functionality, such as by relocating the cargo hooks for better usability.



Fig. 8 Comprehensive functionality enhancements

This open, flexible space enables active application in various kinds of lifestyles that involve loading and carrying things, as shown in Fig. 9. For example, long, heavy

objects such as construction materials or a motorbike can be accommodated, it can be used as an office or a shop where customers can be received, etc.

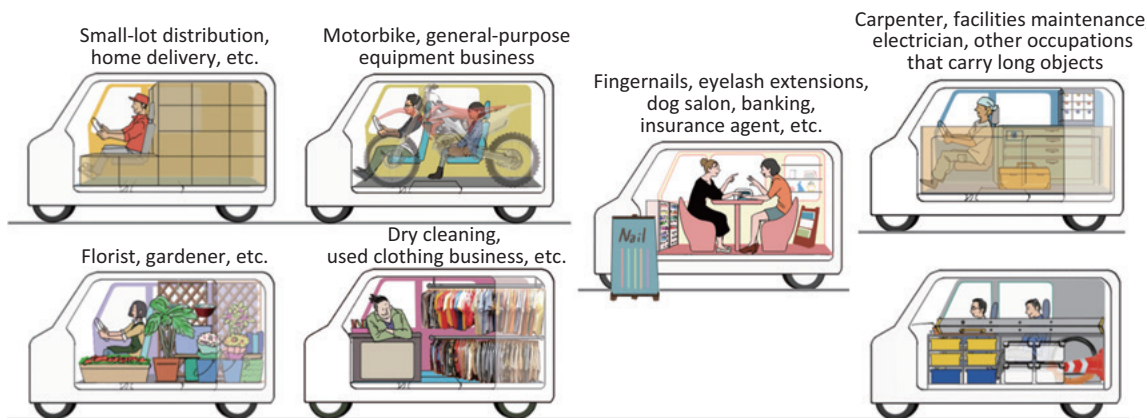


Fig. 9 Conceptual images of uses for large space with low floor

2.2. Feeling of Unstressed Security

Using a microvan for home delivery or other similar work in urban areas involves repeated stop-and-go driving as well as entering and exiting the vehicle many times. For drivers who repeat such movements all day long, a driving environment that is easy to use and less tiring was

investigated. The resulting conceptual image, as shown in Fig. 10, is of the body axis held straight as in a yoga pose. This was taken as the direction to pursue for driving posture. The aim was a driver's seat that embodies thorough care for the driver's body by helping to maintain good posture and also that supports older people and smaller women.

"Maintaining good posture" as in yoga pose

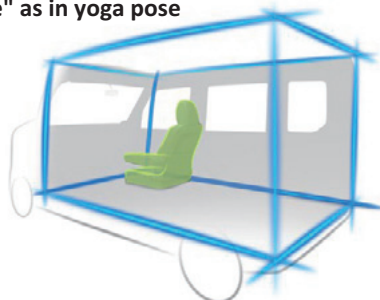


Fig. 10 Driver's seat with sense of unstressed security

The pedal layout was also positioned directly in front of the driver, as shown in Fig. 11. Adopting the FF layout made it possible to do this by positioning the front tires relatively farther forward.

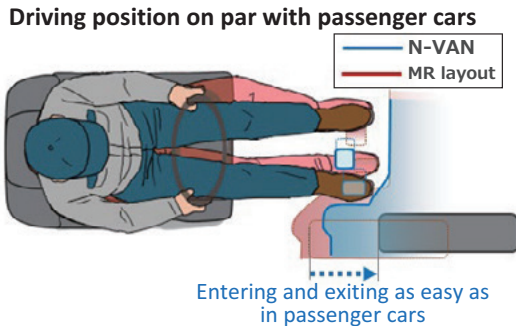


Fig. 11 Driver's seat helps maintain good posture

For the hip-point configuration, positions were set so that entering and exiting the vehicle would be easier and involve less vertical movement at the center of the body, as shown in Fig. 12.

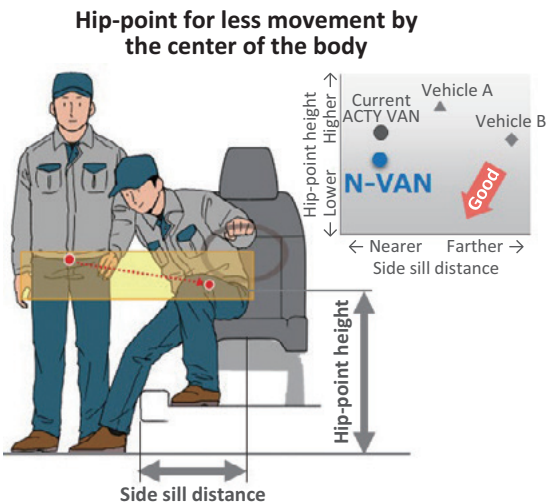


Fig. 12 Greater ease of access

As shown in Fig. 13, the design of the driver's seat emphasized a feeling of unstressed security with thorough care for the driver's body and commercial functionality. The other three seats (passenger seats) were designed so that, when folded down into the low floor, they would form a flat surface without gaps or crevices.



Fig. 13 Seating by function

For the driver's seat, it is important for drivers to feel that it both shows consideration for their bodies and provides commercial functionality. A comfortably sized seat frame on a par with passenger car seats was therefore used. The designers also carried out the design according to the Three Realities Principle, actually shaving down the urethane for the seat, having many people try sitting on it, and then shaving it down some more. The lower part of the seat back was finally given a bolster form that could hold the driver's body firmly to help prevent it from swaying side to side while also helping to mitigate lower back pain. That shape, as shown in Fig. 14, is similar to the seat in the CIVIC TYPE R, which holds the center of the body firmly in place. The upper part was made flat to allow the driver to turn smoothly when checking to the rear. Out of consideration for people who may enter and exit as many as 200 times every day for a home delivery service or other such business, the height of the seat cushion exterior was kept as low as possible to allow drivers easy access.

The cover on the upper surface of the cushion was made in a single piece that wraps around the lower part of the cushion to remove any seams in areas the driver rubs against when getting in and out, making the cover less likely to tear.

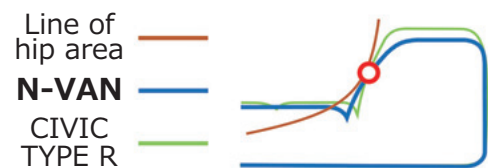


Fig. 14 Comparison of seat-back sections

In order to make it possible to rest comfortably during breaks, a large headrest and fully reclining mechanism were also adopted, as shown in Fig. 15. To enable comfortable driving, higher grades are equipped with large armrests. The front passenger seat can also be used as a table for convenience in preparing documents, eating, and other such activities inside

the vehicle. The dive-down seat has been given new functions, and new orange color of the operating lever and straps make them easier to understand as well as more visible in the dark. These measures have realized a driver's seat that provides a feeling of unstressed security, allowing anyone to find it easy to drive and work for extended periods.



Fig. 15 Front seats

Working people who drive a vehicle with a scratched interior finish may lose credibility with those hiring them to work. As shown in Fig. 16, therefore, the upper and lower parts of the doors and lining were given different surface textures. The upper side that people touch has a leather-like texture that is pleasing to the touch. The texture on the

lower side, where cargo is more likely to contact and cause scratches, was given a satin-like finish.

Care was also given, as shown in Fig. 17, to make the surface concave-convex with slits so that scratches would be less conspicuous than on a flat surface.

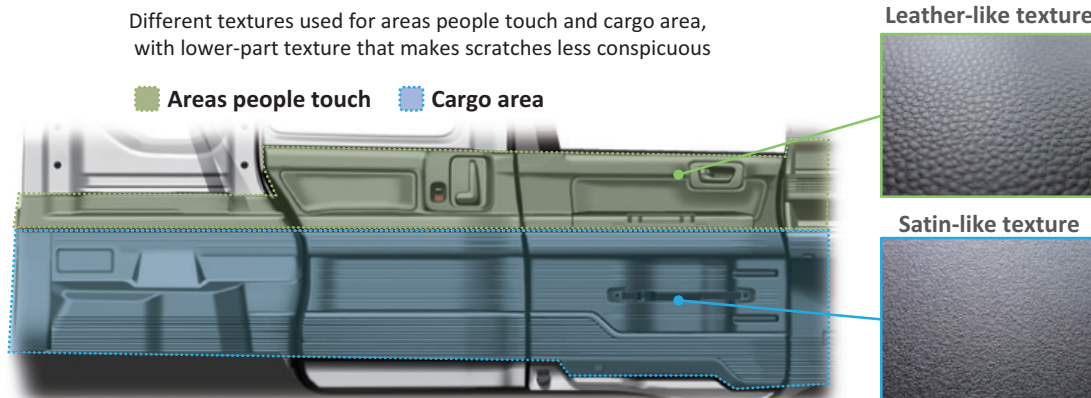


Fig. 16 Measure 1 to keep appearance attractive longer

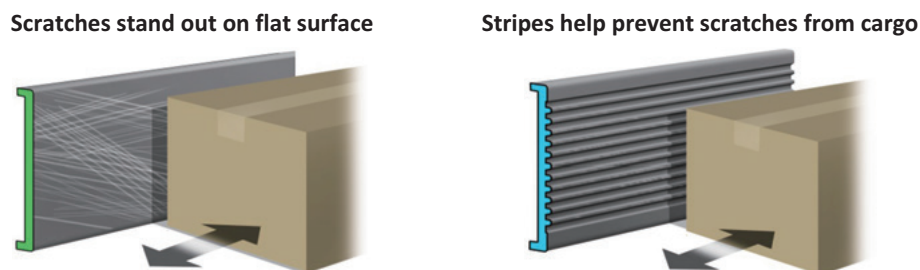


Fig. 17 Measure 2 to keep appearance attractive longer

Two sets of color variations are available, matched to customer usability. For the G grade interior color, the expectation is of vehicle use under corporate or other company ownership. As shown in Fig. 18, grey was chosen for this interior finish because scratches will be inconspicuous even when the vehicle is used freely by various people, it feels spacious, and it can have a long

lifetime of secure, comfortable use.

For the L grade, the expectation is for careful vehicle use under private individual ownership. Aiming for the image of a clean tool, the interior finish was given a dark tone that is easy to clean, resists soiling, helps prevent stains from being conspicuous, and conveys a feeling of unstressed security.

G grade: Grey interior finish for spacious feeling and making scratches unnoticeable



L grade: Dark tone interior finish makes even accumulated grime unnoticeable



Fig. 18 Interior color variations

2.3. Feeling of Solid Stability

Market research indicated customers want more storage space. Our approach was to provide shelves that can help keep the instrument panel and trim areas clean and orderly.

Thin shelves would seem flimsy and lacking in robustness, and would not add appeal as a tool. As shown in Fig. 19, styling for thick, solid shelves with beams along their length was configured.

Thin shelves seem flimsy, lack robustness



Thick, solid shelves look robust



Fig. 19 What robust shelves are

Since our customers' businesses commonly use materials that are about the size of A4 paper, initially a tray to hold A4 paper and a pocket for tissues were configured. Then a beam with a feeling of solid stability was stretched across each of upper, middle, and lower levels, as shown in

Fig. 20. The flow of this motif of three sturdy horizontal beams was continued from the door to the rear edge of the side lining to create the sense of an interior space enclosed by beams, producing the robust feeling of the solid stability of tools.

Balancing solid stability of shelves with that of tools

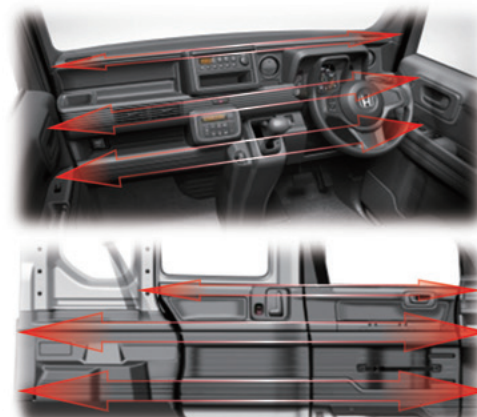
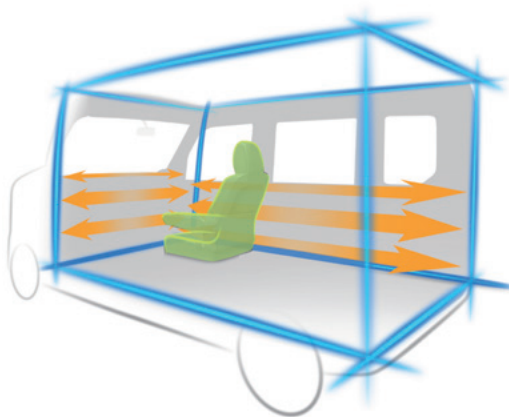


Fig. 20 Three beams expand across the entire area for a feeling of solid stability

Maintaining the concept of feelings of flexible usability, unstressed security, and solid stability creates an integrated design for the entire space that expresses the solid embodiment of a tool for a life that involves loading and carrying things. This is an experience design interior,

as shown in Fig. 21, that appears easy to use and open for flexible use in a variety of ways, conveying the experiential value of a space that invites work with an added sense of security, and that will remain usable for a long time.



Fig. 21 Interior as a whole

2.4. Exterior Design

The exterior styling was based on the concept of “a tool for a life that involves loading and carrying things,” which is intended to be a familiar tool that is easy to work with. The two keywords shown in Fig. 22 were defined with this in mind. One is “beautility,” signifying that it can be loaded and used as the tool of a professional. The other is a “feeling of unstressed security,” signifying that it provides a feeling of safety and reliability not just to the person using it, but also to the others around. With this as the exterior styling concept, the design fuses functionality with a feeling of unstressed security to express the next generation of loading and carrying. With this conceptual basis, the design proceeded first with the intention to pare away waste for a

simple expression of functionality. The image that eventually resulted conveys the boxy tool feel that demonstrates the full-scale emphasis on functionality commonly found in heavy equipment and machine tools. That, however, can also convey a strength that may be intimidating. Since a microvan frequently travels on narrow back-streets for home delivery and other such work, it is better not to present pedestrians with such an intimidating appearance. A balance was therefore sought between communicating the feeling of a tool and also giving people in the vicinity a feeling of unstressed security. As shown in Fig. 23, an exterior design was achieved that neither has the austere feeling of an entirely commercial vehicle nor the styling of a passenger car, but fuses functionality with a feeling of unstressed security.



Fig. 22 Exterior concept



Fig. 23 Simple design fusing functionality and feeling of unstressed security

A study was also made of expression of the capacity to carry large amounts of cargo. The result was a square form. In order to create such a form, which is a square shape that looks like large amounts of cargo can be loaded into it, it was considered necessary to have flat body panels of a kind not previously found at Honda. With a simple, flat shape and nothing more, thick steel panels will be needed to provide strength. Three lines of beading were therefore added to assure the needed strength. The illustration on the right side of Fig. 24 shows a cross-section of the front door under deformation. Making it one large surface reduces its strength, so it was formed as a structure consisting generally of three surfaces. The radius parts joining the upper and lower portions are linked together by the three lines of beading in the middle, forming a large surface that initially appears to be simple and flat, but actually has a complex surface structure. In this way, the distinctive three lines of beading originated not just as design but also as functional elements. This design with beading motif is used on a duralumin suitcase with the aim of providing actual strength together with design elements conveying the feeling of strength as well as the ability to make scratches less conspicuous. In the case of commercial vehicles, the company or shop name and logo or other such symbol are often painted on the body. Customer opinions were therefore sought during development to verify how the concave-convex beading would affect the appearance of the logo and so on.

The view was expressed that even if the suitcase is

scraped or scratched, if it is to the extent of scraping on the convex part of the beading, then damage to the logo and so on would be slight. Taking this into consideration, the convex shape was configured.

Thinner panels are also used for the roof shape in order to reduce weight. Places where customers would put their hands when mounting a stepladder to wash the vehicle were identified and an optimal shape was created in coordination with the body design division so that strength would be helped to ensure with no more than the necessary amount of rounding. This avoided excess rounding that would conflict with the boxy design. The design of the front of the vehicle was also implemented with consideration for the balance between “functionality” and “feeling of unstressed security.” The intention was to present people in the vicinity with a clean-cut, unthreatening face in order to convey a feeling of unstressed security. There is a strong tendency for customers to anthropomorphize their vehicle, with the headlamps as eyes and the radiator grille as a mouth. The headlights were therefore given a generally horizontal motif to express gentleness, while the radiator grille was also given a horizontal motif to keep it from being any larger than necessary, creating a clean-cut expression. The headlights are also more than just expressive elements. As shown in Fig. 25, they are designed primarily for safety. The headlights were placed as high up as possible, and the reflector was designed to brightly illuminate a large area. The turn signals were positioned to illuminate higher up and more toward the exterior.

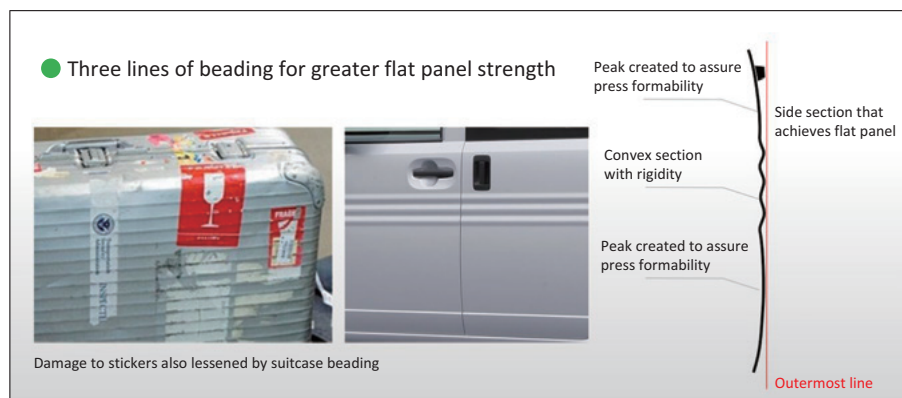


Fig. 24 Design with three lines of beading born from function

The position lamps form a line of illumination extending to the very exterior, clearly indicating the vehicle width and making the vehicle more visible. In addition, the radiator grille was kept as small as possible, contributing to enhanced aerodynamics and heightened fuel economy. The design at the rear has the combination lamps configured vertically and made as narrow as possible to enlarge the opening, as shown

in Fig. 26, to allow the large tailgate opening. Conventional microvans position the rear combination lamp at the rear bumper or other such lower site. For considerations of safety, however, LEDs were used in an extra-narrow design to enable higher placement, enhancing visibility of vehicles to the rear. This created a simple design that fuses functionality and a feeling of unstressed security.

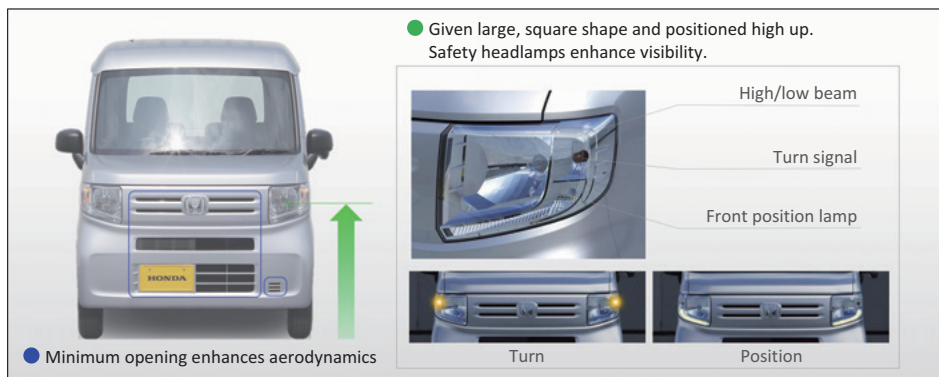


Fig. 25 Lights designed with primary concern for safety

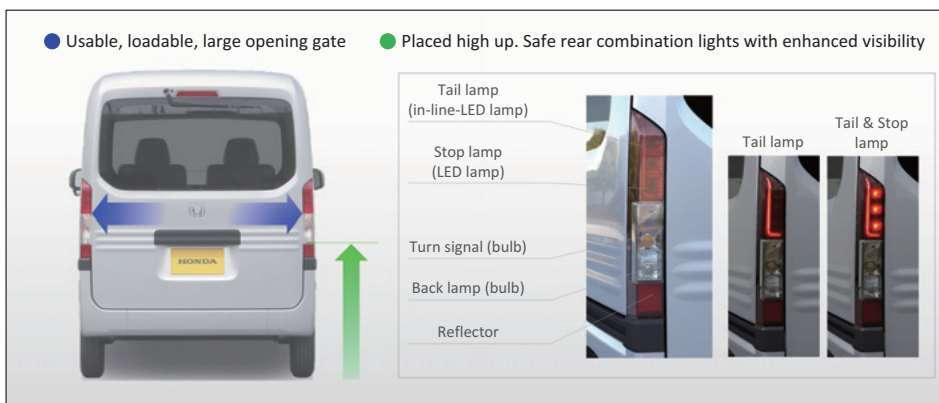


Fig. 26 Rear combination lamp design achieves balance of large opening and safety

3. +STYLE Grade

The +STYLE grade, which can highlight individuality, was configured in order to support a world view of each customer who places an emphasis on style in addition to functionality. There are two varieties. For customers who use the vehicle lightheartedly and pleasurably, there is +STYLE FUN. For those who insist on being cool and looking good, there is +STYLE COOL.

3.1. +STYLE Grade Exterior Design

The aim with +STYLE FUN was a van style that would greet the customer with a smile. The facial expression of a vehicle is primarily influenced by the design of the headlights. The design was first verified many times over using computer graphics, and then transferred to a full-scale model for further trial-and-error work, leading to creation of the expression shown in Fig. 27. Since the second-

generation N-BOX went on sale, the N series has had position lamps forming illuminated circles as a design icon that identifies the N series the instant the lights are turned on. This was inherited by +STYLE FUN. As shown in Fig. 28, the position lamps with LED light guide rings have high and low beam projector-type LEDs placed inside the rings. The turn signals are positioned on the outside for better visibility. A look of originality was created through measures such as black coating on the housing. The front grille uses the same components as +STYLE COOL except that a platinum-finish chrome plating is applied only to the very middle of the three bars. The other two bars above and below are the same color as the body, projecting an atmosphere of enjoyment that is entirely unique. The wheel caps have a piano black finish coating applied in sections to convey further enjoyment. For the L grade, a separate color is used just around the face and on the wheel caps to produce a largely individual feel and achieve an expression of friendlier fun.



Fig. 27 Van style greets customers with smile



Fig. 28 Detailed design expresses sense of fun

The objective with +STYLE COOL was a van style that is cool and looks good. The use of purple and other dark body colors to make the chrome sparkle was understood to be a conventional method that has a deeply rooted, universal appeal for custom product lines. Since this vehicle is also a tool for work, care was also taken not to overdo the custom orientation. For example, consideration was given to client impressions when an interior finish contractor parks the vehicle in front of the work site. The aim here was not to be too conspicuous, but rather to find a balance that does not betray the custom model user's feelings. As shown in Fig. 29, the design was finished to be eye-catching to

some extent while achieving a stylish appearance that is not overly flashy.

In order to project a cool and stylish appearance, a low roof was initially adopted and a tailgate spoiler was installed, as shown in Fig. 30. The facial area presents a feeling of breadth and strength with the front extrusion, e.g. the chrome-plated grille that gives a sense of unity with the headlights. The LED fog lamps are bordered by chrome-plated garnishes, while the license plate garnish also glows with chrome plating. The rear combination lamps are given clear lenses, while sections of the interior have black coating. This succeeds in producing a cool, good-looking appearance.



Fig. 29 Van style greets customers with cool look



Fig. 30 Detailed design expresses sense of cool

3.2. Exterior Color

There are said to be two choices for the exterior color of a microvan used as a commercial vehicle: white or silver. The work environment has changed, however, due to women's participation in society and other reasons, and it was decided, therefore, that having color variations was important for representing the business and for expressing the lifestyles of customers who want to emphasize style as well as functionality. The type of line-up shown in Fig. 31 was therefore deployed.

Garden Green Metallic is a new color exclusively for the N-VAN. As shown in Fig. 32, it was developed with the aim of realizing a color that would fit in as a familiar presence in a wide variety of lives and livelihoods, and that

would also highlight individual style.

As its base, a natural green expresses a wide range of lifestyles. On top of that, the highlighted portions were given a beige tone, and were chosen as natural colors that fit closely with people's feelings, giving very different impressions depending on who views them.

Use in a variety of different lifestyles and business scenarios was also taken into account to create Brilliant Sporty Blue Metallic that gives a fresh impression, and Premium Pink Pearl was added for a feeling of gentleness. Although the number of colors is limited, the color palette is arranged to communicate over the greatest breadth, highlighting the individuality of customers, and giving them color choices that suit their style.

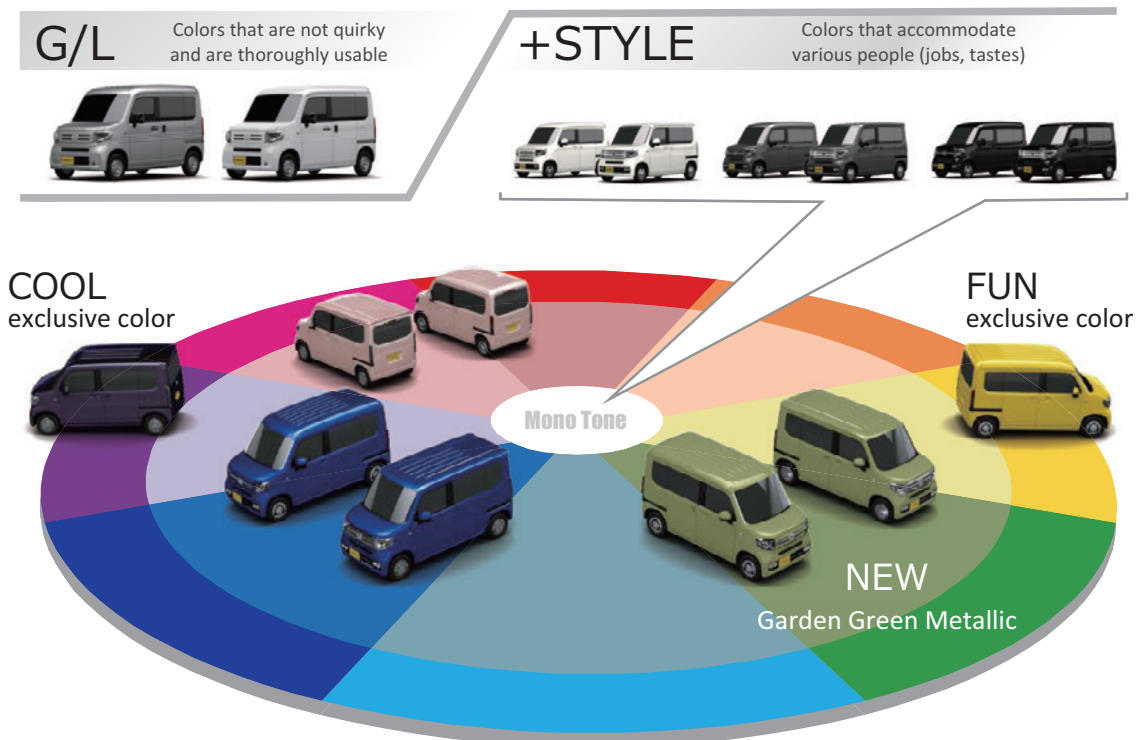


Fig. 31 Line-up of exterior colors

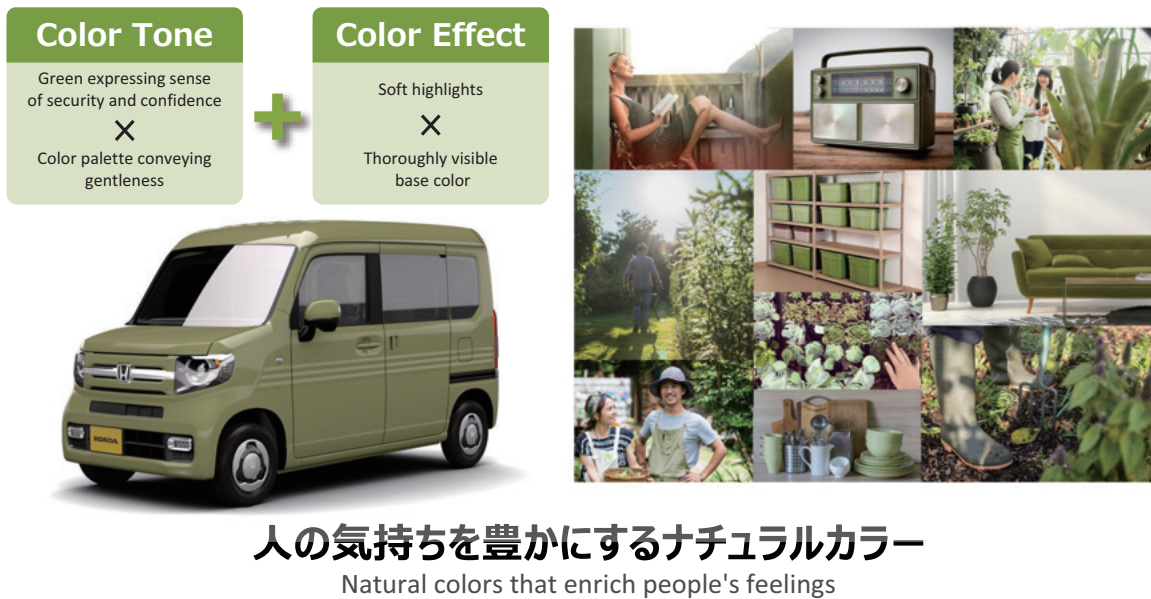


Fig. 32 Concept of exclusive new color, Garden Green Metallic

3.3. +STYLE Interior

The interior color, materials, and finish (CMF) of +STYLE aim to produce a stylish and high-quality tool-like feeling as shown in Fig. 33.

Taking the L grade interior finish as a base, fabric is applied as the front door lining, and the beam that reaches end-to-end of the instrument panel is given a decorative silver color for a feeling of solidity. Matching the combination of decorative silver and piano black tones applied around the steering wheel and door handles, a world view has been produced to support customers who want to highlight a style that is an addition to a functionality contrasting with the base.

In order to make decorative portions more resistant to scratching and marring, pre-dyed resin with the grain of metallic particles designed to reduce the appearance of production flow marks is used to express a highly distinctive material feel of silver.

The panels in the upper part of the cargo area do not have the interior finish, and instead are fully prepared to have touches of the exterior color effectively applied as accents for the interior, which otherwise has coordinated monotonous.

This all makes it possible to produce an interior space that matches the atmosphere and individuality of customers who want an added emphasis on style.



Fig. 33 Conceptual images of +STYLE interior CMF

4. Enriched Potential for Life with Loading and Carrying Created by N-VAN

Since its founding, Honda has sought to help enrich customers' lives through the philosophy of the Three Realities Principle, which focuses on the actual place, the actual object, and the reality of the situation. With this philosophy as a foundation, Honda Design has striven to think more deeply about the lives of our customers in the context of the ever-changing times, and pursued a policy of implementing experience design that yields experiential value. The N-VAN design proceeds in step with that policy, and in order to further enrich a “life that involves

loading and carrying things” in accordance with the times, development was pursued with the objective of creating a new standard for the next-generation microvan. This was accomplished with a conscientious effort to identify the issues involved and create next-generation value that realizes customer expectations. For customers who prioritize functionality, the proposed solution is the G and L grades, which fully plumbs the depths of functionality, as shown in Fig. 34. For customers desiring style in addition to functionality, the proposed solution is the +STYLE grade, which prioritizes style, as shown in Figs. 35 and 36. This approach broadens the richness of lifestyles that involve loading and carrying things.

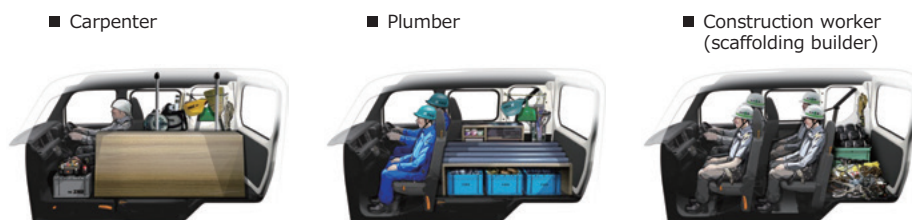


Fig. 34 G and L grades



Fig. 35 +STYLE FUN grade



Fig. 36 +STYLE COOL grade

It is the designers' sincere hope that customers will find in the N-VAN experiential value that makes this vehicle an easy-to-use tool they'll keep close at hand as important to their everyday activities of loading and carrying. When that occurs, the designers will believe that the N-VAN has achieved widespread acceptance as a new microvan standard.

5. Conclusion

In the N-VAN, a microvan that has undergone its first full model change in 19 years, with a design that expands the potential for enriching lifestyles that involve loading and carrying things, has been realized. This was based on the conceptual approach of experience design, which involves thinking deeply about the customer's experiential value.

As a result, a new standard has been created for a new microvan that will become an important everyday tool for people whose lifestyles involve loading and carrying things.

お客様がコトを創造できる道具 = N-VAN

Tool for customers to create events and experiences = N-VAN



沢山の積む・運ぶ生活を豊かにしたい!

We want to enrich many lives with loading and carrying things!

Fig. 37 N-VAN goal

■ Author ■



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ABSTRACT

Ever since the revival of the model name in 2016, Honda Africa Twin has been well-supported by the customers as an adventure motorcycle enjoyable on off roads as well as for touring on pavement. After four years since the initial launch in 2016, a full model change has been conducted in this project, renewing everything from the engine, frame body, suspension to the exterior, gaining more power by the increased engine displacement while reducing weight of the complete motorcycle. Accordingly realized are the more off-road friendly Africa Twin, and the Africa Twin Adventure Sports more suitable for touring with abundance of extra equipment for long, comfortable rides.

1. Introduction

The first-generation Africa Twin was an adventure model in which the technical features were fed back from the NXR750, which won the Paris-Dakar rally four years consecutively since 1986. To win the rally, the motorcycle has to be highly rideable to travel through the hard route and comfortable for the rider to maintain concentration for a long period of riding. The Africa Twin has both the rideability and the comfort at a high level.

The first-generation Africa Twin was born as XRV650 in 1988. After undergoing model changes such as an increase of engine displacement, its production came to an end in 2003. Backed up by the strong voices from the enthusiastic customers for a revival of Africa Twin, it was reborn as CRF1000L Africa Twin⁽¹⁾ in 2016. Moreover in 2018, the Africa Twin Adventure Sports was added as an adventure model that extends the fun of riding including touring. Four years after the revival, a thorough model change has been conducted in the 2020 year model, renewing everything from the engine, frame body, suspension to the exterior, to further enhance the on and off road capabilities of the two types. The CRF1100L Africa Twin (Fig. 1) is more suited to off-road usage while the CRF1100L Africa Twin Adventure Sports (Fig. 2) is more for comfortable touring.

The technical features for enhancement for off road and touring uses are discussed hereafter.

Note that each model is referred to as per the following in this paper.

Previous model, STD: CRF1000L Africa Twin

Previous model, AS: CRF1000L Africa Twin Adventure Sports

Developed model, STD: CRF1100L Africa Twin

Developed model, AS: CRF1100L Africa Twin Adventure Sports



Fig. 1 CRF1100L Africa Twin

¹ Honda Motor Co., Ltd.

Table 1 Comparison of specifications and equipment between developed and previous models

Item	Developed model		Previous model	
	CRF1100L Africa Twin	CRF1100L Africa Twin Adventure Sports	CRF1000L Africa Twin	CRF1000L Africa Twin Adventure Sports
Displacement (cm ³)	1083		998	
Bore x stroke (mm)	92.0 x 81.5		92.0 x 75.1	
Maximum power (kW/rpm)	75/7,500		70/7,500	
Maximum torque (Nm/rpm)	105/6,250		98/6,000	
Curb weight (kg)	226 {236}	238 {248} [240 {250}]	230 {240}	243 {253}
Seat height (mm)	870 850 (Low position)	870 850 (Low position)	870 850 (Low position)	920 890 (Low position)
Fuel tank capacity (L)	18.8	24.8	18.8	24.2
Windscreen	Low height	High height (Manually adjustable)	Low height	High height
Tire	With tube	Tubeless	With tube	
Electronic suspension	-	- [Equipped]	-	-
Headlight	LED	LED	LED	
Cornering light	-	Equipped	-	
Meter	LCD		LCD	
Display	6.5-inch touchscreen colored TFT		-	
Apple CarPlay*	Adopted		-	
Cruise control	Equipped		-	
Riding mode select	4 fixed modes and 2 user modes		3 fixed modes and 1 user mode	
ABS mode select	2 modes (on- and off-road)		-	
Torque control	7 levels and off setting		7 levels and off setting	
Wheelie control	3 levels and off setting		-	

Numbers in { } show DCT model.

Numbers in [] show optional electronic suspension model.

*Apple CarPlay is trademark of Apple Inc.



Fig. 2 CRF1100L Africa Twin Adventure Sports

2. Aims of Product Development

The heritage of Africa Twin is that the rider can enjoy both off road riding and touring on the pavement. As mentioned earlier, previous models were offered in two types; STD and AS. The STD is slim and light in weight for more agile off-road capabilities. With the bigger fuel tank

and the larger fairing equipped, the AS is more suitable for touring.

To make the features of the two types more distinguishable, we set a target at brushing up the off-road capabilities of STD model while enhancing the AS for more comfortable touring. If we pursue more comfort for touring using the previous AS model as a platform, a loss of the off-road capability is presumable due to an increase of weight from additional equipment, etc. An increase of weight would also be a limiting factor for enhancement of off-road capability in the STD model. Accordingly in this model, we decided to aim at realization of a STD model having good off-road capability and an AS model having enhancements for touring by reviewing all parts. Table 1 shows major specifications.

3. Enhancement of Off-road Capabilities

We have further enhanced the outstanding agility, which is a virtue of the Africa Twin among those in the large on-off road model category. The three major technical measures are;

- (1) Reduction of weight in the engine and the chassis
- (2) Reduction of inertia moment by centralization of mass in the complete motorcycle
- (3) Reviewing of frame stiffness

3.1. Weight Reduction

In this developed model, the weight of complete motorcycle has been reduced from the previous model by 4 kg in STD and 5 kg in AS while maintaining the same or better general characteristics such as the strength despite the higher power output from the latter-discussed increase of displacement and the abundant touring equipment.

3.1.1. Reduction of engine weight

In this developed model, the engine displacement has been increased to enhance performance. Generally speaking, an increase of engine displacement often causes an increase of engine weight due to the enlargement of engine size and the increase of strength of parts to deal with the increased power output. Nevertheless in this developed model, the engine weight has been reduced by 2.5 kg in the manual transmission model and 2.2 kg in the DCT model from the previous model. Figure 3 shows major technical features of the new engine. The key measures for engine weight reduction are discussed hereafter.

The total weight of an engine depends very much on the weight of main motion system parts such as the pistons, crankshaft, etc. as Fig. 4 shows. The increase of stroke to increase the displacement also increases the inertia force from the reciprocating parts. If the reciprocating parts becomes heavy for retention of strength, the inertia force in the reciprocating parts increases further, causing the parts to become even heavier to deal with the inertia force. Accordingly, with an aim at control of the inertia force in the reciprocating parts at the same level as the previous model, we set a target weight reduction at 8.9% while maintaining the same durability as the previous model.

With respect to the reduction of reciprocating parts weight, the details are discussed here about the piston and the piston pin. For realization of an optimum piston shape by minimizing excessive material, the direction of die draw has been changed to reduce the weight in the piston crown. A reduction of piston crown weight lowers inertia force

in the direction of rotation around the piston pin, which contributes to a reduction of slapping noises between the piston skirt and the cylinder. This permits reduction of the piston skirt surface area required for control of the slapping noise, allowing further weight reduction. As a result, the skirt width is reduced by 11.4 mm, the height is less by 3 mm as Fig. 5 shows. Coupled with the reduction of material from the piston crown, the weight of piston as a single part is reduced by 7%.

The piston pin is required to help ensure lubrication even when subjected to loads and deformed. In the previous model, the deformation is controlled by the stiffness from the wall thickness and maintained oil film by retaining a constant oil clearance. In this developed model, the employment of the new surface treatment that makes the material harder and is able to better maintain

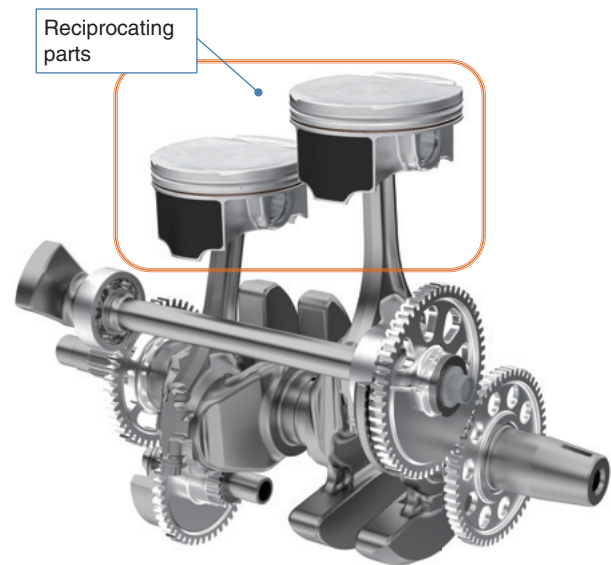


Fig. 4 Reciprocating parts in main motion system

Changed point	Displacement increased	1
	TBW: throttle boar diameter increased	2
	Exhaust gas control valve	3
Weight reduction technology	Aluminum cylinder liner	4
	Balancer gear: scissors mechanism eliminated	5
	Optimized reciprocating parts' shapes	6
	Manual transmission: clutch size reduced	7
	DCT: gear material changed	8
Characteristic technology	Biaxial primary balancer	9
	2 spark plugs per cylinder with phased firing	10
	270° phased crankshaft	11
	Built-in oil tank dry sump system	12

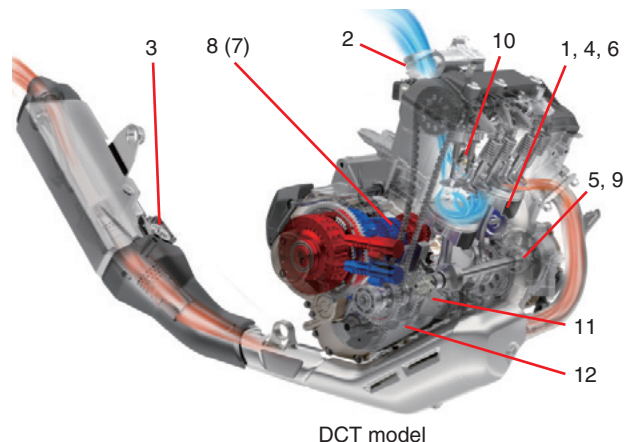


Fig. 3 Key technologies of powertrain

oil film helps ensure durability despite the lowered circumferential stiffness. Accordingly, the inside diameter has been increased by 1.8 mm while maintaining the same outside diameter, which corresponds to a 32% reduction of thickness (Fig. 5). Thus, the weight of piston pin as a single part has been reduced by 19%. Consequently, the total weight of reciprocating parts has been reduced by 8.9%, which equalizes the inertia force of reciprocating parts to that of the previous model.

The sub gears in the anti-backlash systems used in the balancer drive and the primary drive in the previous model for gear noise reduction have been eliminated for weight reduction. As a typical example, Fig. 6 compares the front balancer gear construction to that of the previous model. The two sub-gears help eliminate gear backlash by pinching the mating gear like scissors. In this developed model, we achieved the target performance by reducing the backlash by the measures such as the narrow tooth thickness tolerance realized by the revised tooth finish method, and the reduced tolerance of center-to-center distance of gears. Figure 7 shows sensual assessment of the front balancer gear noise by in-house specialists. With the backlash tolerance narrowed by 26% from the previous model, the target noise

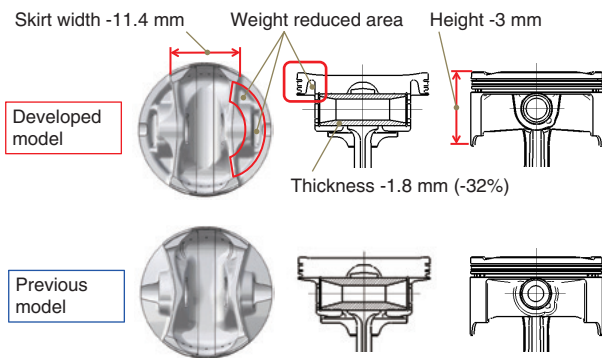


Fig. 5 Comparison of reciprocating parts

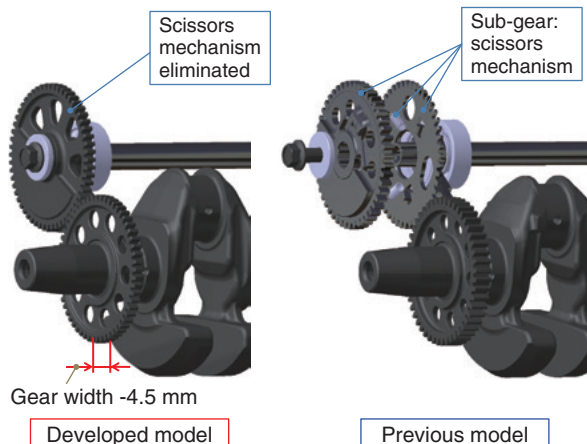


Fig. 6 Comparison of front balancer gear

level has been achieved.

Although the crankshaft becomes larger due to the 6.4 mm extension of stroke, its weight is maintained virtually the same as the previous model by the modification of the shape to the details such as the removal of excess material from various areas, and the reduction of gear width resulting from the elimination of the sub-gear in the anti-backlash system (Fig. 6). As a result, despite the increased engine displacement, the total weight of main motion system parts has been reduced by 820 g from the previous model.

Due mostly to the reduced weight of the main motion system parts, the center-to-center distance of major engine parts and the overall width of engine except those related to the stroke extension are maintained the same as the previous model. With more weight reduction measures taken such as the change of cylinder sleeve material from the cast iron to the aluminum composite, downsizing of the clutch, and the reduction of gear width by the use of high-strength material, the new engine is lighter and more powerful than the previous model (Fig. 8).

3.1.2. Reduction of chassis weight

With an aim at a thorough reduction of weight, elaborate studies were conducted on the chassis strength and stiffness, the materials, and the production method to redesign the

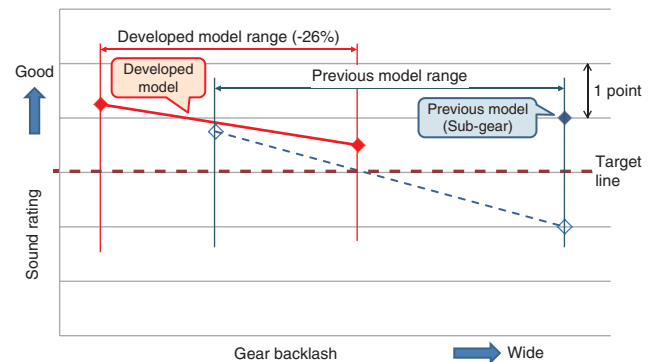


Fig. 7 Comparison of front balancer gear sound ratings

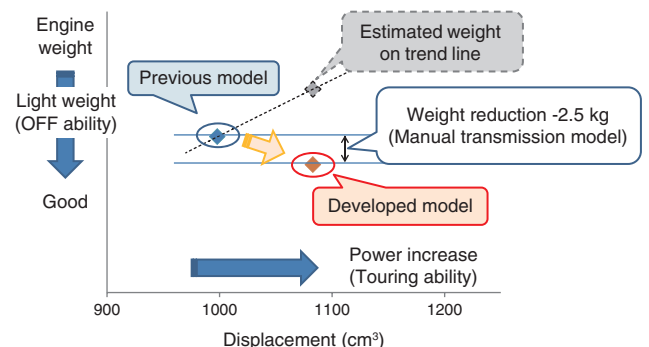


Fig. 8 Comparison of engine weights

frame body from the basic structures. Figure 9 shows the parts having effects for weight reduction of the developed model.

Unlike the front-rear integral construction of the steel frame body of the previous model, the developed model uses the two-split construction with the bolt-on rear frame made of light-weight aluminum. The reviewing of stiffness balance of the steel main frame to be discussed later in Section 3.3. allows elimination of the front cross pipe. Also, the various engine hanger parts are redesigned to the details to change the right-side lower pipe from the bolt-on split type to the welded one-piece construction while maintaining the same engine mount-ability as the previous model. Moreover, while the pivot plate uses the same construction as the previous model in that the two pressed plates are mated and welded, the plate thickness is reduced from 1.6 mm to 1.4 mm in the inner plate and 1.8 mm to 1.6 mm in the outer plate by the employment of high-tension sheet of 600 MPa grade for the inner plate.

To reduce weight in the rear frame and the swing arm made of aluminum, the cast parts having a high degree of design freedom and the forged parts featuring durability are combined and welded together using extruded pipes (Fig. 10). With these measures taken, the weight is reduced by 1.8 kg from the complete frame body, and 0.5 kg from the swing arm, totaling a 2.3 kg reduction from the main structural parts of the frame, contributing to the weight reduction of the complete motorcycle.

3.2. Reduction of Inertia Moment by Centralization of Mass in the Complete Motorcycle

To enhance agility, it is essential to reduce inertia moment of the complete motorcycle in three axes; yaw, roll, and pitch. Especially on bumpy or rolling off-road surfaces, a reduction of inertia moment that affects turning or up-and-down motions results in an agile handling and a

quick converging of vehicle motions induced by an external disturbance, allowing riding on rough roads in a more relaxed manner. Hence the weight should be reduced from the parts far from vehicle's center of gravity.

Especially a reduction of weight from the previously-mentioned rear frame and swing arm contributes to a mass centralization. In addition to that, the catalyst that purifies the exhaust gas is moved toward the front of vehicle in the proximity of the exhaust port for more efficient purification

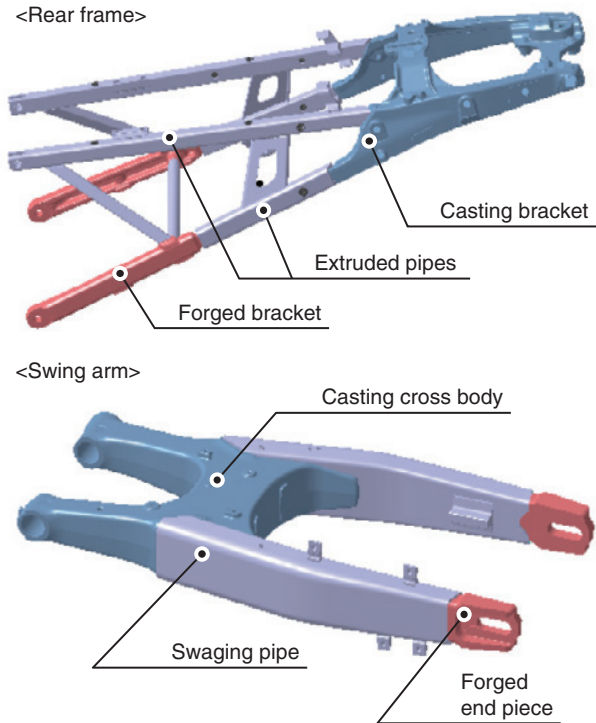


Fig. 10 Configurations of rear frame and swing arm

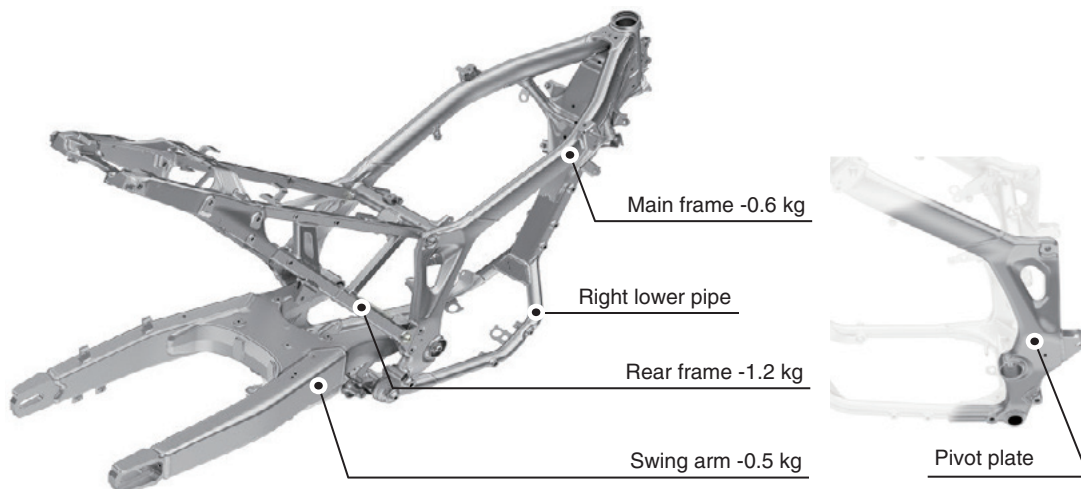


Fig. 9 Main points of modification of frame body and swing arm

to satisfy the emission norms. The catalyst relocation allows the muffler, which is a heavy item in the rear of the motorcycle, to be moved to 85 mm nearer to vehicle's center of gravity (Fig. 11).

With these measures for mass centralization taken, the yaw inertia is reduced by 4.0%, and the pitching inertia by 9.5%, contributing to the enhancement of agility (Fig. 12).

3.3. Reviewing of Frame Stiffness

When the motorcycle is shaken up and down vigorously from external forces on loose rough surfaces in off roads, it is important for the frame body to have sufficient flexibility to allow the motorcycle to respond to and follow rider's input so that the vehicle motions settle gently. Such frame characteristics reduce rider's fatigue and provide him/her with a peace of mind. In this developed model, we aimed at an enhancement of the characteristic handling of Africa Twin to allow the rider to travel through hard terrain with confidence by pursuing the flexibility.

In the previous model, the deformation of the main pipe occurring from the reaction forces from the road surface or at the time of braking is controlled by the front cross pipe. In this developed model, the deformation of the main pipe is

controlled by the reinforcement around the head pipe by the redesigned gussets and the reviewing of the main pipe layout in that the pipes are more parallel by the 20 mm reduction of width, allowing elimination of the front cross pipe (Fig. 13). These frame modifications contribute to the lateral flexibility while maintaining the same strength and durability of the frame body and vehicle stability at the time of braking as the previous model. Figure 14 shows an example of CAE analysis data of the frame body when the lateral force is applied to the front and rear tire contact patches. It is evident that the stresses are dispersed widely from the pivot plate to the main pipe in this model. This means that the entire frame body flexes, contributing to such characteristics that allow vehicle movements from external forces to settle gently. The resultant handling characteristics allow the rider to have confidence even on off roads. Moreover, the more agile handling from the reduced frame stiffness helps the rider enjoy off-road riding more than before.



Fig. 11 Comparison of muffler size

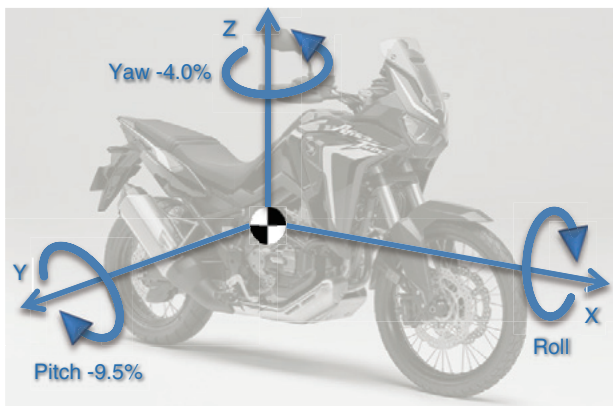


Fig. 12 Result of moment of inertia

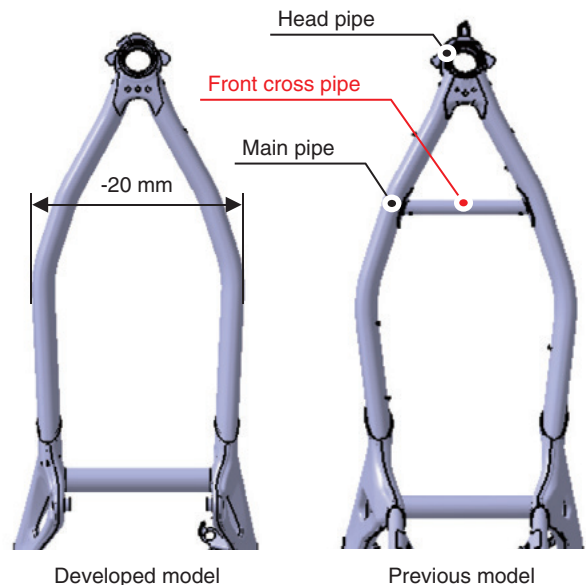


Fig. 13 Top view of main body frame

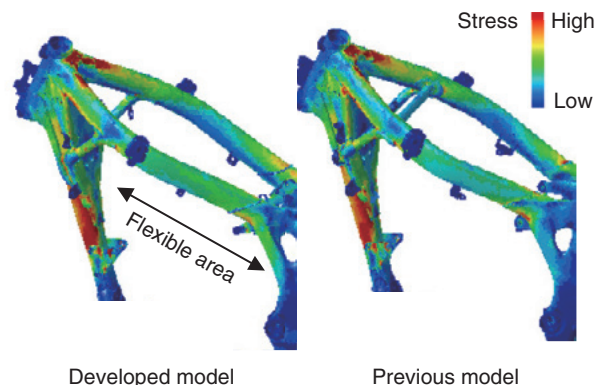


Fig. 14 Frame body analysis result

4. Enhancement for Touring Use

It is important for a touring motorcycle to reduce mental and physical fatigue from long rides. To deal with the mental fatigue, the engine performance is enhanced. Compared to the previous model, the extra torque in the low engine speeds helps assure stress-free acceleration even when having a passenger and/or luggage, which brings about psychological relaxation. With respect to the physical fatigue, the wind protection is enhanced, the riding position is reviewed and the seat comfort is enhanced. Among those, the following two measures are discussed hereafter.

- (1) Enhancement of engine performance
- (2) Enhancement of wind protection

4.1. Enhancement of Engine Performance

In Africa Twin models, one of the priorities is in the power output characteristics in the engine speeds customers use frequently. That said, a quick acceleration is important sometimes on motorways or the likes especially in the target market such as Europe. A stress-free acceleration with abundance of extra power enhances rider comfort. In this developed model, a target is set at an increase of power by 6% in the entire engine speeds so that an adequate acceleration is available from any engine speed. Taking into account a balance with the weight reduction, the engine displacement is increased by 85 cm³ from the previous model to 1083 cm³ (theoretical). Upon reviewing of other factors such as the intake/exhaust systems, the power is higher by 6% or more in all engine speeds with a maximum of 8% from the previous model (Fig. 15). As a result, the acceleration is approximately 5% better than the previous model (Fig. 16).

The increased power in all engine speeds provides the rider with an extra confidence regardless of the vehicle

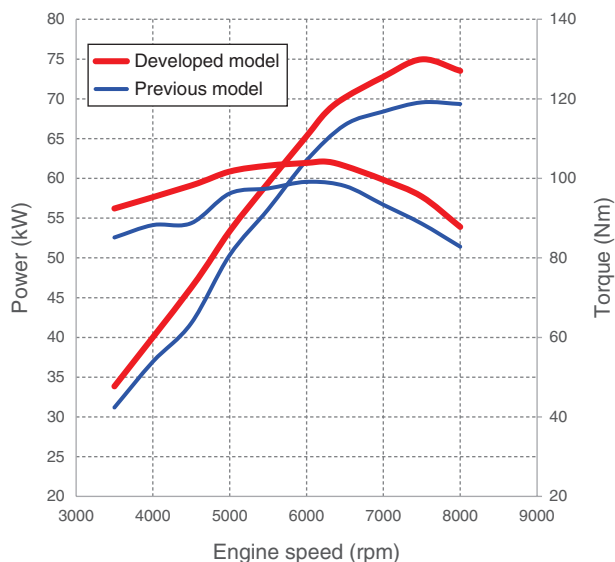


Fig. 15 Engine performance

conditions such as with luggage or the situation such as in uphill or at high speeds, enhancing comfort in touring. It also contributes to a fun of riding in off roads exclusively from a high engine performance.

4.2. Enhancement of Wind Protection

In the developed AS model, the wind protection is enhanced for more comfort in long touring. The wind protection in rider's head and torso areas is discussed here.

4.2.1. Wind protection around head

In the developed AS model, the tall windscreen longer by 215 mm than the STD type is employed for a better wind protection around the head (Fig. 17). The manual five-stage height adjuster is employed in the windscreen retainer. The height adjuster is composed of the two angled rails and links, allowing setting of the screen at any of the five stages by operating the right and left adjuster knobs (Fig. 18). With this construction employed, the height is adjustable by 60 mm and the angle by 5° in the fifth stage to change the

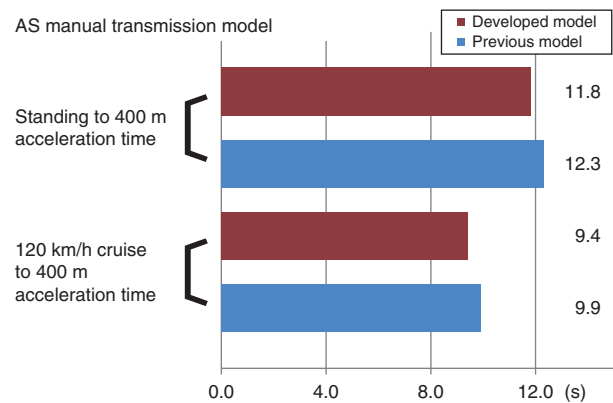


Fig. 16 Comparison of acceleration performance

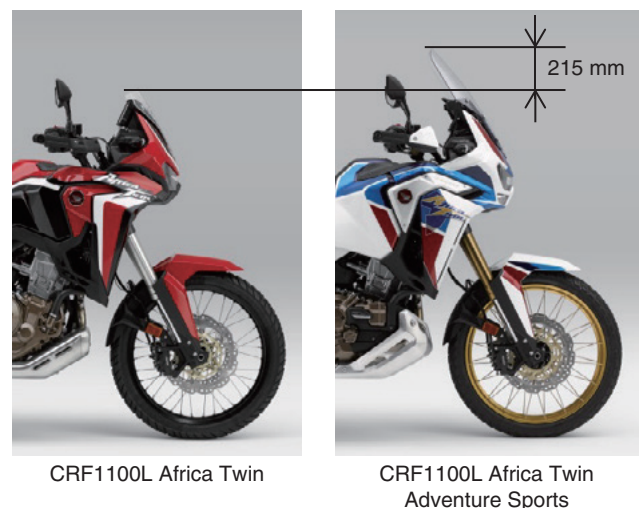


Fig. 17 Comparison of screen height

wind protection for rider's preference.

Figure 19 shows air velocity distribution around rider's head analyzed by CFD. In the first stage, the wind protection is targeted at the same level as the AS type of the previous model. The reduced air blasts on rider's head by this new screen helps ensure comfort in long touring. The second through the fifth stages are provided to permit adjustment in accordance with riding posture or rider's physique. Compared to the first stage, in which the height

is equivalent to the previous model, the wind pressure is lowered around the head in the fifth stage, which is an evidence of enhanced wind protection.

4.2.2. Wind protection around torso

The fairing is exclusively designed for the developed AS model having 50 mm more width than the STD type for better wind protection around the torso. Figure 20 shows the air velocity distribution around rider's lower body by

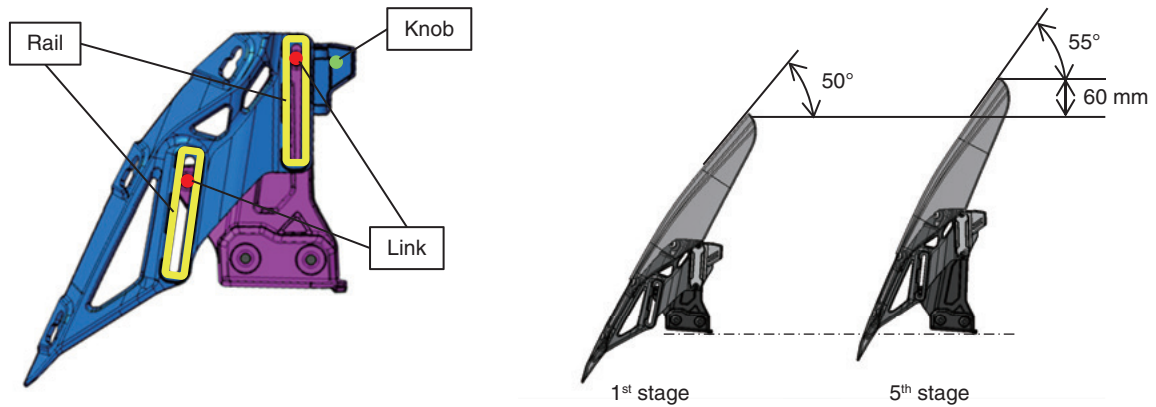


Fig. 18 External view of manually adjustable windscreen

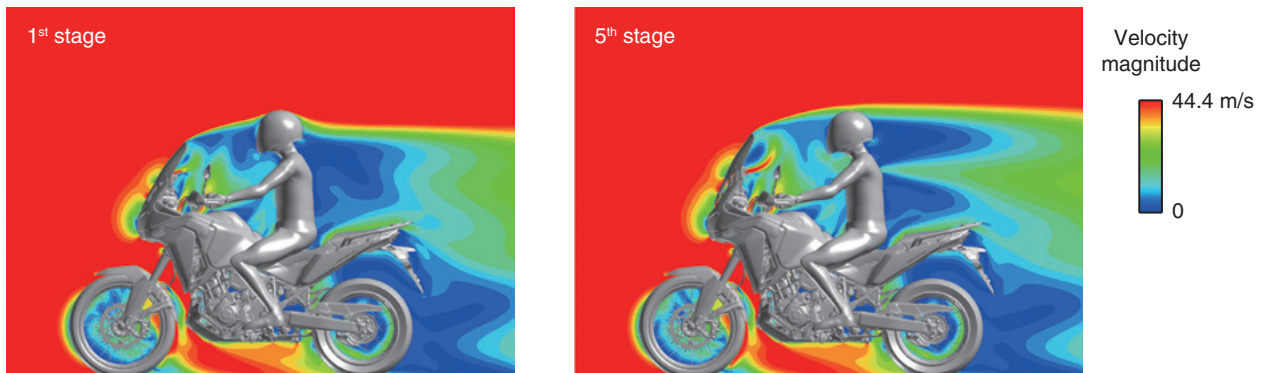


Fig. 19 Result of velocity distribution analysis of upper body by CFD

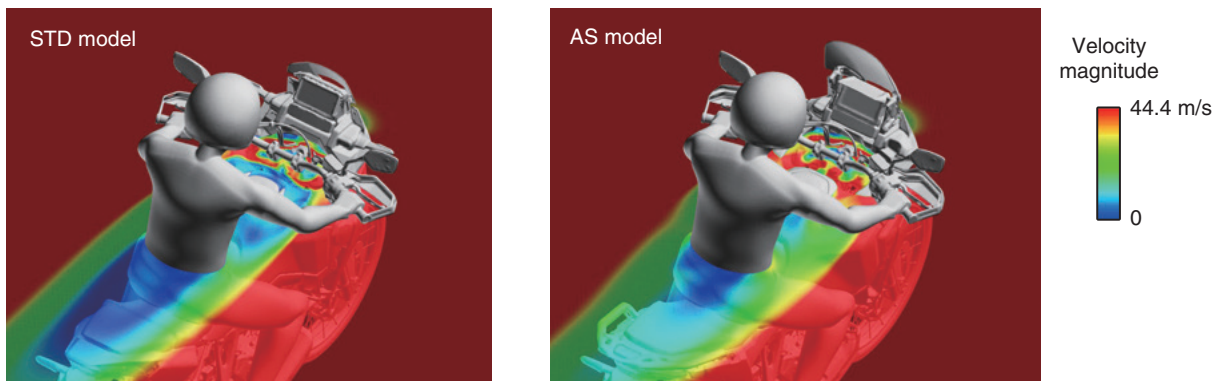


Fig. 20 Result of velocity distribution analysis of lower body by CFD

CFD analysis indicating that the modified fairing reduces wind blast to the rider.

As a result of the above, in addition to the high level of comfort the previous AS model features, the employment of the new windscreen adjustable for riding posture and/or rider's physique and the redesigning of fairing contour enhance the wind protection for the rider to reduce physical fatigue.

5. Enhancement of Vehicle Behavior Control

An enhancement is also realized in the control of vehicle behavior. With the Inertial Measurement Unit (IMU) equipped, six parameters shown in Fig. 21; the angular velocity of pitch/roll/yaw axes and the acceleration in the fore-and-aft/right-and-left/up-and-down directions are measured to identify dynamic motions of the vehicle on real-time basis. The use of the acquired data enhances preciseness of various controls to help ensure smoothness of vehicle behavior. The items subject to the control by the IMU are shown below.

(1) Honda Selectable Torque Control (HSTC):

The traction control to moderate behavior when the tire spins idle or slips sideways

(2) Wheelie control:

The traction control to restrict pitching angle and angular velocity when the front end is lifted up

(3) ABS:

The control of brake fluid pressure to moderate braking when cornering and to help prevent rear wheel lift at the time of braking

(4) Control of DCT by conditions:

Control of shift timing to help prevent unintended gear shift by the DCT when going uphill/downhill or cornering

(5) Cornering light (AS only):

Control of cornering light in accordance with the bank angle⁽²⁾

(6) Electronically-controlled suspension (optional only in

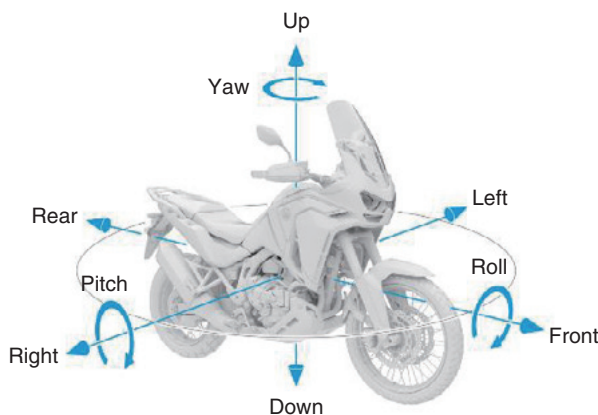


Fig. 21 Vehicle motion direction component from IMU

AS model):

Control of damping force to reduce jerky motions when braking or jumping⁽³⁾

(7) Quick shifter (optional equipment):

Control to identify erroneous operation to enhance shifting accuracy when cornering

6. Enhancement of Human Machine Interface (HMI)

The touch panel, 6.5-inch TFT display is provided to enhance communication between the rider and the motorcycle (Fig. 22).

The large color LCD is employed for easy viewing of abundant information to help ensure rider's acquisition of correct information from the meter while concentrating on riding. To allow instinctive setting of various functions, the meter is designed so as to permit setting operations from the touch panel when the motorcycle is staying still. Also, as shown in Fig. 23, connecting the meter with iPhone with a USB cable allows use of Apple CarPlay. Use of voice command by Siri for various apps such as navigation enhances convenience.



Fig. 22 Multi-information display



Fig. 23 Apple CarPlay

7. Conclusion

The Africa Twin more suitable for off road use and the Africa Twin Adventure Sports that allows more comfortable touring with the abundance of equipment have been developed through this project by increasing power output and reducing weight of the motorcycle. With the engine displacement increased, the power is higher by 6% or more in the entire engine speed range. A weight reduction is achieved by reviewing of the major components such as the engine and the frame. With the weight reduced by 4 kg from the previous STD model, the developed STD model is more suitable for off road use. The developed AS model is lighter by 5 kg than the previous AS model despite the addition of various features for comfort such as the enhanced wind protection. Coupled with the enhanced engine performance in the entire engine speed range, the AS model is even more suitable for touring.

We hope customers will enjoy new adventures on the Africa Twin which has realized at a higher level the model concept “Go anywhere - a true full-scale adventure model that allows riding on vast land of dream as well as for daily commuting” passed on from the previous model.

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Development of Electronically-controlled Suspension System for 2020 CRF1100L Africa Twin Adventure Sports ES

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ABSTRACT

The Honda Africa Twin is a full-scale adventure model featuring off-road and touring capabilities. As a 2020-year model, we have developed the CRF1100L Africa Twin Adventure Sports ES equipped with the new electronically-controlled suspension. Four suspension modes (HARD, MID, SOFT, OFFROAD) are provided to help ensure optimum performance in the wide variety of usage from high-speed long touring with a passenger and/or luggage up to challenging off-road riding. The riding modes are designated taking into account such five parameters as the engine power, the engine brake, the clutch characteristics (DCT model only), and the ABS characteristics in addition to the suspension modes. The rider can select any mode from the handlebar switch even when riding to adjust the motorcycle characteristics to best-suit his/her desire depending on the situation and vehicle conditions.

1. Introduction

The Honda CRF1000L Africa Twin was developed in 2016 as a full-scale adventure model featuring off-road and touring capabilities. The more touring-oriented Adventure Sports (hereafter AS) type was added in 2018 to broaden the fields the customers enjoy the adventure model. Although the higher suspension performance resulting from the 20 mm longer suspension stroke was well received, the increased seat height limited the appeal of this model only to riders of certain inseam length.

The 2020 CRF1100L Africa Twin has been developed as a successor of the above-mentioned model. In this model, development was conducted on the basis of two concepts: the CRF1100L Africa Twin featuring even more polished off-road capability and the CRF1100L Africa Twin Adventure Sports featuring more comfort in touring by the addition of features for comfort⁽¹⁾. In both types, a target seat height was set at 870 mm to standardize to a compact body size for off-road capabilities and easy maneuvering, and further enhance the features of both types while making it easy for the rider to set his/her feet on the ground. Regarding the suspension length, the front suspension stroke is 230 mm and the rear axle travel is 220 mm for

both types, which are derived from the 2018 CRF1000L Africa Twin (Table 1).

As a model having its roots in the Paris-Dakar Rally racer, it is a must to achieve high off-road capabilities as well as maintaining comfort in long touring. Especially the AS type is required to be more secure and comfortable under a wide variety of conditions such as cruising on motorways, negotiating through twisty mountain roads and even unpaved road. The motorcycle is subjected to a wide variety of conditions such as changing environmental conditions such as the temperatures, climate, road surface, sometimes carrying a passenger and/or luggage. We target at offering a model that can “go anywhere, go further” to realize your dream of long trip by the enhanced performance that best-suits various kinds of riding conditions to enable secure and comfortable riding. As a means to satisfy such variety of requirements, we considered an electronically-controlled suspension.

In this paper, we discuss the control system, setting, and the features of 2020 CRF1100L Africa Twin Adventure Sports ES (hereafter “newly-developed model”) equipped with the electronically-controlled suspension. Figure 1 shows the newly-developed model.

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Table 1 Specification comparison of previous models and developed models for export (US, EU)

		2018 model		2020 model	
		AS	STD	AS	STD
Front suspension stroke	[mm]	252	230	230	
Rear axle travel	[mm]	240	220	220	
Seat height	[mm]	920	870	870	



Fig. 1 2020 CRF1100L Africa Twin Adventure Sports ES

2. Aims of Product Development and Overview of System

The riding mode selection system is already applied to the Africa Twin from the 2018-year model with an aim at

offering confidence-inspiring characteristics by allowing the rider to select an optimum mode depending on the situation and vehicle conditions.

The riding mode system in the preceding model was composed of a combination of engine-related characteristics such as the engine power, the engine brake, and the driving force characteristics. In the newly-developed model, the system has been modified to integrate three essential functions for control of a motorcycle: run, turn, and stop. This system features an integral control of a total of five parameters such as the engine power, the engine brake, the clutch characteristics (DCT model only), the ABS characteristics, and the suspension characteristics. Figure 2 shows presumed situation of each mode and the characteristics of complete motorcycle.

The rider can select any mode from the left handlebar switch even when riding. Turning the throttle grip fully to the closing direction completes a mode shift. Note that when the motorcycle is stopped, the mode can be selected by touching the screen on the multi-information display composed of the 6.5-inch TFT LCD panel (Fig. 3).

To satisfy the demands under a wide variety of situation and vehicle conditions under which the Africa Twin is supposed to be used, the demands on the suspension also vary widely. In the newly-developed model, we pursued a wide damping force setting range for a high degree of setting freedom to allow control of vehicle behavior by changing the damping force on a real-time basis responding to rider's input and vehicle's running conditions. Taking advantages of the electronically-controlled suspension SHOWA EERA that satisfies the said demands, we decided to realize such a motorcycle as if equipped with a number of different suspensions having various setups.

Regarding the suspension modes that are linked with the

Riding mode		Suspension mode	Road condition	Characteristic
TOUR		HARD	On-road	More sportier and stable riding even with passenger and full luggage
URBAN		MID	Variety	The most balanced in various situations (The Africa Twin)
GRAVEL		SOFT	Uneven road, gravel, wet	More secure and comfortable on unstable roads
OFFROAD		OFFROAD	Off-road	Maximize real off-road performance

Fig. 2 Presumed situations and riding characteristics

riding modes, the MID mode that excels in the total balance of riding comfort and handling in various situations along with the HARD, SOFT, and OFFROAD modes optimum for a specific situation are designated. Figure 4 shows various situations and recommended suspension modes. The aims of each mode are as per the following:

- (1) HARD: The mode specifically for on-road touring
Reduces excessive pitching motions for comfort when carrying a passenger and/or luggage and stability in high-speed for on-road
- (2) MID: The mode having a best total balance
Features total balance of riding comfort and handling in various situations
- (3) SOFT: The mode specifically for rough roads or slippery surfaces
Features smooth and soft ride for comfort and to inspire confidence
- (4) OFFROAD: The mode specifically for agile handling on off roads
Excels in tracking rugged road surfaces and absorbing large impacts to increase off-road capabilities

3. System Composition

3.1. Basic Configuration of Electronically-controlled Suspension

The electronically-controlled suspension system to employ in the Africa Twin is required to be durable and reliable under severe conditions where the components are subjected to scattering of gravels and sticking of mud. A light unsprung weight is also essential for a suspension with high tracking-ability. To satisfy such requirements, the front fork is based on the SFF-CA⁽²⁾ construction in which the sensing system containing the stroke sensor in the right-side front fork leg is separately provided from the damping force control system having the cartridge and the electronically-controlled valve in the left-side fork leg. The rear shock absorber is based on the BFRC⁽³⁾ construction in which the mechanical valve and the electronically-controlled valve are laid tandem in the upper part outside of the cylinder. This allows mounting of all related parts such as the stroke sensor, the electronically-controlled valve, and the wire harnesses on the upper part of the motorcycle, which



Fig. 3 Multi-information display and left handlebar switches

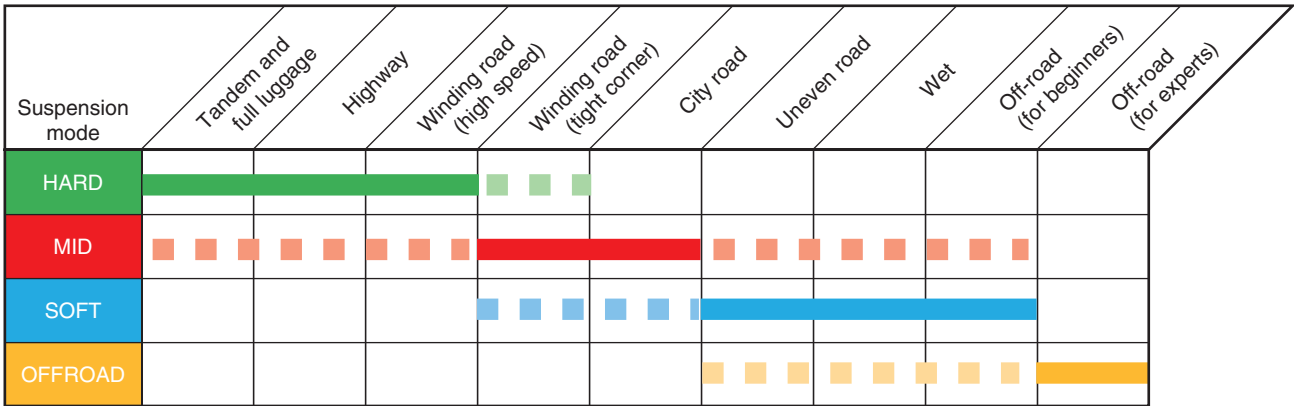


Fig. 4 Optimized conditions image

increases protection and contributes to the higher durability and reliability as well as reducing unsprung weight. Both in the front and rear suspensions, the electronically-controlled valve, which is activated by the linear solenoid, is laid in the damper oil passage. The damping force is induced by both of the electronically-controlled valve and the mechanical valve. Figure 5 shows the configuration of the front and rear suspensions.

3.2. Electronically-controlled Suspension System

The mode of the electronically-controlled suspension is linked with the riding mode the rider selects. The conditions of the motorcycle are constantly monitored by the front fork stroke sensor, the Inertial Measurement Unit (IMU), and the FI-ECU, and the information is transmitted to the exclusive suspension ECU. The current from the suspension ECU activates the linear solenoid to change damping force by changing the oil passage in the electronically-controlled valve on a real-time basis. Figure 6 shows overview of the electronically-controlled suspension system.

Discussed hereafter are the features of the SHOWA EERA we consider suitable for the newly-developed model. The first feature is the VP-MAP control in that the suspension stroke speed (velocity of piston: VP) is first calculated by the input from the suspension stroke sensor, and then the damping force is changed by activating the control valve in accordance with the VP. This allows setting of damping force at any level within the adjustable range. The second one is the high-speed response that takes a maximum of 15 millisecond (0.015 sec) from sensing of

vehicle conditions until changing of the damping force.

Taking advantages of the first feature, the four suspension modes are designated to satisfy the demands from a wide variety of situations and vehicle conditions the Africa Twin is presumed to be used as well as making the differences of riding comfort and handling clearly distinguishable. Additionally, the damping force is set very low only when the VP is extremely low to allow

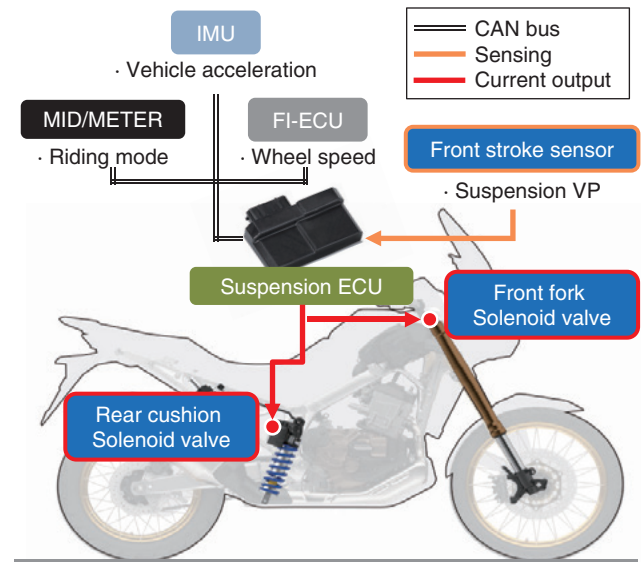


Fig. 6 Overview of control system

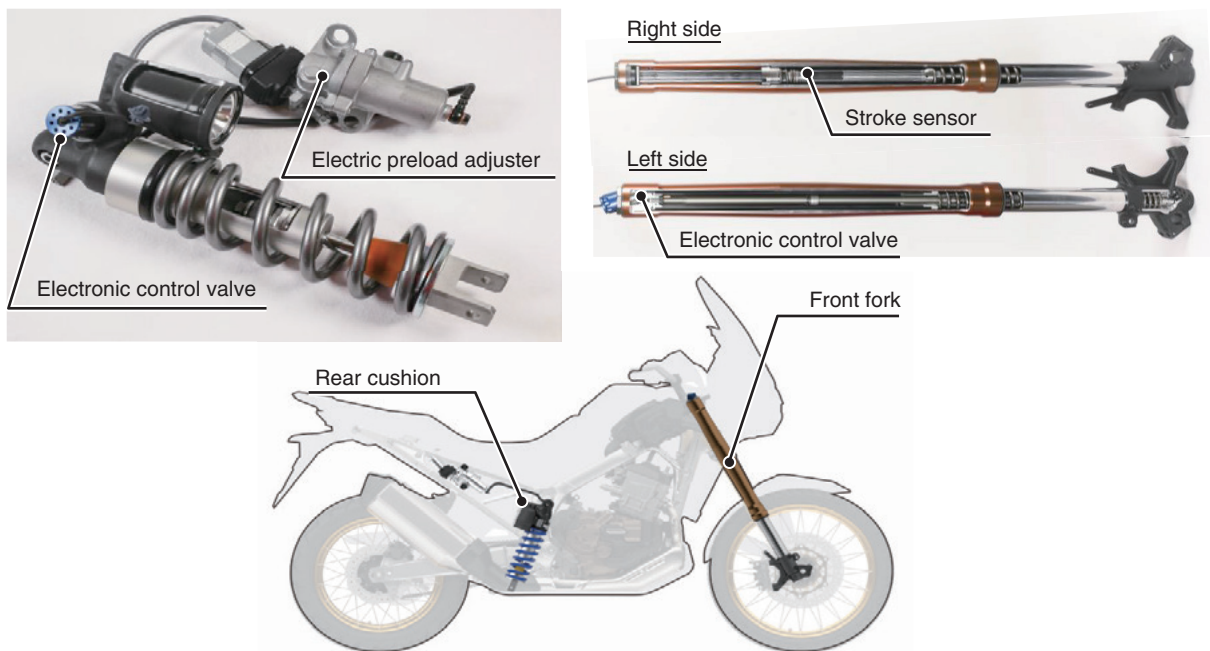


Fig. 5 Electronically-controlled front fork and rear cushion

quick shifting of suspension from rebound to compression and vice versa, providing smooth suspension actions and contributing to the superb riding comfort.

Taking advantages of the second feature, the extent of damping force change and the timing of change are set at an optimum level on the basis of the input from the stroke sensor, IMU, and FI-ECU. Conducting actual running tests over and over in various kinds of presumable situations, the system is tuned so as to control rapid changes to help ensure gradual changes while instantly responding to rider's operation and/or changes of terrain and changing damping force. This gradual change of damping force helps eliminate an unnatural sensation when the electronic control intervenes.

Also, as a consideration in the employment of electronically-controlled suspension, the system is basically configured so as to hold the damping force at the middle between the MID mode and the HARD mode when a malfunction such as a broken wire or other damage occurs in the electronically-controlled system. The damping force will not be fixed at the maximum or the minimum. Therefore, even when the system malfunctions during a travel, the system permits the customer continue the travel just like having a conventional suspension and maintains the riding comfort and handling.

This is the optimum electronically-controlled suspension system that satisfies a variety of performance demands of this adventure model including the durability and reliability under severe conditions.

4. Suspension Tuning for Each Mode and Applied Technical Measures

The MID mode excels in the total balance of comfort and handling under various riding conditions the Africa Twin is presumed to be used. Using the MID mode as a reference, the aims and the setup of three other modes are discussed below.

- (1) OFFROAD mode: The damping force increases gradually in accordance with the suspension VP. Also controls the damper when jump landing.
- (2) HARD mode: The highest damping force among these modes is most suitable for high loads and/or high speeds. Also controls the damper for deceleration.
- (3) SOFT mode: The lowest damping force among these modes for riding comfort. The damper control is linked with the vehicle speed.

The features of each mode are indicated by the data measured from actual running tests. The model for comparison in this chapter is 2020 CRF1100L Africa Twin Adventure Sports (hereafter as “the type without ES”), which has the same front and rear suspension stroke and has no electronic control.

4.1. OFFROAD Mode (Riding Mode: OFFROAD)

In the OFFROAD mode, the setup is exclusively for off-

road use to help ensure agility on off roads. In the off road where the road is very bumpy and the rider continuously encounters various gaps from large ones to small ones, the suspension should be such that helps to keep the wheels on the road surface as well as absorbing big impacts.

On the front end, the damping force is set low when the suspension moves slowly to keep the wheels on the road surface. For absorption of large impacts and a quick convergence of vehicle body movement, the damping force is set high when the suspension moves quickly. Unlike in three other modes as Fig. 7 shows, the characteristics is progressive in that the damping force increases gradually in accordance with the suspension VP. In a soft terrain like on sand, the handle bar tends to shake right and left because the front wheel sinks in the sand and the weight shifts toward the front end. To deal with this issue, the front compression damping force is set high from a low VP. The damping force on the rear end is set higher than in the SOFT mode across the entire region for a higher ride-ability under even more severe road conditions.

With an aim at reduction of shocks when landing from a jump, we incorporated the jump landing control. The

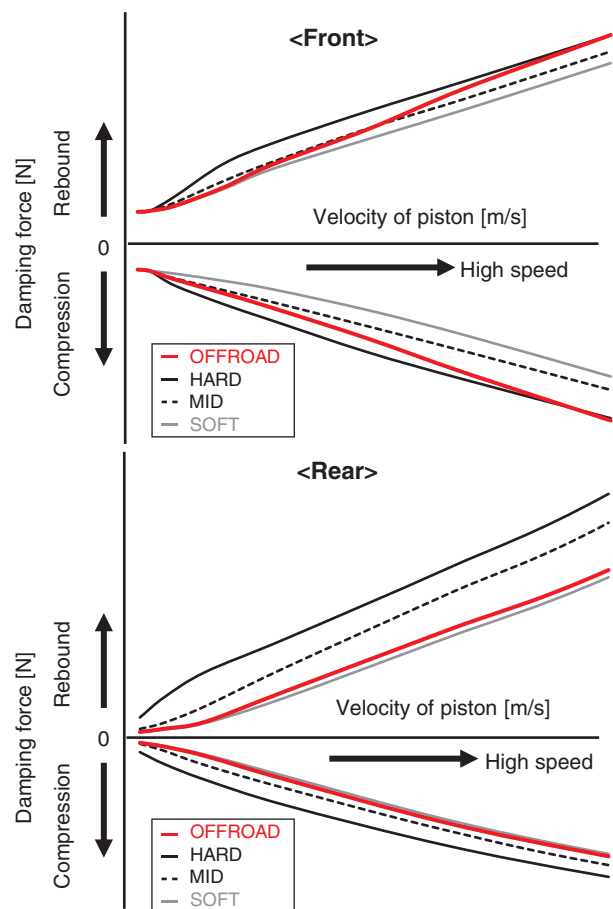


Fig. 7 Comparison of damping force characteristics of each mode

system identifies a jump from the total acceleration data in three axes from the IMU, and instantly increases damping force of front and rear suspension to prepare for landing. Figure 8 shows the data taken from in-house jumping test ramp. In the OFFROAD mode, the vertical acceleration of the sprung mass at the time of landing is less by 41% than the type without ES, which means a reduction of landing impact. This reduces suspension bottoming impacts when jumped unexpectedly from a large gap or during a fun ride on off roads, and provides the rider with a sense of security.

4.2. HARD Mode (Riding Mode: TOUR)

The HARD mode is exclusively tuned for on-road touring to help ensure comfort even under high-load conditions where the sprung mass increases such as when carrying a luggage and/or a passenger. Aims are also set at such characteristics that show stability when riding on twisty roads at a brisk pace or cruising on motorways at high speeds.

Accordingly, the damping force is set at the highest from the low VP to stabilize vehicle behavior by controlling excessive vehicle body movement at the time of acceleration and cornering (Fig. 9). In the low VP region that largely affects the handling, the damping force is increased by 25% in the front compression, 20% in the rebound, 40% in the rear compression, and 75% in the rebound from the MID mode. Especially the largely increased rear damping force helps ensure impact absorption and gentle convergence of vehicle body movement even when the sprung mass is increased by the luggage or the passenger.

The control of damping at the time of deceleration is also incorporated to reduce “nose dive,” which is such a phenomenon in that the front end of the motorcycle sinks and the motorcycle tilts to the front when braking. It is such a control that temporarily increases the damping

force in the compression side of the front suspension and the rebound side of the rear suspension depending on the degree of deceleration detected by the IMU. Figure 10 shows the measurements taken in the HARD mode when braking from 80 km/h on the flat paved road. Compared to

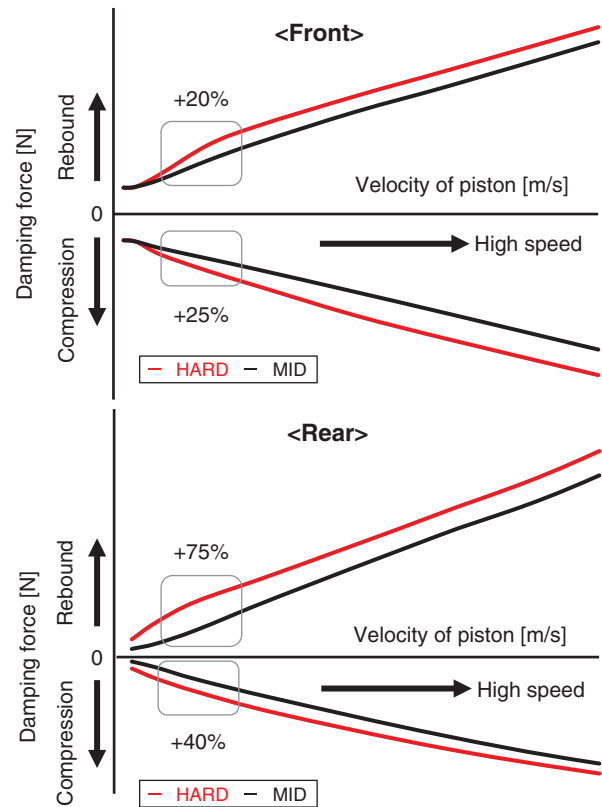


Fig. 9 Damping characteristics of HARD mode

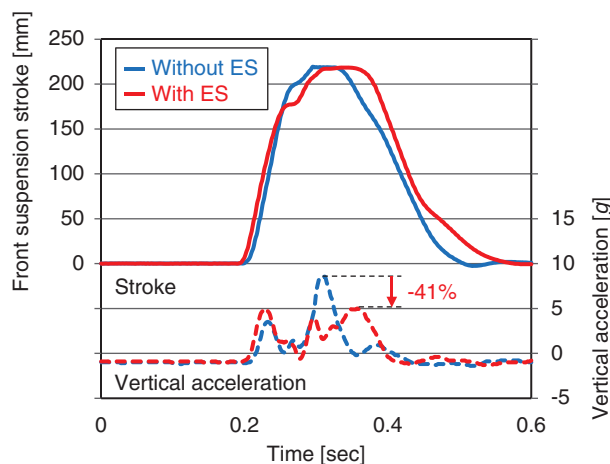


Fig. 8 Front suspension stroke and vertical acceleration of sprung mass when jump landing

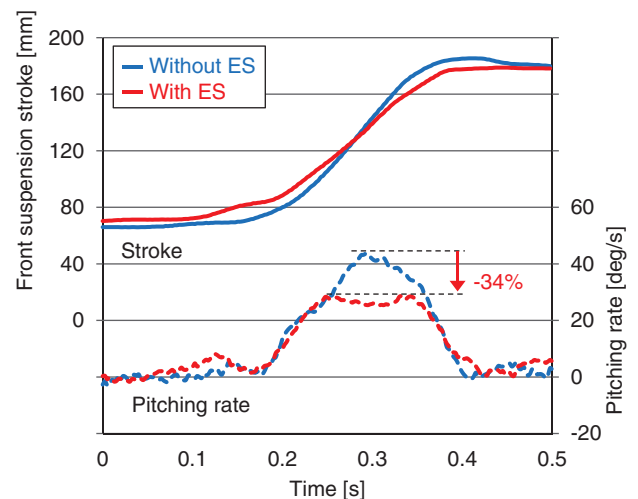


Fig. 10 Front suspension stroke and pitching rate when braking hard

the type without ES, the changes of front suspension stroke at the time of braking is moderate, reducing the pitching angular velocity of the vehicle by 34%. The nose dive at the time of braking is thus controlled to moderate pitching motions.

4.3. SOFT Mode (Riding Mode: GRAVEL)

The SOFT mode is tuned exclusively for the specific purpose of the adventure tourer, i.e., for softer rides so that the rider can comfortably ride the motorcycle with a sense of security even when the road surface conditions are unstable. When riding on rough surfaces or slippery surfaces, it is necessary to always stabilize tire-to-ground contact pressure by tuning the suspension in such a manner that lets the suspension work smoothly to absorb impacts to the rider to help ensure compliance.

Hence, the damping force is set at the minimum in the SOFT mode. In the medium VP region that largely affects the riding comfort, the damping force is less than in the MID mode by 20% in the front compression, 10% in the rebound, 15% in the rear compression, and 30% in the rebound. On the other hand, an excessively low damping force slows convergence of vehicle body motions at high speeds. To achieve stability at high speeds and riding comfort at low speeds, the speed-dependent control system is incorporated in that the two different damping force characteristics are provided and used depending on the vehicle speed. Incorporating two damping force characteristics for the low speeds of 80 km/h or under (V0) and those for high speeds of 130 km/h or above (V1), and gradually changing the characteristics when the speed is between the two thresholds, the motorcycle motions are maintained as natural as possible. Figure 11 shows image pictures of the damping force characteristics of V0 and V1. The damping force at V1 is higher than at V0 in the front compression and front/rear rebound.

The average vertical acceleration of the sprung mass when traveling straight at 60 km/h on the cobble stone road, on which small bumps and depressions appear continuously, is compared (Fig. 12). In the SOFT mode, the acceleration is 15% less than the type without ES, which means that the shock transmission to the rider is reduced. The soft rides are evident from the data.

4.4. ABS-linked Control

When braking hard and the ABS intervenes, pitching motions that rock the motorcycle back and forth sometimes occur aside from the kick back that notifies the rider of the ABS intervention. That occurs because the moment the brake fluid pressure is lowered by the ABS, the increased ground-contact pressure of the front tire from the hard braking is reduced, causing the front suspension to change stroke direction from compression to rebound. If the rebound motion can be controlled at a minimum, the ground-contact pressure of the tire at the time of hard braking is stabilized, allowing control of pitching motions.

This system has a newly developed ABS-linked damper control that increases damping force in the front rebound to control extending motions when a hard braking that causes the ABS to function is detected and the brake fluid pressure is lowered. The ABS-linked damper control is applied to all

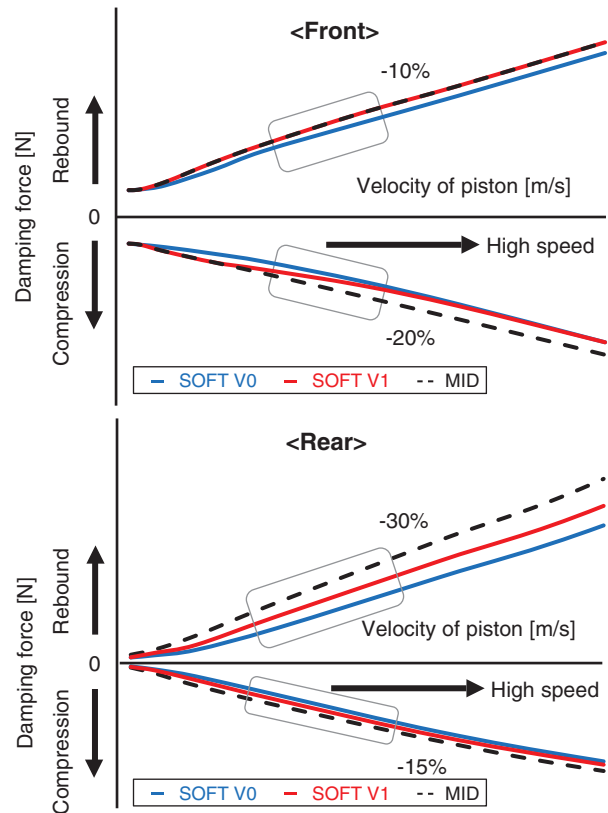


Fig. 11 Damping characteristics of SOFT mode

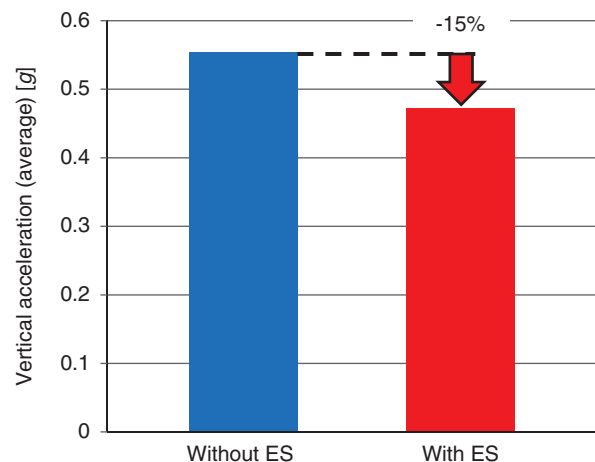


Fig. 12 Vertical acceleration of sprung mass when passing through cobble stone road

suspension modes. Figure 13 shows measurements taken in MID mode when a hard braking that activates ABS is applied from 40 km/h on the flat paved surface. The pitching angular velocity when the ABS is functioning is reduced by 45% from the type without ES. The pitching motions that rock the motorcycle back and forth when the ABS functions is thus controlled to moderate vehicle body motions.

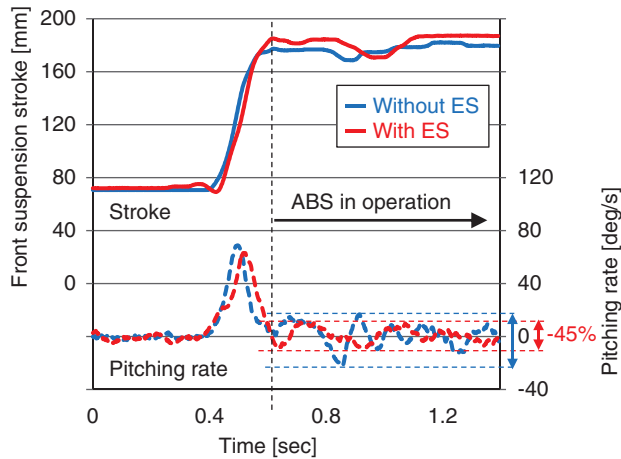


Fig. 13 Front suspension stroke and vertical acceleration of sprung mass when braking hard

5. Conclusion

The electronically-controlled suspension is newly developed for the 2020 CRF1100L Africa Twin Adventure Sports ES. Combining the high-degree of damping force tune-ability, which is a feature of SHOWA EERA with the control system that instantly changes damping force depending on the running conditions, the four suspension modes are designated for a wide variety of usages from the touring with a passenger and/or a luggage to the serious off-road riding. The riding modes, in which such five characteristics as the engine power, the engine brake, the clutch characteristics (DCT model only), and the ABS characteristics in addition to the suspension modes, are designated. The rider can select any mode from the handlebar switch even when riding to adjust the motorcycle characteristics to best-suit his/her desire depending on the situation and vehicle conditions. We hope this motorcycle will satisfy the owner for a long time as a partner that turns on his/her adventure spirit and motivates him/her to “go anywhere, go further.”

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Cornering Lights of 2020 CRF1100L Africa Twin Adventure Sports Using Additional Light Source

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ABSTRACT

After the revision of United Nations regulations in 2013, cornering lights are permitted for motorcycles. A number of cases of cornering light applications to motorcycles are seen up until now. We have developed the cornering lights for comfortable touring, especially suitable for riding suburban roads mainly at moderate speeds, and applied to the CRF1100L Africa Twin Adventure Sports. Using the said motorcycle, we conducted studies on the three key factors in the designing of cornering lights; the setting the operating range according to the bank angle, the setting the light distribution with an additional light source, and the control of visual distraction. The operating of cornering lights is determined from the frequency of bank angles measured from actual night riding. The distribution of light from the additional light source is determined so as to illuminate the cornering direction at the same intensity as the dipped beam. Regarding the visual distraction, the cornering lights are designed so as to increase intensity gradually after turning it on until reaching 100%. A hysteresis is also set in the switching to help prevent flickering. With these measures taken, the cornering lights suitable for touring have been realized.

1. Introduction

The bend lighting generally seen in automobiles illuminates the going direction depending on the steering angle. There are two ways for that function: the one that moves the dipped beam (LO beam) to the direction of steering and the other that turns on the additional light source in which the light distribution is exclusively designed⁽¹⁾.

On the other hand, with respect to the cornering lights for motorcycle, the United Nations regulations (UN regulations)^{(2), (3)} approve only such a type that turns on the additional light source that illuminates going direction depending on the bank angle, rather than the steering angle at the time of cornering (enacted in 2013). At this occasion, we applied the cornering lights using the additional light source first time in Honda motorcycles to the CRF1100L Africa Twin Adventure Sports (CRF1100L AS)⁽⁴⁾ having such a basic concept as “a true adventure model that invites you to adventure trips across the lands of challenge.” The aim of comfort technology in the CRF1100L AS are targeted at “go anywhere, high touring ability” presuming

long-distance touring. In that concept, we presume night riding on suburban roads as the typical situation where the cornering lights are especially effective to enhance visibility. The new system is developed with an aim at retention of illuminated road surface area inside of the going direction even when the bank angle increases in night riding on suburban roads. Figure 1 shows CRF1100L AS with the right cornering light turned on.

In the CRF1100L AS, the cornering lights are located under the right and left headlamps. Each lamp is composed of three LED light sources. As the bank angle increases, the LED turns on one after another starting from the outer-most one (Fig. 2).

The following three are the key factors in the designing of cornering lights for motorcycles.

- (1) Setting the operating range according to the bank angle
- (2) Setting the light distribution with an additional light source
- (3) Control of visual distraction

The details of the three factors in the development of cornering lights for the CRF1100L AS are described from the next chapter.

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Fig. 1 CRF1100L AS with right cornering light turned on

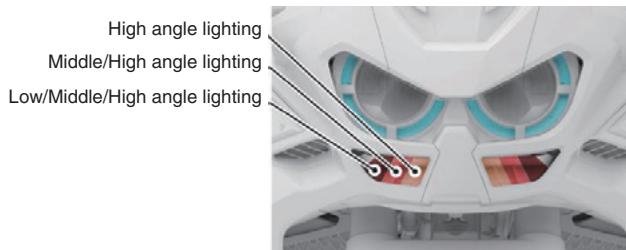


Fig. 2 Lighting pattern of cornering light of CRF1100L AS

2. Setting the Operating Range According to the Bank Angle

2.1. Bank Angle Frequency

As the cornering lights are illuminated depending on the bank angle in motorcycles, it is necessary to detect bank angle and setting the operating range according to the bank angle of the cornering light accordingly.

The UN regulations do not allow illumination by cornering lights when the bank angle is less than 5° because the added light may give glare to oncoming drivers. Taking into account the fluctuations of bank angle sensor reading from unevenness of road surface or other reasons and the changes of headlight distribution when accelerating or decelerating, we chose to turn on the cornering light when the bank angle is more than 10° .

To determine operating range according to the bank angle of the cornering lights, we measured frequency of bank angles from actual night running tests using the CRF1100L AS.

The measurements were taken on the EU suburban course⁽⁵⁾ in the Honda test course where road illuminations

were scarce at night. Figure 3 shows the bank angle frequencies measured with the Inertial Measurement Unit (IMU) when tested by a number of test riders with a height of 170 cm up to 180 cm.

The horizontal axis represents the angle, the vertical axis bar graph represents the relative frequency, and the line graph represents cumulative relative frequency.

When the CRF1100L AS was tested on the suburban road at night, the bank angle frequencies were virtually the same when the bank angle was between 10° and 24° , and 99.9% within 34° .

2.2. Bank Angle to Turn On Each LED Lamp

The test data in the preceding section indicates that the bank angle of CRF1100L AS ranges widely from 10° up to 34° when tested on the suburban road. Accordingly in the CRF1100L AS, three additional light sources are incorporated on one side, and the threshold bank angle is set at 10° , 18° , and 26° , which means three even splits with an increment of 8° . The equally-split angles to turn on the cornering light is aimed at an equalization of operating timing in the process the bank angle increases. Figure 4 shows threshold bank angle and the lighting pattern of the cornering lights.

The system is designed in such a manner that a

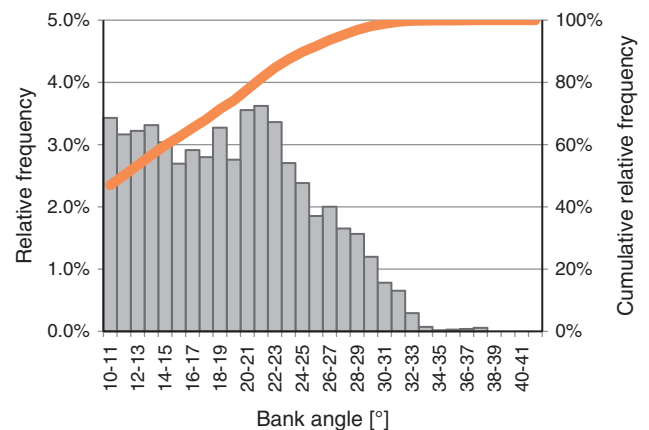


Fig. 3 Bank angle frequencies when tested on EU suburban course at night using CRF1100L AS

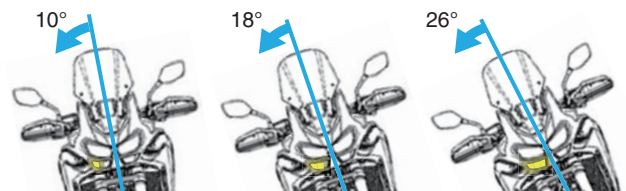


Fig. 4 Threshold bank angle and lighting pattern of cornering lights in CRF1100L AS when leaning right

cornering light turns on at a bank angle, and the other one turns on additionally as the bank angle increases. The lamp remains on until the bank angle becomes lower than the prescribed operating bank angle. Therefore, when the cornering light for above 18° turns on, two lamps are illuminating. When the one for above 26° turns on, all three lamps are illuminating.

3. Setting the Light Distribution with an Additional Light Source

3.1. Parameters to Determine Light Distribution

To help prevent disturbing of driver’s vision of oncoming vehicle, the upper part of headlight beam is usually cut off. As the motorcycle leans when cornering, the illuminated area inside of the going direction decreases. It is therefore necessary to adjust the light distribution of the cornering lights into such a direction that compensates the area lacking illumination. Figure 5 shows image pictures of the area lacking illumination inside of the going direction as the bank angle increases in a right corner.

In automobiles, as the steering angle of front wheels changes depending on the turning of steering wheel and determines turning radius accordingly, the direction of illumination of the bend lighting depends only on a single parameter. On the other hand in motorcycles, as the motorcycle turns while leaning at a bank angle at which the centrifugal force and the reaction force from the road are balanced, the turning radius depends on the balance of the bank angle and the vehicle speed.

It is therefore necessary in motorcycles to set the direction of cornering light illumination accordingly not only to the bank angle but also to the vehicle speed when turning. In the CRF1100L AS, as the running on suburban roads at moderate speeds was presumed, studies were conducted at a speed of 50 km/h when turning.

3.2. Light Distribution Direction Design

Two types of cornering lights are already applied to mass-production motorcycles; the high-speed type which illuminates far ahead presuming use on motorways having a large corner radius, and the low-speed type presuming use in city having a small corner radius such as in an

intersection (Fig. 6).

As the high-speed type is intended to enhance visibility on motorways having gentle curves, the system is set in such a manner that the more the bank angle, the farther the illuminated area extends. On the other hand, as the low-speed type is aimed at enhancement of visibility in city such as in an intersection, the setting is such that the more the bank angle, the illuminated area extends more toward inside of the direction of banking. Thus, the light distribution is adjusted to the specific purpose.

In view of the concept of CRF1100L AS, we set the light distribution so as to illuminate medium-distance area with an aim at enhancement of visibility at moderate speeds presuming curves in suburban roads. As the illumination is often non-existent in suburban roads, we consider that riders will often feel cornering lights useful. When the speed is 50 km/h, the turning radius is approximately 110 m at which the bank angle is 10° and the first cornering light turns on, where the angle included between the future position after traveling for 2.5 sec⁽⁶⁾ and the light source of the cornering lights is approximately 9°. When 50 km/h, the turning radius is approximately 40 m at which the bank angle is 26° and the third cornering light turns on, where the angle included between the future position after traveling for 2.5 sec and the light source of the cornering lights is

Type	High-speed riding	Low-speed riding
Illumination image		
Add direction image (3 additional light sources)		

Fig. 6 Examples of cornering lights for motorcycles

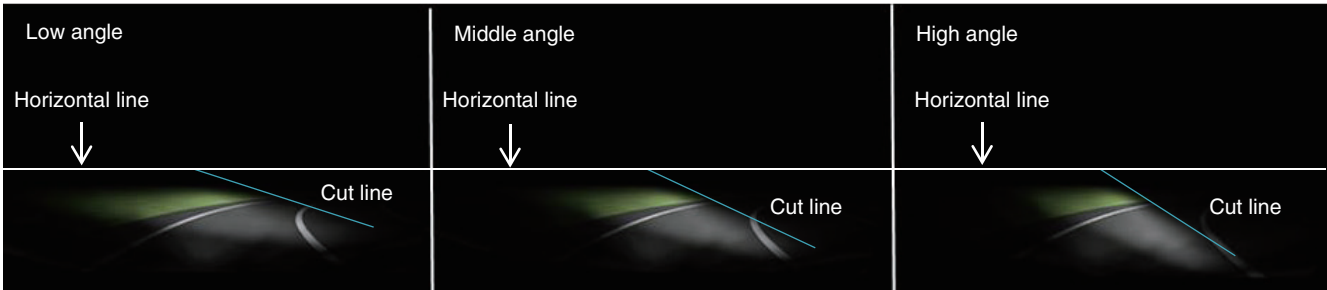


Fig. 5 Area lacking illumination inside of going direction as bank angle increases when only LO beam used

approximately 25°. Based on these findings, we set the light distribution in the middle of the above angles at 17° (Fig. 7).

3.3. Setting the Light Distribution Range

To determine light intensity that forms a basis of light distribution design, we have had a number of riders with a height between 165 cm and 180 cm ride the motorcycle on the earlier-mentioned EU suburban course using the LO beam to clarify luminance on the road surface at which the rider feels comfortable. As the majority of riders perceived adequate illumination when the luminance was above 8 lx (8 lx zone), we set a luminance standard of cornering lights at above 8 lx zone. Figure 8 shows the 8 lx zone when using the LO beam of CRF1100L AS. The picture indicates that the light distribution of the LO beam of CRF1100L AS is such that covers the road surface area having a depth of 5 m-30 m and a width of 6 m.

We have designed the light distribution in such a manner that covers a depth of 15 m-25 m and a width of 6 m in the direction of banking so that the 8 lx zone the cornering light illuminates does not look strange when overlapped with the

8 lx zone the LO beam illuminates. The orange frame in Fig. 8 shows the illuminated zone.

3.4. Dynamic Light Distribution Design

As Fig. 6 shows, there are several types of light distribution of cornering lights depending on the purpose; the one that extends light distribution ahead as the bank angle increases and the other that extends illumination to inside of the banking direction. In either type, presuming that the speed increases as the bank angle increases, the illuminated zone is shifted depending on the increase of speed and the presumed radius of the curve.

In the meantime, during daytime cornering, the rider keeps looking at the corner exit. Riders rarely change their line of sight during cornering. We have therefore designed the light distribution in such a manner that does not require the rider to change the line of sight even at night. In other words, we have designed the light distribution so as to maintain illumination area in the inside of going direction even when the bank angle increase. Figure 9 compares the light distribution on the 8 lx zone with and without the cornering lights at each bank angle when leaned when right cornering. The solid lines show the 8 lx zone when the cornering light and the LO beam are turned on. The broken lines show the 8 lx zone when only the LO beam is turned on.

As Fig. 9 shows, when the bank angle increases only with the LO beam turned on, the illuminated zone decreases, failing to maintain the 8 lx zone in the going

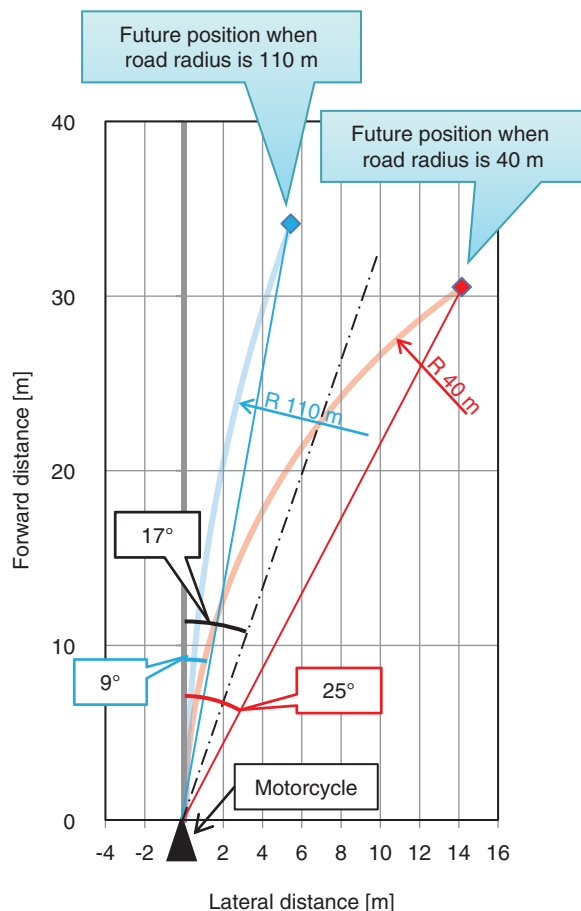


Fig. 7 Future positions after traveling for 2.5 sec on road having turning radius of 110 m and 40 m, and line in middle

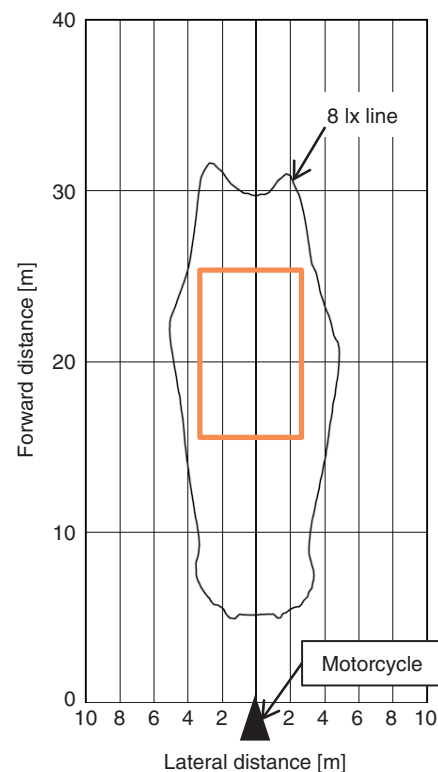


Fig. 8 LO beam light distribution

direction. On the other hand, when the cornering lights are equipped, the 8 lx zone in the going direction is maintained.

With the cornering lights installed in the CRF1100L AS, a number of test riders having a height from 165 cm up to

180 cm tested on the previously-mentioned EU suburban course, and confirmed that the light distribution was effective for cornering. Figure 10 compares CG pictures of illuminated road surface in the right corner when only the LO

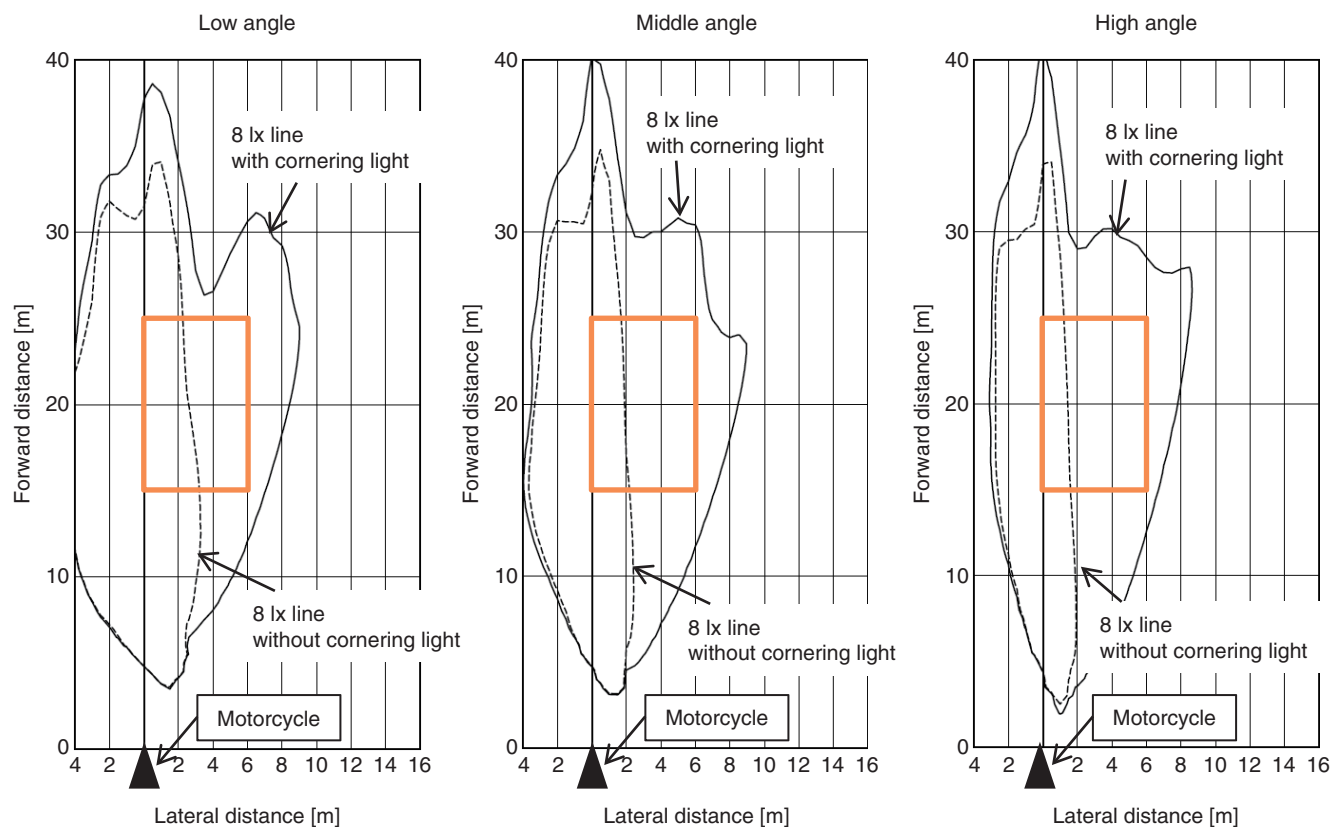


Fig. 9 Comparison of light distribution with and without cornering lights at each bank angle when right cornering

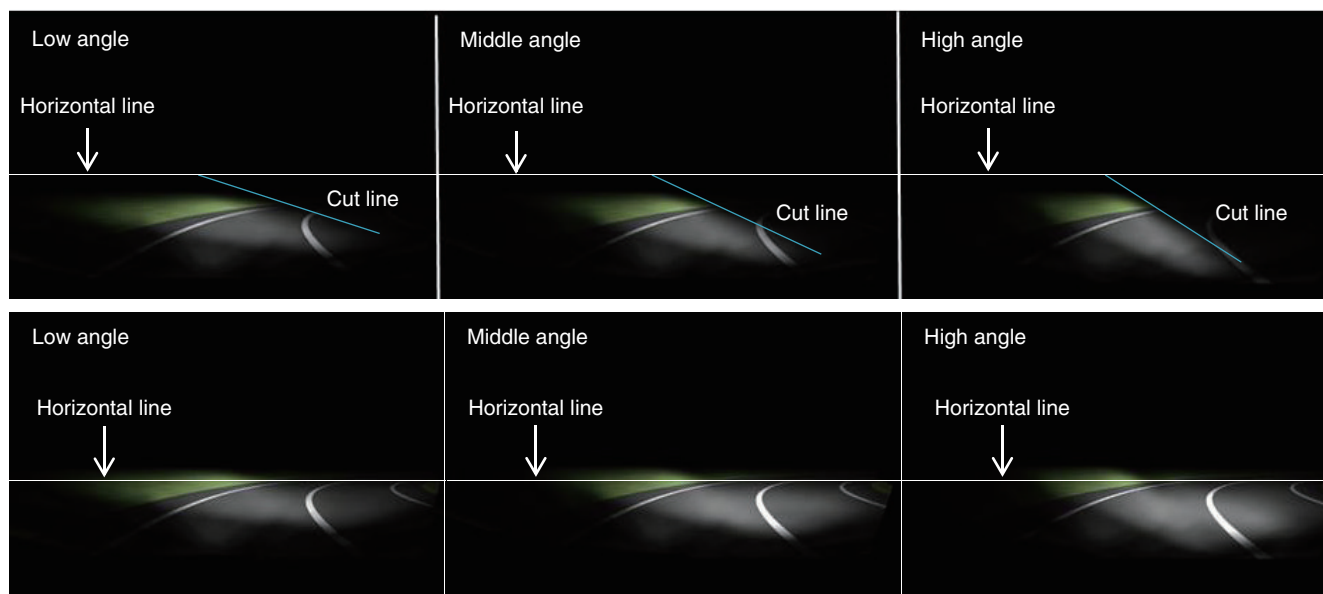


Fig. 10 Comparison of CG pictures of illuminated road surface in right corner when only LO beam is provided and when cornering light is provided

beam is provided and when the cornering light is provided.

It is obvious that the inside of going direction is adequately illuminated when the cornering lights are provided.

4. Control of Visual Distraction

The cornering lights turn on and off depending on the bank angle. Due to the nature that the lamp flickers when switched on and off, it is necessary to help prevent visual distraction, in other words, unnecessary attention, from the rider himself/herself or the drivers in the vicinity. We have therefore taken the following measures to deal with sudden changes of intensity when the additional light source is turned on and the flickering when turned on and off.

4.1. Gradual Increase of Intensity of Additional Light Source

When the additional light source is turned on to supplement and enhance the illumination on the road surface at the threshold bank angle, a sudden change of luminance occurs in the specific zone. It is therefore necessary to take measures so as not to draw rider's attention to the unnatural changes. In the CRF1100L AS, in addition to the retention of illuminated zone the rider looks at as mentioned in the preceding chapter, the system that gradually increases intensity is incorporated so that the rider does not feel a sudden change of luminance. Since the LED light source⁽⁷⁾ responds quicker than the filament bulb when turned on or off, it is necessary to intentionally control switching.

Regarding the duration the LED light gradually increases intensity, we have tested various cases from 0.1 sec up to 0.5 sec from turning on until reaching 100% intensity with an increment of 0.1 sec at a corner entry speed of 50 km/h on the earlier-mentioned EU suburban course. Upon the assessment by 10 in-house experts, 0.1 sec is too fast, 0.3 sec too slow. Accordingly, we concluded 0.2 sec best.

4.2. Flickering when Additional Light Source Turns On and Off

The cornering lights of CRF1100L AS are designed to turn on depending on the bank angle, starting from 10° up to 34°. The three thresholds are three-split with an increment of 8° as mentioned earlier. If no special considerations are taken, flickering of the cornering lights occurs when riding across the threshold bank angle back and forth. Especially near 10°, which is the smallest bank angle to turn on, even a light leaning such as for a lane change causes the additional light source to turn on and off. To deal with this issue, the bank angle to turn off the lamp is set at a smaller angle than the angle to turn it on. In other words, hysteresis setting helps prevent the flickering.

Regarding the threshold bank angle and the hysteresis, tests were conducted from 1° with an increment of 0.5°. When riding across the threshold bank angle back and forth,

flickering occurred in the additional-illuminated zone. When tested on the EU suburban course at 50 km/h, the flickering was still noticeable when the hysteresis was set at 1.5°. It virtually disappeared above 2°. Accordingly, the hysteresis is set at each of the three thresholds; the bank angle to turn on at 12°, 20°, and 28°, the one to turn off at 10°, 18°, and 26°. Figure 11 shows the hysteresis set at each threshold bank angle when cornering.

4.3. Validation by Actual Motorcycle

From the above findings, it has been confirmed that the gradual increase of intensity from turning on up to 100% in a period of 0.2 sec along with the 2° hysteresis set at the threshold bank angles keeps rider's attention from being drawn by the unnatural changes when the cornering light is turned on as well as helps eliminate flickering at the time of switching. Thus the settings help prevent the visual distraction to the rider himself/herself or other drivers from the flickering.

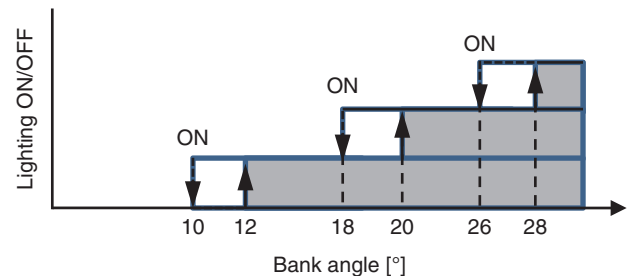


Fig. 11 Hysteresis set at each threshold bank angle

5. Conclusion

In accordance with the model concept of the CRF1100L AS, we have developed the cornering lights for motorcycles presuming use on suburban roads at night during a long touring. The following three measures were taken.

(1) Setting the operating range according to the bank angle

The necessary switching pattern of the cornering lights were set after measuring frequencies of bank angles occurring in the actual night riding tests using the motorcycle presumed to be equipped with the lights.

(2) Setting the light distribution with an additional light source

The light distribution when leaning is set so as to minimize strangeness when overlapped with the 8 lx zone of the LO beam.

(3) Control of visual distraction

To control visual distraction from sudden changes of luminance and/or flickering, the control system is designed so as to gradually increase intensity up to 100% after turning on the cornering lights along with the hysteresis set at the thresholds.

We hope the enhanced touring capabilities of CRF1100L AS will be well-accepted by customers, and the cornering lights will help customers enjoy unique riding that can be experienced only at night.

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Experimental Environment for Verification of Speech-based News Delivery System

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ABSTRACT

An original spoken dialogue system was developed that is capable of diverse responses to user utterances while communicating information using news articles distributed on the Internet. Most conventional spoken dialogue systems are question-and-answer types, and are not suited to communicating large amounts of information such as news articles. In addition, users are unable to interrupt news article read-aloud systems with questions. Therefore, new key technologies related to spoken dialogue systems were developed, including conversation summarization technology, a paralinguistic recognizer, pause adjustment, and a speech synthesizer, and an experimental system was constructed that is capable of spoken dialogue in Japanese using news articles distributed in real time on the Internet. This enabled easy system verification in various usage scenarios. Practical application of this system will enable spoken dialogue in the manner of a conversation partner for drivers while driving.

1. Introduction

The automotive industry business environment is changing precipitously on a global scale, and new technologies and services such as connected, autonomous, shared, and electric (CASE) are being developed at a rapid pace. Advances in connected technology in particular are letting drivers increasingly enjoy a variety of services while in the car, and in-car systems capable of spoken dialogue such as smart speakers are becoming more and more common. One example of this is the Honda Personal Assistant, which understands intentions from driver utterances and provides functions such as music playback, route search, and display of user manuals.

This type of in-car spoken dialogue system has evolved with the advancement of connected technology, and processing such as speech recognition and language comprehension that was formerly executed by onboard units is increasingly executed on the Cloud. This has dramatically increased system performance, and linkage with other Cloud services such as music distribution and geographic information is also expanding.

Furthermore, as automated driving becomes more widespread, the use of time in cars is also about to change. Drivers have thus far had to focus on driving, but if

driving is performed only when needed, more time can be spent freely while on the move, and needs for external communication will also increase. The present level of automated driving in this process has the constraint that the driver needs to constantly watch the road ahead. For this reason, a spoken dialogue system that enables communication only by voice is thought to have high value. In this manner, it is thought that in the CASE era, demand will grow for a spoken dialogue system that can be a conversation partner for drivers while driving.

Therefore, we developed an original spoken dialogue system⁽¹⁾ that is capable of diverse responses in accordance with user utterances while communicating information in news articles distributed in real time on the Internet.

This paper introduces an experimental environment created for verification of this system, which enables spoken dialogue with the user via a tablet terminal.

2. Spoken Dialogue Systems

2.1. Conventional Spoken Dialogue Systems

Most conventional spoken dialogue systems such as smart speakers are question-and-answer (Q&A) or read-aloud types.

Q&A-type systems return a single response to a single

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question. For example, if the user asks, “What is today’s weather?” the system returns a response such as, “Today’s weather in Tokyo is clear.” With this method, the system does not speak spontaneously, so the user is unable to freely engage in dialogue.

In a read-aloud-type system, for example, if the user asks, “What is today’s news?” the system reads aloud news articles in the manner of, “The 19th Round Mexican Grand Prix Final Race was held starting from 1:10 p.m. on October 29. The weather that morning was blue skies, but...” Therefore, with this method as well, even if the user asks a question, the system does not answer, so the user is unable to engage in dialogue.

These types of conventional spoken dialogue systems generally consist of a speech recognizer, dialogue manager, and speech synthesizer (text-to-speech) as shown in Fig. 1. When the user voice is input to the system, the speech recognizer first converts it to text and then passes the converted text to the dialogue manager. The dialogue manager references the scenario database and generates a response sentence in accordance with the user utterance intention. Finally, the generated response sentence is passed to the speech synthesizer and the system voice is output.

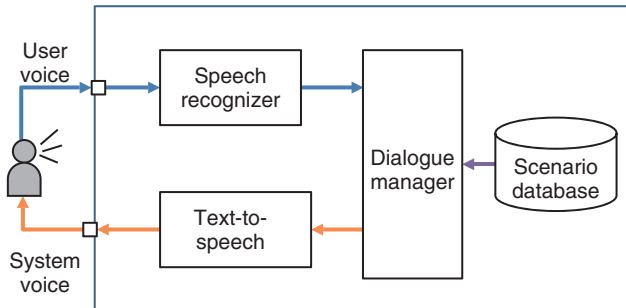


Fig. 1 Architecture of conventional system

2.2. Proposed Spoken Dialogue System

In contrast, the proposed spoken dialogue system realizes free dialogue between the user and the system using news articles distributed on the Internet. For example, if the system utters the sentence, “The 19th Round Mexican Grand Prix Final Race was held.” and the user asks, “When?,” the system can respond, “At 1:10 p.m. on October 29.”

With conventional system technology, the system was unable to respond even if the user asked a question about the information that the system was currently communicating. The system also performed response processing after receiving a question from the user, which made highly responsive dialogue a challenge. The proposed system consists of a dialogue pre-processing block and a dialogue processing block as shown in Fig. 2. The dialogue pre-processing block collects and analyzes news articles on the Internet in advance to create a scenario database of utterances to be communicated to the user and a QA database for responding to questions from the user.

These dialogue pre-processing and dialogue processing blocks realize Q&A during information communication and highly responsive dialogue, which are challenges for conventional systems.

2.2.1. Dialogue pre-processing block

The dialogue pre-processing block uses conversation summarization technology to generate scenarios and Q&A from news articles. This conversation summarization technology is realized by the scenario generator and QA generator shown in Fig. 2. The news articles input to this system are expressed using written language and are not suitable for voice transmission. Therefore, the dialogue pre-processing block summarizes the news articles for conversation and converts them into spoken language. The summarized sentences are stored in the scenario database, and sentences not used in these summaries are stored in the QA database. In addition, Wikipedia and other information

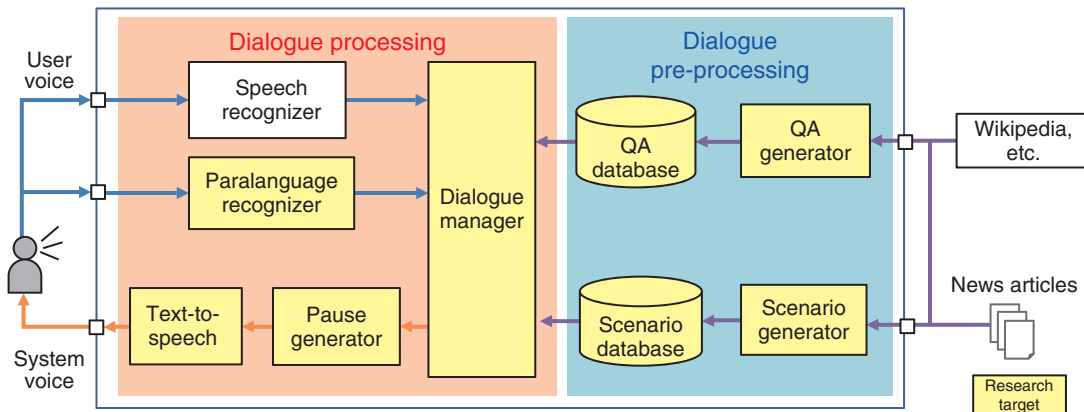


Fig. 2 Architecture of proposed system

on the Internet is used to generate definitions of words extracted from the news articles, which are used for Q&A.

2.2.2. Dialogue processing block

The dialogue processing block converts the scenario database information from text to speech and communicates it to the user. Furthermore, when the dialogue processing block recognizes a user utterance, it uses the QA database information to respond in accordance with the utterance contents.

The dialogue processing block has a paralinguage recognizer as shown in Fig. 2, which performs system actions in accordance with the utterance intention. Paralinguage refers to peripheral language information such as intonation, rhythm, and pauses.

For example, if the system says, “The 19th Round Mexican Grand Prix Final Race was held,” and the user asks, “The Mexican Grand Prix?,” conventional speech recognition alone can acquire only the text information “The Mexican Grand Prix,” so the user’s intention cannot be interpreted. However, the proposed system recognizes six types of paralinguage to tell whether the user’s intention is a question or a request for repetition. If the sentence ending seems to have rising intonation, the system determines that the user is asking a question and can perform Q&A in the manner of, “The Mexican Grand Prix is...” If the sentence ending has falling intonation, the system determines that the user wants agreement and repeats, “Yes, the Mexican Grand Prix.”

The dialogue processing block also has a pause generator as shown in Fig. 2, which adjusts the pauses between system utterances to realize a conversational rhythm that makes it easy for the user to understand and ask questions. The proposed system estimates the pauses between phrases within utterances and the pauses between utterances, and inserts pauses into system utterances. This realizes pauses that make it easier for the user to understand and to interrupt mid-utterance, even when communicating large amounts of information such as news articles.

The dialogue processing block communicates large amounts of information such as news articles, so it also has a speech synthesizer that is capable of distinctive speech in accordance with the roles of utterances within the discourse structure.

3. Key Technologies

3.1. Conversation Summarization Technology

A summarization model that uses deep learning⁽²⁾ was developed to generate conversational summaries from news articles.

3.1.1. Word importance estimation model

Important sentences are extracted from news articles to create summaries from those articles. The important sentence extraction model used a maximum coverage

model^{(3),(4)} which extracted the set of sentences that covers as many important words as possible within the limited number of sentences. Values estimated by random forest, which is a machine learning technique traditionally used for classification and regression, were used to extract the important words in articles. This study applied deep learning to extract important words.

Figure 3 shows the word importance estimation model, which uses deep learning. This model uses BERT⁽⁵⁾, and estimates the importance of words in context. BERT is a natural language processing model that enhances task performance by pre-training with large amounts of document data. The training data used 100 news articles that were summarized by three workers. The auxiliary information input to the model used the following twelve types of information.

- (1) Morphological information consisting of part of speech class, part of speech subclass, conjugated form, conjugation, category, and domain
- (2) Index value representing the word appearance frequency (Term Frequency: TF)
- (3) Index value representing the rarity of a word (Inverse Document Frequency: IDF)
- (4) Product of TF and IDF (TF-IDF)
- (5) Whether the word is included in the title
- (6) Whether the word is in parentheses
- (7) Positions of the sentence and paragraph in the article
- (8) Unique expression class
- (9) Modification type
- (10) Depth of the modification tree (tree representing the modification relation of clauses)
- (11) Number of clauses of the modification source
- (12) Position of the clause from the start of the sentence

The worker ID was used to mix and learn data created by multiple workers, and the worker information was distinguished and given by 1-of-k. 1-of-k is a vector expression with one component as 1 and the remaining components all 0.

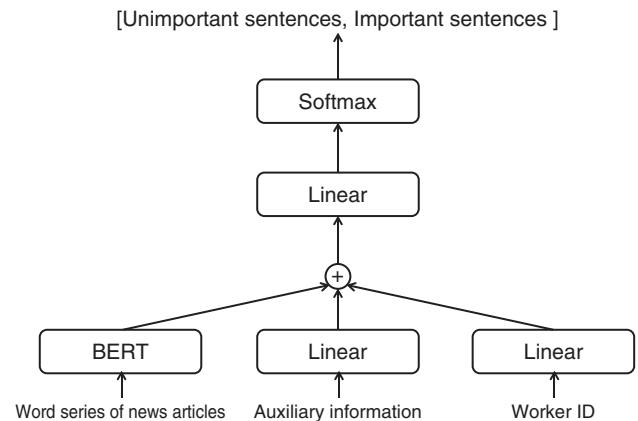


Fig. 3 Word importance estimation model

Figure 4 shows the model evaluation results. The rating scale used ROUGE-1, which is a text summary rating value that represents a better rating closer to 1.0. SEM1 is the model that learned using the data of a single worker without BERT pre-training or auxiliary information, SEM1_pre is the model with pre-training added to SEM1, SEM1+_pre is the model with auxiliary information further added to SEM1_pre, and SEM2+_pre is the model that learned using the data of two workers with BERT pre-training and auxiliary information. For comparison, RF is the random forest results, Human is the worker results, Random is the results when random sentences are extracted, and LEAD is the results when the first K sentences of the article are extracted. The experiment results showed that the proposed method, SEM2+_pre, provided the best results and achieved higher performance compared to the conventional method, random forest.

3.1.2. Sentence compression model

News articles are described in written language, so a single sentence contains a large amount of information. Therefore, articles are converted into a form suitable for communicating in spoken language by reducing the amount of information contained in a single sentence and performing sentence compression. Sentence compression was formulated as a sequence labeling problem at the clause level. A sequence labeling problem is a problem that assigns an appropriate label string to each element of a sequence. This study labeled whether or not to include clause units in utterances.

Figure 5 shows the sentence compression model using deep learning. This model uses BERT, and differs from the word importance estimation model in that the embedded expression of words obtained by BERT is constructed for each clause by self-attention⁽⁶⁾. Like the word importance estimation model, the training data used 100 news articles summarized by three workers. The auxiliary information input to the model was the same as that used by the word importance estimation model minus the sentence and paragraph positions.

Figure 6 shows the results evaluated by accuracy when test data was input to the model. SCM1 is the model that

learned using the data of a single worker without BERT pre-training or auxiliary information and SCM1_pre is the model with pre-training added to SCM1. SCM1+_pre is the model with auxiliary information further added to SCM1_pre, and SCM2+_pre is the model that learned using the data of two workers with BERT pre-training and auxiliary information. For comparison, BiLSTM shows the results with sentence compression using bidirectional long short-term memory (LSTM), which is a deep learning model that can handle time series data using the word appearance frequency vector (bag of words) that constitutes the auxiliary information and clause as the feature. In addition, Human shows the worker results, Random shows the results when random clauses are extracted, and NoCompression shows the results without sentence compression. The experiment results showed that the proposed method, SCM2+_pre, provided the best results and achieved higher performance compared to BiLSTM.

3.2. Paralanguage Recognizer

Deep learning was used to generate a user utterance intention recognition model, and a paralanguage recognizer⁽⁷⁾⁻⁽¹¹⁾ was created to realize system responses that

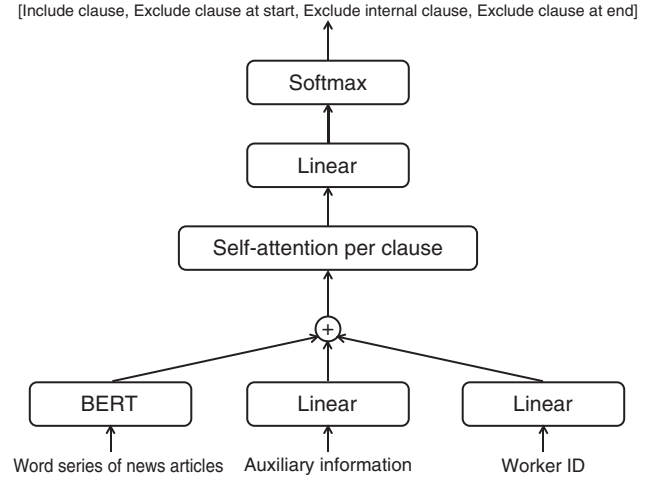


Fig. 5 Sentence compression model

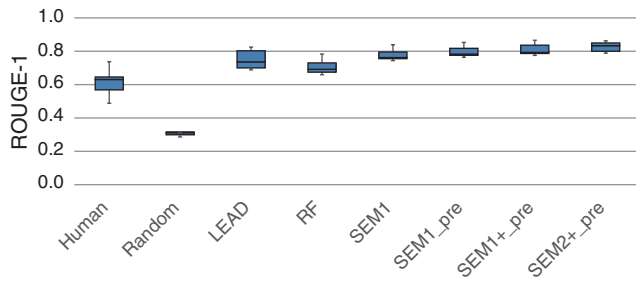


Fig. 4 Evaluation results of important sentence extraction

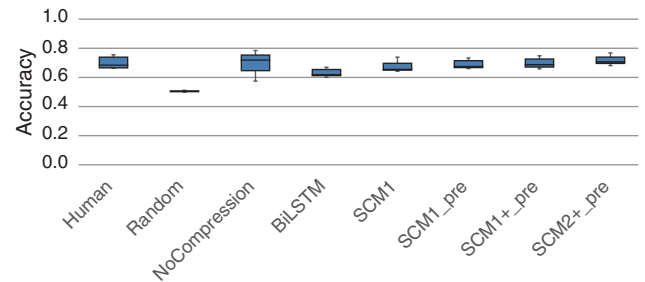


Fig. 6 Evaluation results of sentence compression

Table 1 User intention types, their effects, and corresponding system actions

Effects	User intention	System action
Increasing information	Question	Answer
	Request supplement	Provide explanations
	Request repeat	Repeat
Decreasing information	Disinterest	Change topic
	Already known	Omit details
Avoiding overlaps	Wait request	Listen

Table 2 Discrimination results of intention recognition

		With BERT pre-training With auxiliary information			With BERT pre-training Without auxiliary information		Without BERT pre-training Without auxiliary information	
		P	P+U	P+U+S	P+U	P+U+S	P+U	P+U+S
Question	Majority vote	0.920	0.958	0.962	0.957	0.961	0.940	0.951
	At least one vote	0.920	0.957	0.961	0.953	0.956	0.923	0.938
Request supplement	Majority vote	0.836	0.911	0.913	0.901	0.906	0.895	0.896
	At least one vote	0.827	0.882	0.887	0.881	0.887	0.847	0.865
Request repeat	Majority vote	-	-	-	-	-	-	-
	At least one vote	0.700	0.826	0.832	0.795	0.805	0.784	0.805
Disinterest	Majority vote	0.893	0.913	0.908	0.903	0.898	0.898	0.897
	At least one vote	0.797	0.811	0.805	0.810	0.804	0.804	0.803
Already known	Majority vote	0.818	0.939	0.939	0.939	0.939	0.939	0.939
	At least one vote	0.702	0.825	0.831	0.817	0.828	0.806	0.817
Wait request	Majority vote	0.716	0.885	0.865	0.885	0.858	0.845	0.838
	At least one vote	0.614	0.688	0.692	0.688	0.689	0.634	0.672

correspond to user utterance intentions.

Figure 7 shows the model for recognizing user utterance intentions. When time series voice data is input to this model, the currently anticipated utterance intent label is output. Training used an utterance intention data set created from approximately 2000 dialogues with this system. This data set was created by labeling user utterances with the user utterance intentions shown in Table 1.

First, a spectrogram generated by cutting out a short voice segment is input to CNN Autoencoder. CNN

Autoencoder is a deep learning model capable of extracting feature values without a teacher. Utterance intention labels can be estimated by inputting rhythm feature values obtained from the middle layer of CNN Autoencoder to discrimination part (P). The final labels are estimated by inputting the user utterance speech recognition results and the immediately preceding system utterance to discrimination part (L). BERT pre-training is applied to discrimination part (L).

Table 2 shows the utterance intention recognition

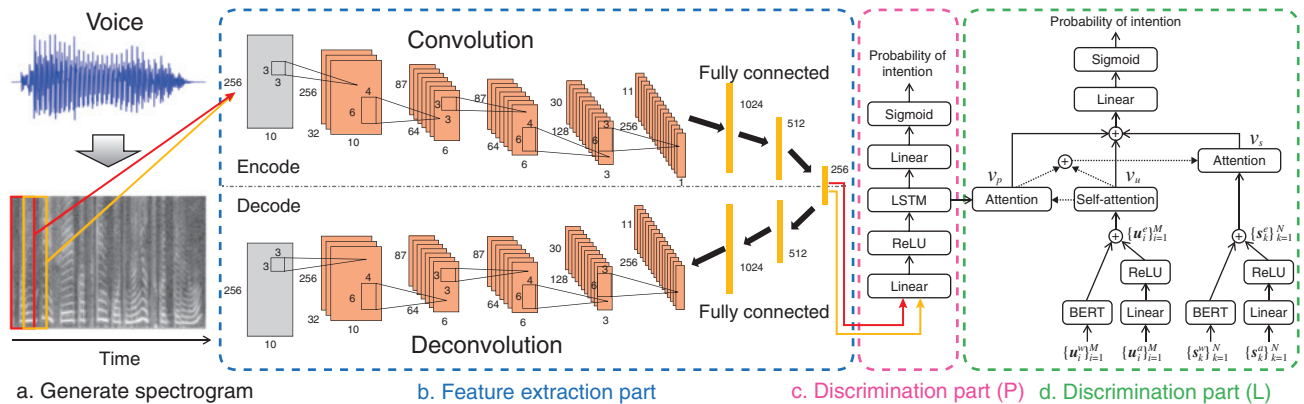


Fig. 7 Intention recognition model

results using this model. P is the results estimated using only the user utterance rhythm, P+U is the results estimated using the user utterance rhythm and speech recognition results, and P+U+S is the results estimated using the user utterance rhythm and speech recognition results and the system utterance. Input of both the user utterance rhythm and the user utterance speech recognition results resulted in higher accuracy for all intentions. In addition, BERT pre-training also increased the accuracy.

3.3. Pause Adjustment

A function was developed that uses deep learning to estimate the pauses of system utterances⁽¹²⁾. This realizes pauses that make it easier for the user to understand and ask questions.

3.3.1. Pause estimation model between phrases within utterances

Figure 8 shows the model for estimating pauses between phrases within utterances. This model uses bidirectional LSTM, and determines the pause between phrases based on the preceding and following LSTM states. The phrase text was input to the model using LSTM.

Model training used a corpus with pause length tags created by having a voice actor read aloud 100 summarized, colloquialized news articles. The voice actor was instructed to observe the following three points when recording the articles.

- (1) Speak with the intention of having the listener understand.
- (2) Speak in a manner that distinguishes important and unimportant parts so that the listener can understand.
- (3) Be aware of the potential for question interruptions while speaking, and insert natural pauses in locations where questions are anticipated.

Figure 9 shows a histogram of the deviation between the pause values estimated using this model and the correct values. Deviation of less than 0.2 s accounted for 77% of the total.

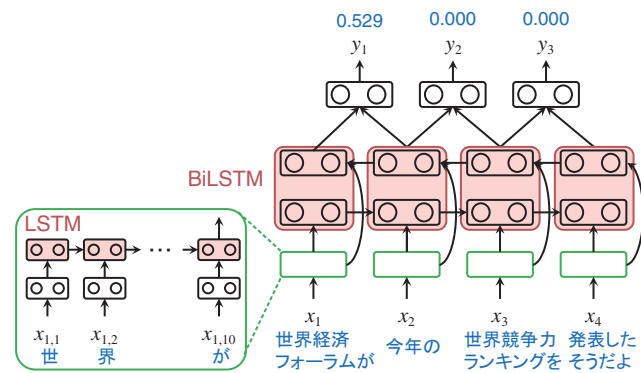


Fig. 8 Pause estimation model between phrases in utterance

3.3.2. Pause estimation model between utterances

Figure 10 shows the model for estimating pauses between utterances. Pauses between utterances are estimated using the information of the current and next utterances. Pauses between utterances were estimated using a Bayesian ridge model, which is a linear regression model, and used the values of the last hidden layer of LSTM in the pause estimation model between phrases within utterances as the feature. Like the pause estimation model between phrases within utterances, training used a corpus with pause length tags. Figure 11 shows a histogram of the deviation between the pause values estimated using this model and the correct values. Deviation of less than 0.5 s accounted for 75% of the total.

3.4. Speech Synthesizer

In order to communicate large amounts of information such as news articles, a speech synthesizer was developed that is capable of distinctive speech using the roles of utterances within the discourse structure⁽¹³⁾. Utterance sentences are divided into “spoken phrase” units that

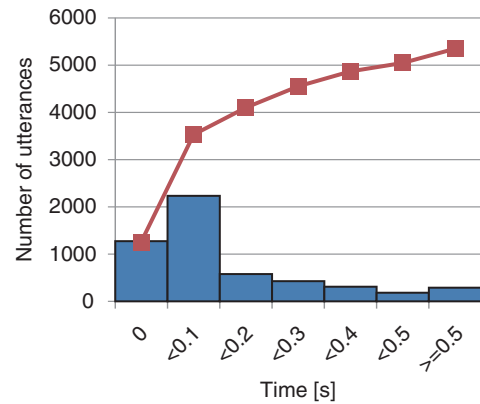


Fig. 9 Pause error between phrases in utterance

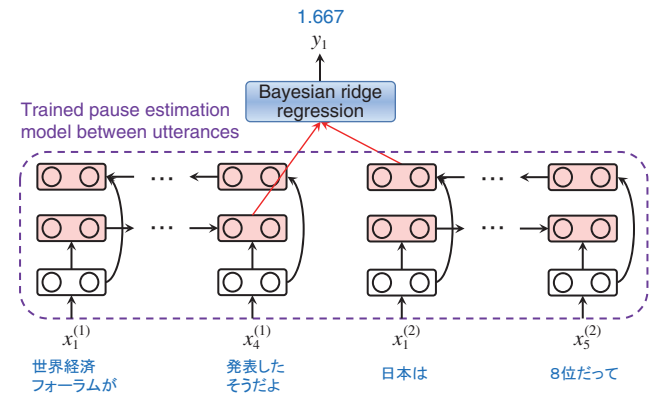


Fig. 10 Pause estimation model between utterances

do not contain more than one new piece of information and can be spoken in a single breath. Spoken phrases are further divided into three roles: sentences containing the information that is the most important to communicate (nucleus), sentences leading into the nucleus (front satellite), and sentences providing supplemental information (rear satellite). These roles are used as auxiliary information for voice synthesis. This enabled us to control the rhythm and pauses of the entire utterance sequence. Figure 12 shows examples of the roles of spoken phrases. Merlin⁽¹⁴⁾, a speech synthesis system based on deep learning, was used as the base speech synthesis system.

3.4.1. Speech synthesis model

Figure 13 shows the voice synthesis model that uses deep learning. As inputs, in addition to linguistic and frame features, this model also applies features (utterance sequence features) that express the positions and roles of

spoken phrases. The spoken phrase position is information that indicates the number of the current utterance within the paragraph.

Speech synthesis model training used a data set created by having a voice actor read aloud 39 news articles. The manuscript was pre-marked with the roles of the spoken phrases, and the voice actor was instructed to observe the following three points.

- (1) Speak in a manner that clearly conveys the contents of nucleus roles to the listener.
- (2) Suppose that the listener is listening while nodding, and speak without leaving large pauses.
- (3) Speak with the intention of communicating news to the listener in a tone similar to everyday conversation.

Table 3 shows the results of calculating the deviation between the speech synthesis model output and the acoustic feature values of the original data by 10-fold cross validation. F0-RMSE and dur-RMSE are respectively the

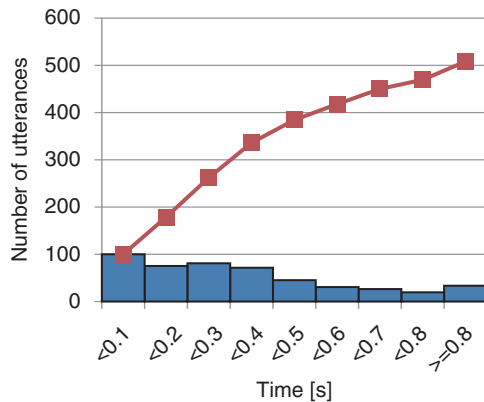


Fig. 11 Pause error between utterances

Paragraph	Position	Role	Content of spoken phrase
1	1	Front satellite	宇宙を観測しているロシアの電波望遠鏡があるんだけど
	2	Nucleus	それが正体不明の「強い信号」を検知したっていつて注目を集めてるんだって
	3	Rear satellite	世界中の天文学者に衝撃が走っているらしいよ
2	1	Nucleus	信号はヘラクレス座の近くの恒星から届いたんだって
	2	Nucleus	その星は地球から約95光年離れていて
	3	Rear satellite	惑星も持っているみたい
3	1	Front satellite	地球外文明の進歩度を表す基準っていうのがあって
	2	Front satellite	それと照らし合わせたんだけど
	3	Nucleus	地球よりはるかに進歩した文明の可能性があるんだって
	4	Rear satellite	まだ確実なことはわからないんだけどね

Fig. 12 Example of discourse structure

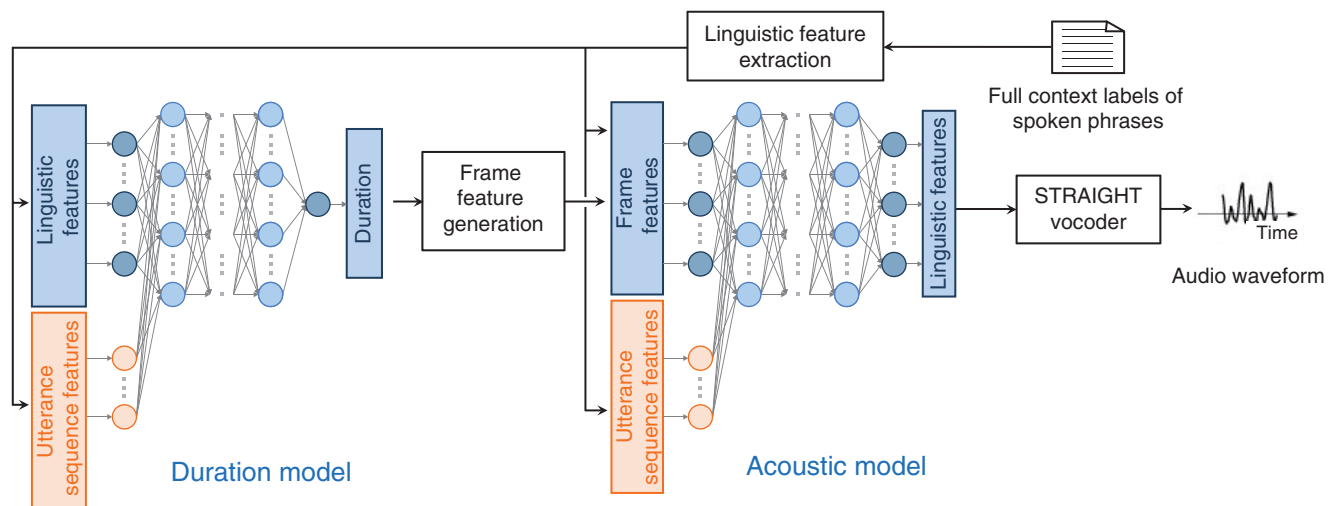


Fig. 13 DNN speech synthesis model considering utterance sequence features

Table 3 Comparison of performances with and without utterance sequence features

	F0-RMSE	dur-RMSE	MCD	BAD
Base line	36.420	4.779	5.064	0.660
Proposed model	35.435	4.768	5.047	0.659

root mean square error of the fundamental frequency and the phoneme duration. MCD and BAD are respectively the mel-cepstral distortion and the band aperiodicity distortion. Mel-cepstral distortion is an objective index for measuring the deviation between the original data and the speech synthesis model output. The addition of utterance sequence features reduced the deviations of the fundamental frequency and the phoneme duration compared to the base line, and also showed slight enhancement in terms of mel-cepstrum and aperiodicity.

4. Experimental System

An experimental system was constructed based on the proposed system described in Section 2.2. This experimental system enables spoken dialogue with the user via a tablet terminal for evaluation of the system by many users in a variety of scenarios inside a traveling vehicle.

Figure 14 shows the configuration of the experimental system. The dialogue pre-processing server collects and analyzes news articles on the Internet. By periodically collecting news articles from the Internet, the dialogue pre-processing server can provide information to the user in real-time. The dialogue processing server performs scenario speech synthesis and other tasks, and the user interacts with

the system via a tablet terminal. Speech recognition used Google Speech API, a speech recognition cloud service provided by Google LLC.

Figure 15 shows an example of using the experimental system. This experimental system uses Japanese language news articles and is capable of spoken dialogue in Japanese. The user performs spoken dialogue using the speaker and microphone of the tablet terminal. This system lets the user hear timely news articles distributed on the Internet and ask the system things they wonder about.

This experimental system can be used to subjectively evaluate willingness to use and to measure items such as information communication efficiency. Verification of the effectiveness of spoken dialog systems will continue in this manner.



Fig. 15 Example of using experimental system

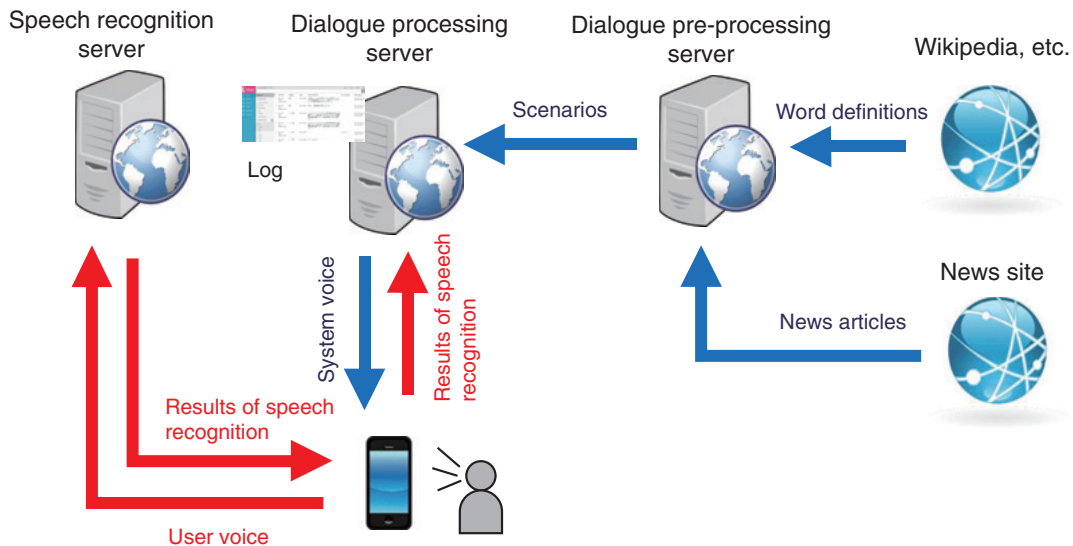


Fig. 14 Experimental system

5. Conclusion

Key spoken dialogue system technologies such as conversation summarization, paralinguage recognition, pause adjustment, and speech synthesis were developed. In addition, a system was constructed that enables dialogue via a tablet terminal equipped with these technologies.

Compared to conventional Q&A systems and news article read-aloud systems, the constructed system enables Q&A during information communication and highly responsive dialogue.

Future plans include evaluation of this system during actual use in a car and support of languages other than Japanese.

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Guide Robot Management System

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ABSTRACT

We have developed the guide robot system to help efficiently give directions to people in public spaces. The ‘management system’ for guide robots can facilitate effective collaboration between multiple units and types of robots in operation by using fleet management algorithm and communication channels through clouds and IoT technologies. It would expand the area in which the robots can operate as well as overcoming some restrictions in network availability. We have tested the system with robots in a public facility, simulating a real-life guiding service, and successfully confirmed its functionality.

1. Introduction

Honda makes this statement in its 2030 Vision: “Serve people worldwide with the ‘joy of expanding their life’s potential’: Lead the advancement of mobility and enable people everywhere in the world to improve their daily lives”⁽¹⁾. The company has also been engaged in the development of robotics technology, as exemplified by ASIMO, with the aim of realizing “a robot that coexists and cooperates with people and performs useful functions in society”⁽²⁾.

As one such initiative, the guide robot system was developed for robots moving in a mixed environment with people. Guide services by robots are provided to general guests for the purpose of exploring challenges involved in robot implementation in society. The guide robot system is configured with two types of robot, the reception robot and the guide robot (Fig. 1).

Guide robot management system (management system) was developed together to allow the network of robots to share information and coordinate between multiple units. The system processes the data transmitted by individual robots to allocate tasks for smoother operation. The system uses a cloud and IoT communications to overcome constraints on infrastructure building thus expanding its operational range.

The system approach of the management system is introduced below.

2. Guide Robot System Configuration

The guide robot system provides two types of service. One is the route guide that shows guests how to get to their destination. The other is the guide that accompanies

them to their destination. These services are distributed between the reception robot [Fig. 1(a)] and the guide robot [Fig. 1(b)] respectively, but their execution is coordinated. When guests specify their destination either by voice or touch screen terminal input, the reception robot indicates the route to the destination (route guide function). Then,



Fig. 1 Guide service scenario

¹ Life Creation Center

the guide robot directs the way to their destination, while accompanying them along the journey (guide function).

The request for a guide received by the reception robot is allocated to a guide robot by the management system [Fig. 1(c)]. In order for the management system to respond to guide needs as required, it monitors the location and operational status of the guide robots in real time and engages in appropriate fleet management. In this way, the robots of two types and the management system operate in a coordinated manner, passing the task smoothly from the reception robot to the guide robot so that guests can navigate the way to their destination without getting lost even in unfamiliar places.

3. Roles of the Management System

The management system has two main roles to play.

The first role is to engage in appropriate fleet management of guide robots so that the system can respond to guide requests [Fig. 2(a)] from the reception robot. Guide requests include the guest's desired destination and facial recognition data which is acquired by the reception robot, with the guest's permission. It is used by the guide robot when guiding the guest. The management system selects one from among the multiple guide robots on standby near the reception robot, taking their operational status, remaining battery charge, and so on into consideration. In order to guide a guest, the guide robot has autonomous navigation functionality and facial recognition functionality. Autonomous navigation plans a route to the destination and navigate the robot itself and the guest while avoiding obstacles. Facial recognition identifies guests using the camera installed at the rear of the guide robot and recognizing their relational position. It is used to make sure the robot speed matches that of the guest and notice separation from the guest. The management system transmits the data needed for autonomous navigation and facial recognition as a set of commands to the guide robot [Fig. 2(b)], which receives the data and initiates the operation.

The second role is to monitor the operational status of the reception robots and guide robots and notify the system operator of any malfunctions. During guide operations, the management system constantly monitors the progress of

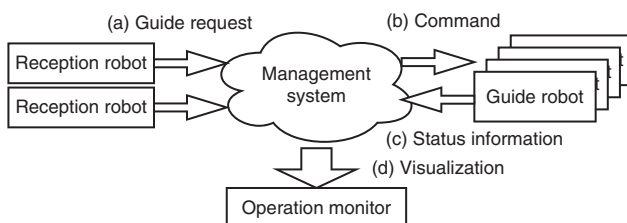


Fig. 2 Guide robot system configuration

tasks [Fig. 2(c)]. When a certain task is completed, the next command is transmitted. The system operator also carries an operation monitoring terminal by which the location and operational status of guide robots can be checked, and when trouble occurs, detailed information regarding the location and nature of the malfunction can be checked through the terminal [Fig. 2(d)].

4. Management System Configuration

The management system is made up of the Honda Robotics as a Service Platform (Honda RaaS) and the guide cloud application (guide cloud). Honda RaaS [Fig. 3(b)] is a platform for development and operation of robotics services, and it is equipped with general purpose functions such as communications, data acquisition, and so on⁽³⁾. In contrast, the guide cloud [Fig. 3(a)] was newly created to realize particular functions specific to guide operation. The guide cloud uses data shared from Honda RaaS as the basis for managing guide jobs and monitoring operational status of the robots. Honda RaaS and the guide cloud are linked by data streaming and the REST API [Fig. 3(c)]. The reception robot, guide robots, and operation monitoring terminal are connected through the Internet using IoT and other such frame of communications. The system operator uses the operation monitoring terminal to check the operational status of the robots, as well as to handle user registration, device registration, and other such configuration work [Fig. 3(d)].

This system configuration has advantages for both development and operation. The advantage in development is that, since it uses the secure communications, device management, data visualization, and other such functions provided by Honda RaaS, resources can be concentrated on application development. The advantage in operation is that, since it does not use dedicated servers and Wi-Fi, it does not have their limitations on robot range of movement or on infrastructure building.

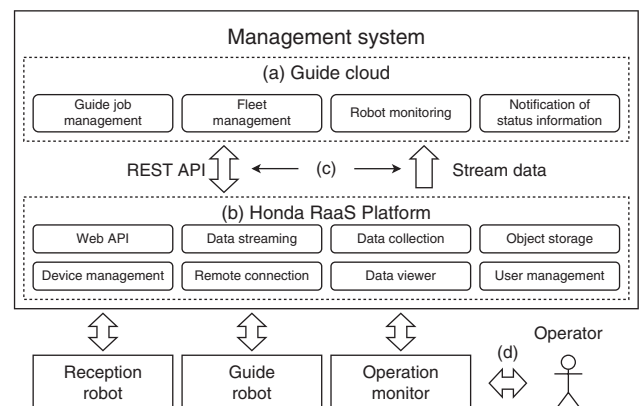


Fig. 3 Management system configuration

5. Guide Cloud Functions

In order to provide guide services, the guide cloud performs guide job management for guide reservations, guide robot selection, and other such functions. It also maintains readiness for contingencies by monitoring the operational status of robots.

5.1. Guide Job Management and Fleet Management

A guide job is one unit of the guide services provided to guests which can have variety of status, reservation in effect, guide job under way, cancelled, and so on. The management system manages the progress of multiple guide jobs simultaneously.

The scenario that precedes the start of a guide service will be described in order here. First, the guest enters the destination by voice or by using the touch screen terminal to search for it, retrieve it, and designate it. Once set of the destination has been completed, the reception robot displays the route to that destination [Fig. 4(a)]. While the guest is operating the reception robot, the management system evaluates the operational status, remaining battery charge, and other such factors of the guide robots, selects one of the robots, and transmits a standby instruction to it. The guide robot enters standby preparatory to performing the guide action [Fig. 4(b)]. At this point, the job may end with just the route guide, depending on the guest's preference, in which case the standby status is cancelled.

When a guide is to be used, the destination information and facial recognition data are transmitted from the reception robot to the management system. The guide robot receives this data from the management system and starts the guide action [Fig. 4(c)].

The system is designed to manage up to several tens each of reception robots and guide robots. Also, in order to make the guide robot selection in accordance with the location information for those guide robots that are on standby near the reception robot, the system was made to allow for flexible replacement of guide robot standby locations during operation.

5.2. Robot Operational Status Monitor and Notification

For a guide action, the guide robot performs the sequence of three tasks of pickup [Fig. 4(d)], navigation [Fig. 4(e)], and return [Fig. 4(f)], in order. The destination and method of operation vary with each task. When performing pickup, the robot moves to where the guest is, greets the guest, and informs the guest of the destination. While navigating, the robot uses the camera to recognize relative position of the guest, adjusting the speed of its autonomous navigation accordingly. The onboard screen displays the direction of turns making it easier for the guest to follow the robot. When the destination is reached, the robot informs of the arrival then greet the guest together with a farewell message. The robot returns to the standby location on its own.

At the point when the guide robot begins to guide a guest, the management system initiates the guide job monitoring sequence (Fig. 5). This monitors the progress of the task, and when execution has been completed, the system transmits the information needed for the next task. Instances of this monitoring sequence are generated only for the guide actions that are executed, so that it can save computing resources.

Contingencies or system trouble may occur during guide operations and prevent the robot from carrying out the operation. In such a case the management system would notify the system operator of the failure via monitoring terminal or email.

Within the management system, tasks are configured as task lists in JSON format. JSON allows for data to be added and expanded flexibly, so in principle, the system can be configured with tasks increased to any number. Each task is configured with the destination name, destination coordinates, task type, and so on (Fig. 6).

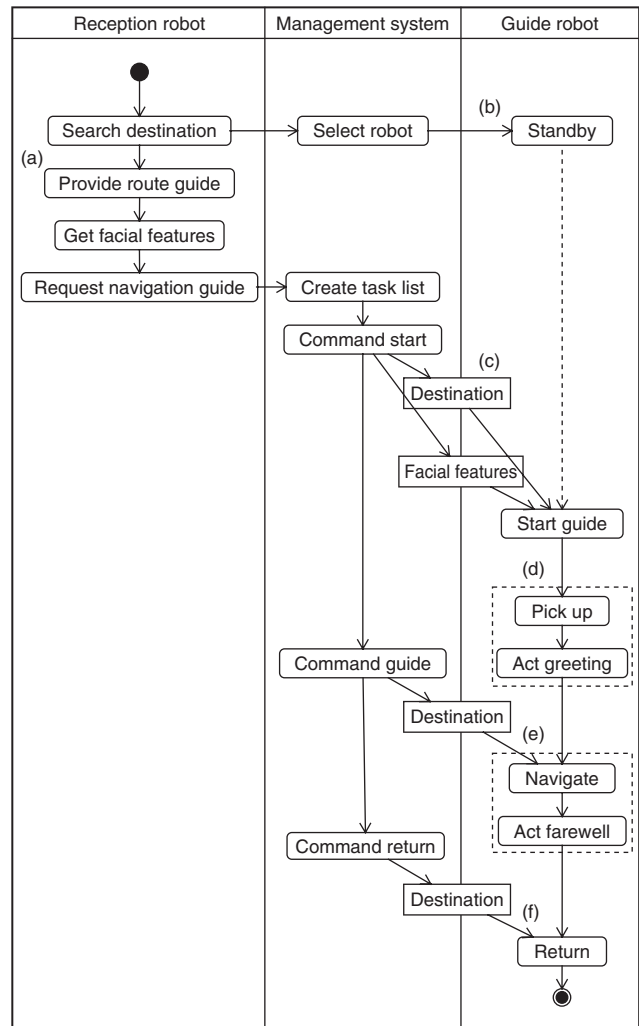


Fig. 4 Guide sequence

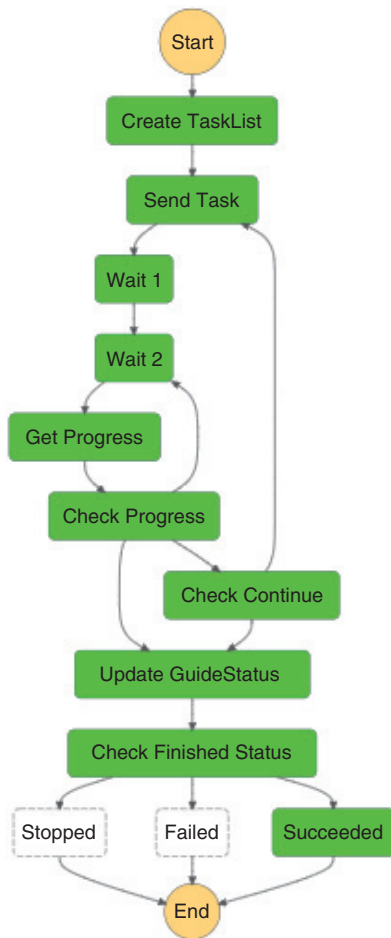


Fig. 5 Guide job monitoring sequence

```

{
  "robotId": "xxxxxxx-xxxx-xxxx-xxxx-xxxxxxxxxxxx",
  "taskList": {
    "Type": "GUIDE",
    "task": [
      {
        "id": 1,
        "type": "picking_up",
        "goal": {
          "name": "meeting_point1",
          "coordinate": [
            "3.11",
            "-4.67",
            "1.59"
          ]
        }
      },
      {
        "id": 2,
        "type": "guide",
        "goal": {
          "name": "McDonald's",
          "coordinate": [
            "-4.12",
            "6.67",
            "1.59"
          ]
        }
      }
    ]
  }
}

```

Fig. 6 Task list example

6. Results of the Trial with Actual Equipment

Confirmation of service envisioning guide services and using actual equipment was carried out at a certain public indoor facility which extends as far as 500 meters in each direction and include many tenants run businesses. New visitors to the facility may find it challenging to figure out what direction to take to reach their destination. Therefore, we concluded that there would be a demand for guide services provided by robots.

Testing of the management system was carried out to confirm whether the system performs guide job management and fleet management according to the design, whether the operational status of robots can be monitored by means of IoT communication, and so on.

No installation of dedicated server or networking infrastructure was needed to conduct the trial. The number of robots used was limited to one reception robot and two guide robots, since the objective of the trial was a confirmation of the system at the initial stage of operation.

We confirmed that the management system functions in the following manner during the testing.

- One appropriate robot would be selected from the two guide robots in accordance with the conditions for operational status and remaining battery charge.
- The transmission of destination and facial recognition data to the guide robot with appropriate timing and other such matters were confirmed. The guide robot recognized the guest correctly and performed the configured tasks of pickup, guidance, and return.
- Data was transmitted to and from the guide robot as it moved throughout the entire facility, and that the guide robot's movement information was updated without delay. Hence the monitoring of the robot and the transmission of commands could be carried out in a stable manner using IoT communications.

A screen capture from the operation monitoring terminal (Fig. 7) shows an example of how the trial of the management system had been conducted. The terminal displays the location and path of the robots on the floor map, together with the detailed status of the robots, including the battery voltage of each robot, and so on. From the observation, it was confirmed that the management system successfully monitor operational status of the robots. We have also confirmed that the system operator is notified properly whenever a trouble occurred to any robots.

From the above results, it was confirmed that the management system performs guide job management and fleet management according to the design, and that it is capable of monitoring the operational status of the robots by means of IoT communications.

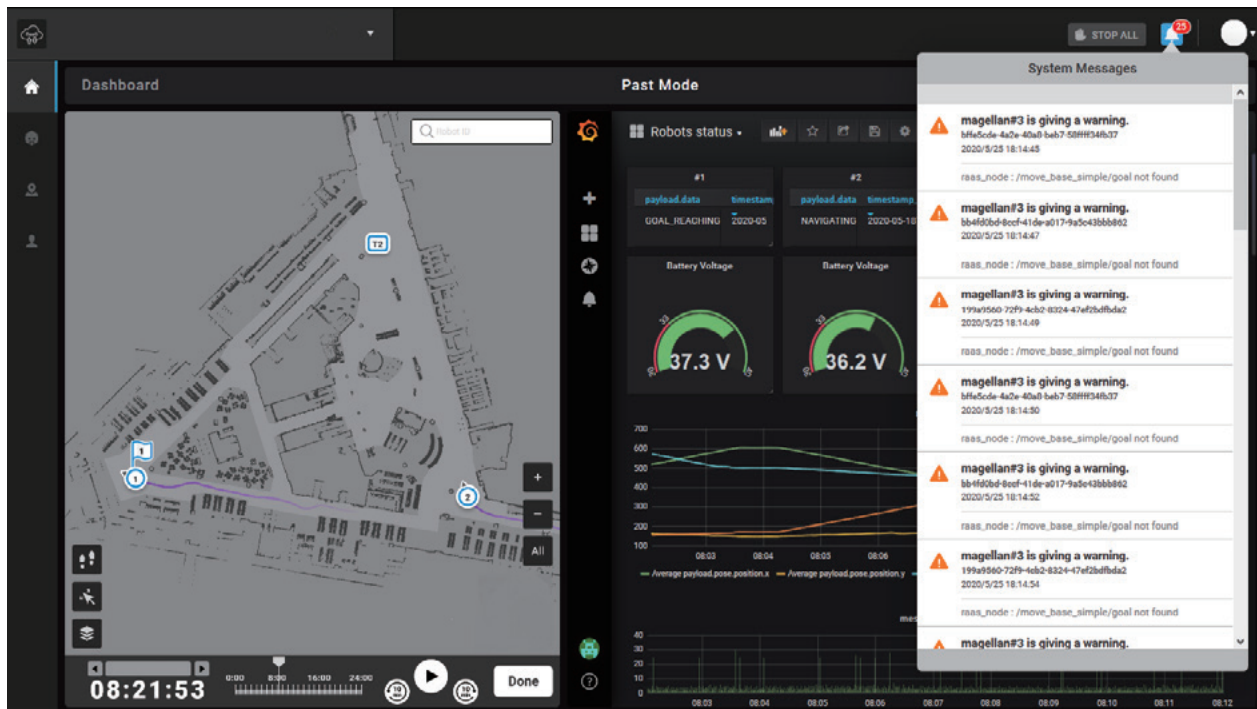


Fig. 7 Operation monitor

7. Conclusion

A guide robot management system was built to use the cloud and IoT communications. In order to realize guide services provided by robots, guide job management, fleet management, robot operational status monitoring, and other such functions were newly implemented, while also using the general-purpose functions of Honda RaaS. Tests were conducted using the actual equipment in a public facility, and it was confirmed that multiple units and types of robots operated appropriately while coordinating information by means of the management system.

Since there is no need to put dedicated servers or networking equipment in place on-site, there is no limitation on the robots' range of movement, and use of the robots can be initiated right away. The system is configured with general-purpose functions using cloud and IoT communications to which specific service functions are added. We believe that this method will be effective for the deployment of various different robotics services.

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Development of Deviceless Tumble Enhancement Method for Small Motorcycles

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ABSTRACT

Using the CFD and targeting at small motorcycles, we have pursued a technology that can enhance the tumble flow in the cylinder only in a low load range of the engine without the need to use any intake path switching mechanisms. In a throttle body with a butterfly valve, a reverse flow occurs after the intake air has passed the throttle valve when the throttle valve opening is small. We have confirmed that installing a flow separator behind the throttle valve that vertically divides the intake port flow can successfully capture the reverse flow into one of the two flow paths. Furthermore, we confirmed that optimizing the separator position can capture most of the intake air into one path, thereby gaining the required amount of flow that can generate tumble in the combustion chamber. Through the analysis of combustion pressure of an actual engine, we have confirmed that the combustion period in the low load range is shorter in the new design than in the conventional port design, which proves that the target tumble effect has been achieved. With the new design applied, the emission norms of EURO5 and India's BS-VI are satisfied as well as improving the fuel economy of the motorcycle by 1.7% in the WMTC mode. For mass production, the separator is created as an integral part of the inlet pipe casting by incorporating a slit in the port core. This enables application of the new tumble port design without adding extra parts or modifying existing production equipment.

1. Introduction

In recent years, as a means to prevent global warming, reducing CO₂ is increasingly required across most industrial sectors. For the mobility sector, achieving better fuel economy is something that is now urgently needed. Therefore, in order to enhance combustion under the condition of a high exhaust-gas recirculation level or in the use of lean air-fuel ratios, such techniques that can enhance the circulation of intake air in the cylinder are being widely studied. With this, the generation of tumble in the cylinder is effective, as a method to enhance circulation of the intake air. Thus far, a tumble enhancement by optimizing the intake port configuration has been widely studied and practically implemented^{(1), (2)}. Akimoto et al. and Nakayama et al. have developed a technique to enhance tumble by implementing a partition inside the intake port and adding a flow path switching mechanism, which has in turn been applied to practical use on passenger vehicles^{(3), (4)}.

However, to use such a method on a small and

inexpensive motorcycle, the addition of exclusive parts for the flow path switching system and associated control system would lead to the issue of implementation and also have a cost impact. To solve these issues, Shirasuna et al. invented a method to enhance tumble by offsetting the inlet valve in the perimeter direction of the cylinder bore⁽⁵⁾. With this method, when the inlet valve lift is low, a part of the opening is masked by the cylinder wall. As this increases the flow towards the exhaust port, it can enhance tumbling.

However, as this method enhances tumble not only in a low load operating condition for practical use of an engine but also in high load conditions, applying it to a small motorcycle leads to the issue of increased noise due to the resulting rapid combustion. As the engine is exposed on most small motorcycles, such noise is easily transmitted to the motorcycle rider. Furthermore, the use of ball bearings to support the crankshaft is a negative factor in terms of noise generation. As such, there are certain limits in increasing the level of tumble.

In this study, we aimed to establish a technology that

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² Innovative Research Excellence Power Unit & Energy

would be useful for small motorcycles to enhance tumble only within a low load range of an engine without using any intake path switching mechanisms. We used computational fluid dynamics (CFD) to analyze the flow around the throttle valve and we discovered that a reverse flow occurs in the port when the throttle opening is low. Also, we found that installing a flow separator in the port can effectively capture part of the reverse flow into one of the divided flow paths. By making use of this phenomenon in the actual intake port of an engine, we established a technology that can enhance tumble only within a low load range of the engine without using any intake path switching mechanisms.

Furthermore, in an attempt to apply the new design to the mass production, the design of core molding die splitting has been modified to create a slit, which serves as a separator, in the intake port core. Accordingly established is the technique that creates the separator as an integral part of the intake port casting without adding extra parts or modifying the existing production equipment.

2. Target Setting

Before conducting this study, we established target values to be achieved based on experimental and CFD analysis results.

2.1. Test Engine and Designation of Tumble Reinforcement Zone

We used an engine of a small scooter for this experiment. Table 1 shows the major specifications of the test engine. Figure 1 shows the cross section of the intake path of said test engine. The butterfly type throttle valve opens clockwise as can be seen in this figure. The fuel injector is placed at the outer periphery portion of the U-shaped inlet pipe.

In order to determine the engine speed and the throttle opening range that would be effective for improving fuel economy, we used a specific WMTC mode to investigate the frequency distribution of engine speed and throttle opening. Figure 2 shows the frequency distribution map. Besides the idling state, the engine is generally operated with a throttle opening of 30% or less. In particular, we can see that an engine speed of around 4,000 rpm and a throttle opening of 15% to 30% are most frequently used. From the above results, we determined that tumble should be enhanced for the throttle opening range of 15% to 30%.

2.2. Setting of Target Tumble Ratio

To set the target tumble ratio, we conducted a number of experiments using a tumble control valve (TCV) system, which can arbitrarily adjust the tumble ratio according to the throttle opening. The tumble ratio characteristics at various throttle openings was assessed by conducting steady flow tests. The definition of tumble ratio and the steady flow test method are as per the reference literature by Shirasuna et al⁽⁵⁾.

Table 1 Vehicle and engine specifications

Engine type	Forced air cooled, 4-stroke, single-cylinder, gasoline engine
Bore × Stroke [mm]	50.0 × 63.1
Displacement [cm ³]	124.9
Compression ratio	10
Valve diameter [mm × number]	Intake: $\Phi 25.5 \times 1$ Exhaust: $\Phi 21 \times 1$
Valve lift [mm]	Intake: 6.3; Exhaust: 6.2
Ignition system	Full transistorized
Fuel system	Fuel injection
Throttle bore diameter [mm]	$\Phi 22$
Maximum power [kW/rpm]	6.1/6500
Maximum torque [Nm/rpm]	10.3/5000
Transmission	CVT
Vehicle dry weight [kg]	107
WMTC mode	Class 1

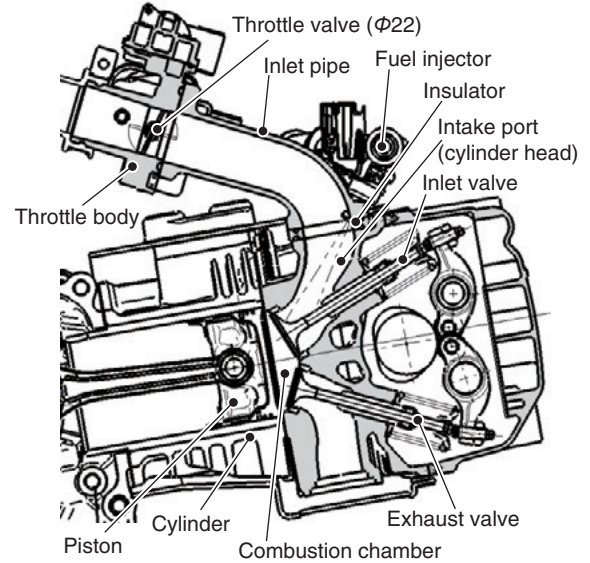


Fig. 1 Section of test engine (conventional port)

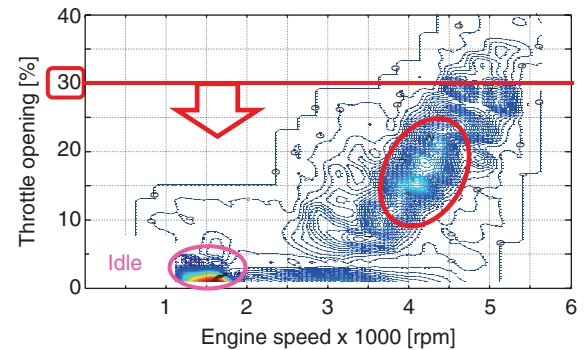


Fig. 2 Distribution of throttle opening and engine speed in WMTC mode

Figure 3 shows a cross section of the tumble port with TCV when the engine is low loaded. We then placed a separator wall for the port downstream of the inlet pipe to divide it into two ports, i.e., a partially open throttle (POT) port for low loading and a wide-open throttle (WOT) port for high loading of the engine. The cross-sectional area of both ports at the port entrance is the same.

Here, we set the throttle valve to open in the counterclockwise direction in the figure to help prevent TCV from interfering with the separator wall when the throttle valve is wide open. The air flow that has passed the throttle valve opening on the WOT port side is forced to change direction by TCV and enter the POT port. As a result, the flow ratio of the POT port increases with respect to the total flow out of the throttle valve. The POT port exit is suitably shaped to increase the directivity of the flow into the exhaust valve side, and also to ease its separation from the wall (refer to circled area in the enlarged view in Fig. 3).

2.2.1. Setting of upper/lower limits of tumble ratio

Figure 4 shows the relationship between the tumble ratio at the throttle opening of 25% and the improvement ratio of brake specific fuel consumption (BSFC) at brake mean effective pressure (BMEP) of 250 kPa. Here, we used an engine speed of 4,000 rpm and a stoichiometric air-to-fuel ratio of 14.7 as measurement conditions. We determined the ignition timing according to the minimum spark advance for best torque (MBT) condition. As the tumble ratio increases, the combustion speed increases and thus the degree of constant volume increases to improve BSFC. As can be seen, when the tumble ratio becomes 1.5 or more, the improvement ratio of BSFC is saturated. From the results, we selected 1.5 as the target value for the lower limit tumble ratio.

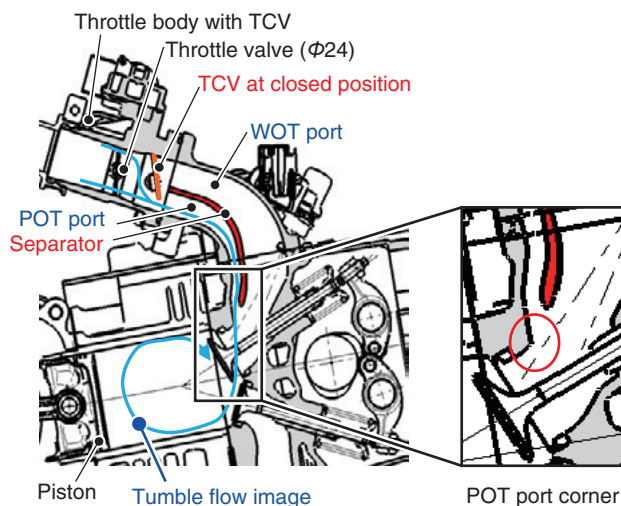


Fig. 3 Tumble port with TCV and detail of POT port exit

Then, we evaluated the effect of the tumble ratio on engine noise through sensory evaluation by experts. In doing this, we used a throttle opening of 25%. As the tumble ratio increases, combustion speed increases, while the rate of pressure increase ($dP/d\theta$) in the cylinder also increases. Accordingly, engine noise due to clearance at the crankshaft bearings increases. It can be seen that a tumble ratio of 2.0 or less is acceptable in terms of engine noise generation. From the results, we selected 2.0 to be the target value of the upper limit tumble ratio.

Figure 5 shows the tumble ratio characteristics when a conventional intake port is used. We can see that the tumble ratio is less than 1.5 for a throttle opening of up to 30% and that it is nearly constant between 1.6 and 1.7 when the throttle opening is 30% or wider.

The red box in the figure shows the target range of the tumble ratio and the throttle opening, as determined from test results previously mentioned.

2.2.2. Target flow ratio of POT port

We used CFD to analyze the air flow in the tumble port with TCV. For this CFD analysis, we modeled the port

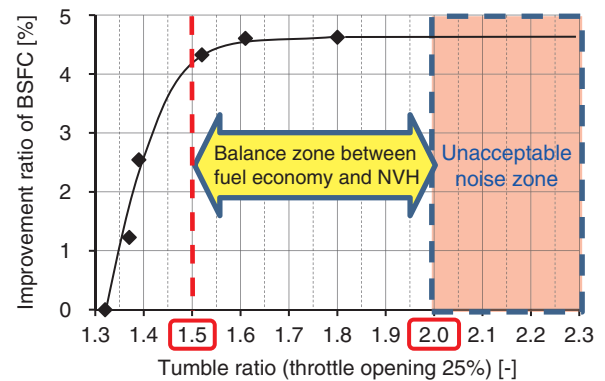


Fig. 4 Relationship between improvement ratio of BSFC, evaluation of engine noise, and tumble ratio

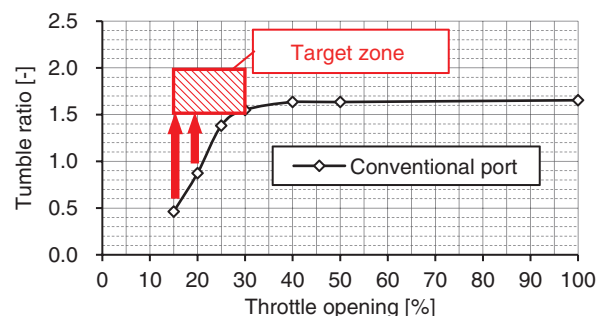


Fig. 5 Tumble ratio characteristics and target zone

configuration based on the method of Ricardo plc. Figure 6 shows the CFD analysis model and the analysis conditions. The details of analysis are as per the reference literature of Shirasuna et al⁽⁵⁾. We used a throttle valve opening of 15%, at which the tumble ratio needs to be improved the most.

We investigated the flow ratio RQ_{POT} of the POT port that can achieve the desired lower limit tumble ratio of 1.5. The flow ratio RQ_{POT} is defined by:

$$RQ_{POT} = \frac{Q_{POT}}{Q_{ALL}} \times 100$$

RQ_{POT} : Flow ratio of POT port [%]

Q_{POT} : Volumetric flow into POT port [m³/s]

Q_{ALL} : Total volumetric flow into cylinder [m³/s]

Figure 7 shows the relationship between the flow ratio of the POT port RQ_{POT} and the resulting tumble ratio when the TCV opening is varied with the throttle valve opening fixed at 15%. From the analysis results, we found that the flow ratio of the POT port RQ_{POT} needs to be 83% or higher in order to obtain the targeted minimum tumble ratio of 1.5.

2.2.3. Target of effective port opening at full load

In order to achieve the same power as that of the

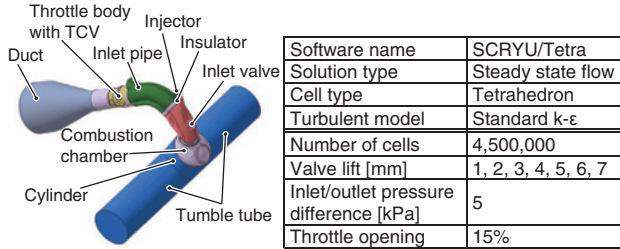


Fig. 6 Model of tumble port with TCV and analysis condition

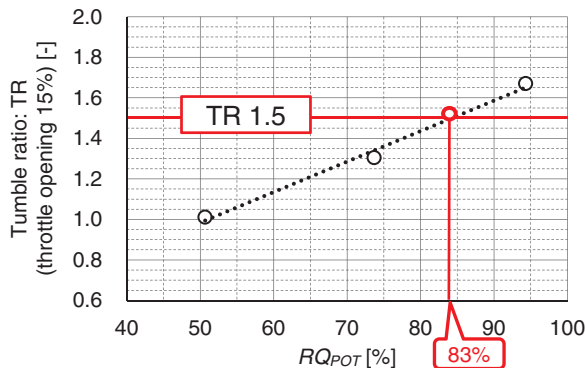


Fig. 7 Relationship between RQ_{POT} and tumble ratio

conventional engine, we used a Z curve (effective port opening area vs. inlet valve lifts) with a target value equivalent to that of the conventional port.

Based on the experimental results for the tumble port with TCV, we determined the target parameters for the tumble port system without TCV to be as follows:

- (1) In the CFD analysis, a POT port flow ratio RQ_{POT} of 83% or higher is to be achieved at a throttle opening of 15%;
- (2) In an actual steady flow test, a tumble ratio of 1.5 to 2.0 is to be achieved for the throttle opening range of 15% to 30%; and
- (3) In a full throttle steady flow test of the port, an effective opening area equivalent to that of the conventional engine is to be achieved.

3. Tumble Enhancement without Using TCV

To find a method that can enhance tumble without using TCV, we first analyzed the basic characteristics of the air flow that is generated downstream of the throttle valve.

3.1. Flow Analysis (CFD)

3.1.1. Straight pipe analysis model

Figure 8 shows a general view of the analysis model. In this straight pipe flow analysis, we used the same flow path configuration as that used in an actual throttle body. To model the downstream of the throttle body, we used a simple straight pipe with no bends, with a length equivalent to that measured from the inlet pipe to the intake port exit at the cylinder head of an actual unit. Figure 9 shows an enlarged view around the throttle valve. We used a butterfly type throttle valve with a throttle bore diameter of 22 mm. In the figure, the valve turns clockwise to open. In this clause, the throttle valve edge that opens towards the upstream is called “leading edge,” while the one that opens towards the downstream is called “trailing edge.”

3.1.2. Results of straight pipe analysis

Like the previous chapter, we assumed a throttle opening

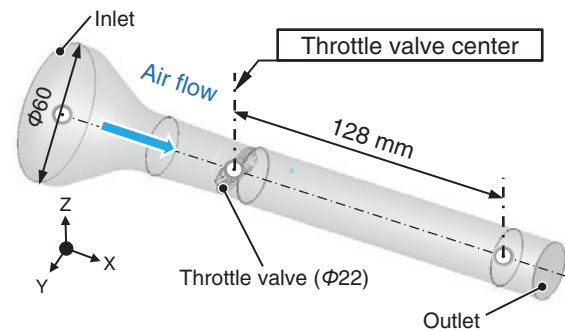


Fig. 8 CFD model for straight port

of 15%, with an inlet/outlet pressure difference of 5 kPa for the CFD analysis. Figure 10 shows the analysis results in the form of flow lines and flow velocity downstream of the throttle valve. The contour of the flow line in the analysis result indicates flow velocity. The white arrow mark shows mainstream flow.

The figures (a) to (c) in Fig. 10 that show the flow lines are from three view directions as described below:

- (a) Upper view along the Z-axis to show flow lines that have passed the throttle opening on the trailing edge side only
- (b) Side view of the flow path as seen from the Y-axis to show flow lines that have passed the throttle opening on both trailing edge and leading edge sides
- (c) Bottom view along the Z-axis to show flow lines that have passed the throttle opening on the leading edge side only

The specific characteristics of the flow, as observed in these figures, are summarized below.

As shown in (a), the central flow that has passed the trailing edge opening moves straight in the upper part of the pipe in Z direction. The edge flow (IIB) that passes both

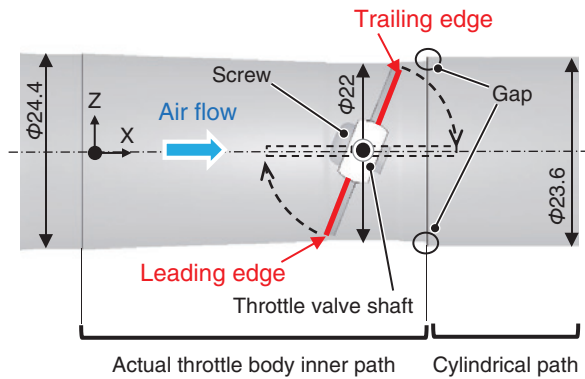


Fig. 9 Detail of throttle valve

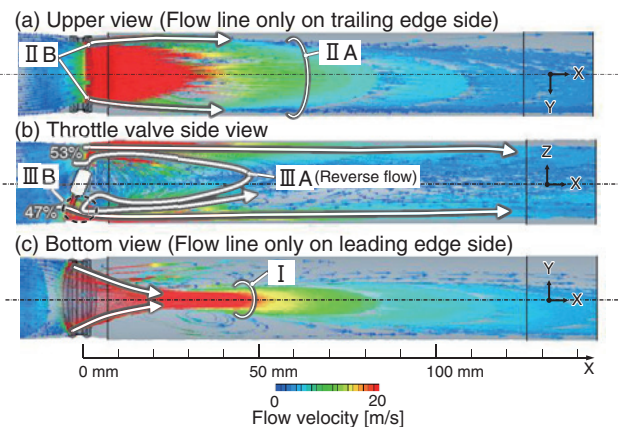


Fig. 10 Flow line for straight port on each side view

ends of the opening flows in the direction in that the flow diffuses in the Y-axis direction while moving toward the lower stream along the cylindrical surface (IIA). It can be seen that the end flow is slower than the central flow, and slower than the flow velocity of the flow that has converged on the leading edge side as (c) shows.

As shown in (b), it can be seen that the total flow into the leading edge and trailing edge openings is almost evenly divided into 47% and 53%, respectively. Also, part of the air from the trailing edge generates some reverse flow towards behind the throttle valve (IIIA).

As shown in (c), the flow on the leading edge side converges towards the center of the pipe (I). That is because the end flow that passes on both ends of the opening flows toward the lower end in Z direction along the cylindrical surface, and merges with the central flow although the central flow in the leading edge side moves straight.

3.1.3. Reverse flow on trailing edge side

The reasons of the reverse flow are discussed hereafter.

Figure 11 shows the pressure distribution on an X-Z section in Fig. 8 downstream of the throttle valve. From the pressure distribution, we can see some low-pressure area (1) behind the throttle valve. We can also see some local low-pressure areas (2) immediately behind both openings.

At first, the slow edge flow on the trailing edge side is pulled back by the low pressure (1), and generates a reverse flow (IIIA) as Fig. 10 shows. Then, the reverse flow (IIIA) is further pulled by the local low-pressure zone (2) on the leading edge side and is guided towards behind the throttle valve (Fig. 10 IIIB). After that, it merges with the converging flow that comes from the leading edge opening towards downstream (Fig. 10 IIIB). The finally merged flow is then separated from the tube surface and flows downstream towards the center of the pipe.

3.1.4. Analysis model of straight pipe with separator

In relation to the results in the previous clause, we focused our attention on the fact that the reverse flow generated on the trailing edge side merges with the mainstream flow on the leading edge side (Figs. 10 and

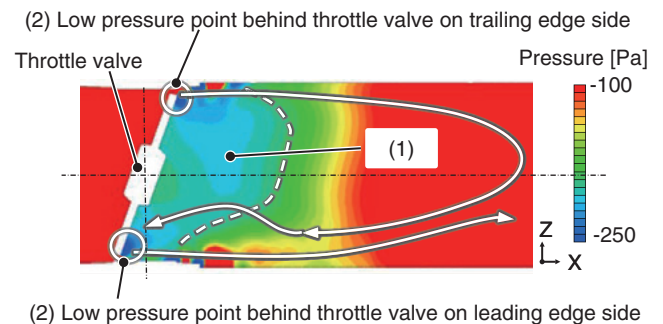


Fig. 11 Distribution of static pressure and aperture flow

11). We thought that installing a separator wall on the leading edge side to form a POT port might be able to capture the reverse flow on the trailing edge side, and would increase RQ_{POT} . Figure 12 shows the analysis model. Based on the straight pipe model discussed in the previous clause, we added a separator in the pipe to be parallel to the throttle valve shaft and the pipe centerline. For application to the test engine, we set the separator length at 120 mm, from 8 mm up to 128 mm downstream of the throttle valve. By means of the separator, we can form simulated POT and WOT ports. In order to evaluate any possible changes due only to the additional separator from the analysis results

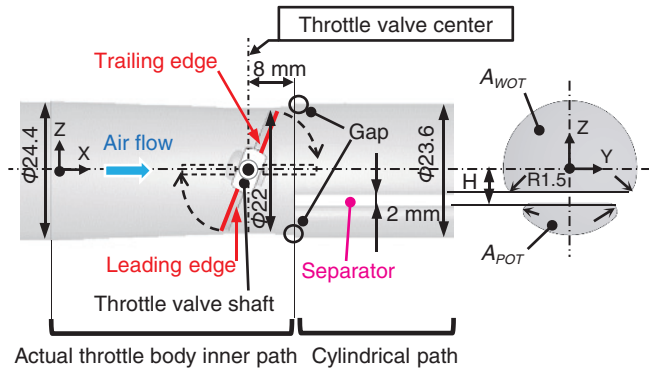


Fig. 12 Detail of throttle valve and separator plate

discussed in the previous clause, we used the same cylinder diameter as the one without a separator. Also, we had the model not change the cross-section areas of the POT and WOT ports along the downstream path before merging the ports near the exit. Considering application to mass production, we chose the thickness of the separator to be 2 mm, which is a typical value used in casting. Regarding the corners formed in installing the separator, we used a curve of 1.5 mm radius to connect the surfaces in order to help avoid adverse effects on the analysis.

3.1.5. Relationship between cross-section area ratio and flow ratio of POT port

Firstly, we investigated the relationship between the cross-section area ratio and the flow ratio of the POT port. The cross-section area ratio of the POT port RA_{POT} is defined as follows:

$$RA_{POT} = \frac{A_{POT}}{A_{POT} + A_{WOT}} \times 100$$

RA_{POT} : Cross-section area ratio of POT port [%]

A_{POT} : Cross-section area of POT port [m²]

A_{WOT} : Cross-section area of WOT port [m²]

We modified RA_{POT} by changing the height H of the separator. We used a throttle valve opening of 15%.

Figure 13 shows the analysis results for different values

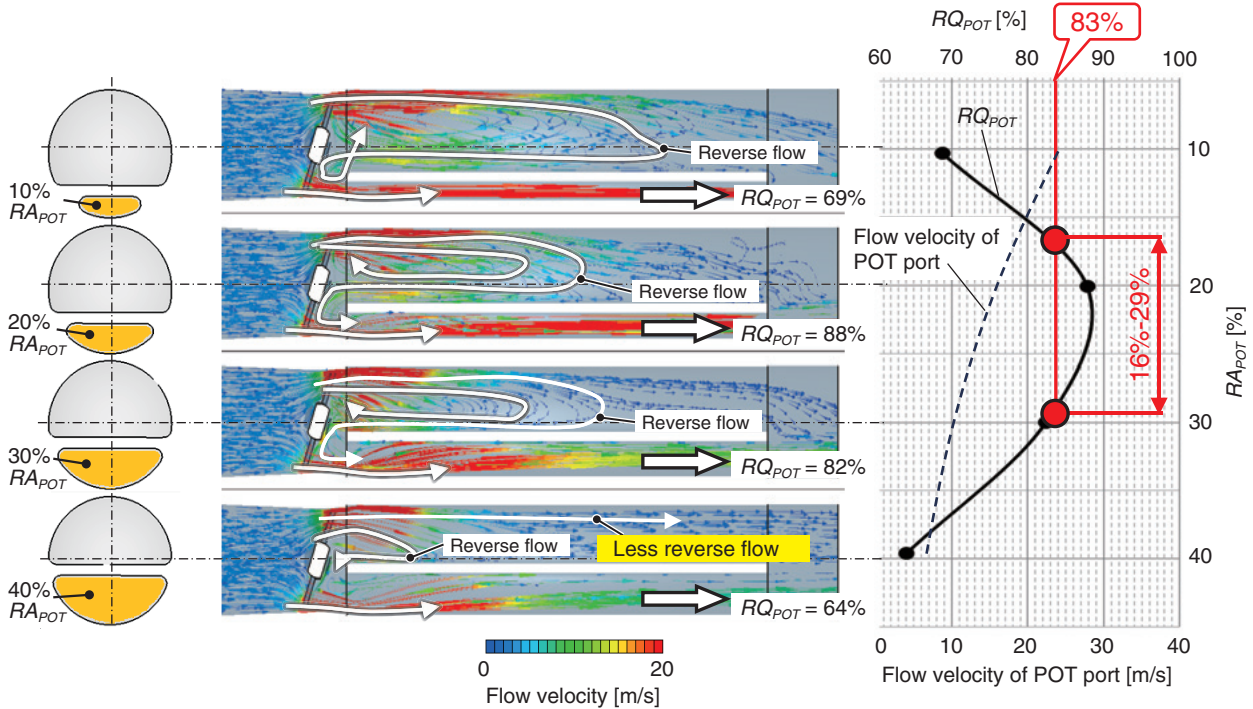


Fig. 13 Result of CFD analysis for straight pipe with each RA_{POT} (throttle opening: 15%)

of RA_{POT} . In the analysis results, the colored contour of the flow lines shows the flow velocity, while the large white arrows show mainstream flows. The graph on the right side shows the value of RQ_{POT} and average flow velocity at the POT port exit for various RA_{POT} values. Shown to the left of the analysis results are the cross-sectional shapes of the pipes.

From the analysis results, we found for every cross-section area ratio that:

1. The flow ratio of each opening to the total flow of the throttle valve was 47% for the leading edge opening and 53% for trailing edge opening. We observed no difference due to the existence of the separator.
2. The reverse flow generated on the trailing edge side is guided by the separator wall to be behind the throttle valve and then flows into the POT port.
3. For all RA_{POT} values, RQ_{POT} has increased from the flow ratio of 47% of the leading edge opening.

Next, we will explain the relationship between RA_{POT} and RQ_{POT} using the graph to the right of Fig. 13.

The RQ_{POT} value of 83% or more is achieved for the port area ratio RA_{POT} of 16% to 29%. RQ_{POT} peaks when RA_{POT} is 20%.

The targeted RQ_{POT} value is not reached when RA_{POT} is 10% and 40%. The reason for this is outlined below.

For RA_{POT} of 10%, RQ_{POT} is 69%. As the POT port opening area A_{POT} nears the opening area of the throttle valve, its ratio to the throttle valve opening area increases. Then, the amount of flow that can enter the POT port becomes limited compared to other cases (RA_{POT} of 20%, 30%, and 40%). In spite of a lot of reverse flow lines, they tend to merge with the trailing edge flow instead of merging with the POT port flow on the leading edge side.

When RA_{POT} is 40%, RQ_{POT} decreases to 64%. Due to the limited space to generate reverse flow on the WOT port side, the amount of reverse flow decreases. As a result, the downstream flow on the trailing edge side increases, while the reverse flow is suppressed.

From the above results, we found that it is important to have a POT port area that is sufficient for the merged flow to fully enter the port, and also to provide enough space to help ensure reverse flow generation.

Accordingly, we selected 20% for RA_{POT} to help ensure a sufficiently high POT port flow ratio RQ_{POT} and a high flow velocity in the POT port for the detailed flow analysis that is described in the next clause.

3.1.6. Effect of separator on capturing reverse flow into POT port

Figure 14 shows the flow analysis results for RA_{POT} of 20%. The large white arrow shows the mainstream flow. Figure 15 shows the pressure distribution analysis results on an X-Z section. From these analysis results, it can be seen as follows.

The converging flow (I) on the leading edge side and the

diffusing flow (IIA, IIB) on the trailing edge side as seen in Fig. 10 are similarly generated.

The diffusing flow on the trailing edge side generates some reverse flow due to the low-pressure region (1) in Fig. 15 (Fig. 14, IIIA). The reverse flow is guided by the separator wall to be behind the throttle valve.

Following that, the reverse flow is pulled by the local low-pressure zone (2) and divided into two flows (Fig. 14, IV).

The flow attracted by the negative pressure on the leading edge side enters the POT port (Fig. 14, V).

The flow IV described above merges with the converging flow that has passed the leading edge opening (Fig. 14, V).

As a result, RQ_{POT} reaches 88%.

From the above results, we can conclude that most of the intake flow can be collected in the POT port formed by the separator wall.

Next, we investigated the relationship between the POT port flow ratio and the throttle opening. With an RA_{POT} of 20%, we varied only the throttle opening to observe results.

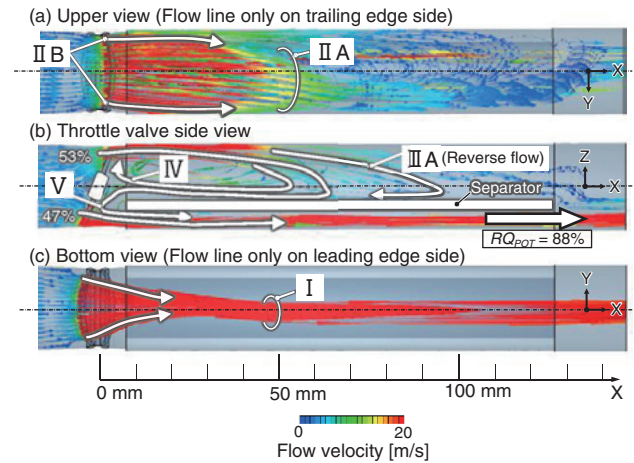


Fig. 14 Flow line for straight port with separator plate

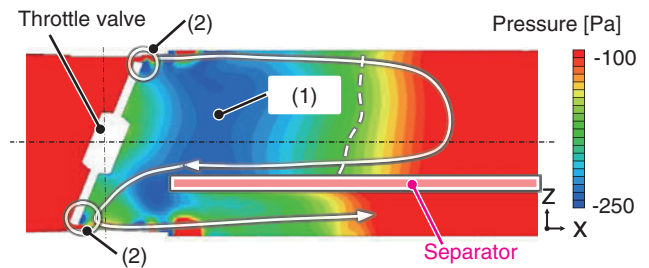


Fig. 15 Distribution of static pressure with separator plate

Figure 16 shows RQ_{POT} , total volumetric flow through the throttle valve (Q_{ALL}), volumetric flow on the leading edge side (Q_{LEAD}) and volumetric flow in the POT port (Q_{POT}) for different throttle opening values. As the throttle opening increases, Q_{ALL} increases quadratically, while Q_{POT} increases gradually compared to Q_{ALL} . As a result, RQ_{POT} becomes lower as the throttle opening increases.

From the above, we came up with the idea that increasing RQ_{POT} could enhance tumble at a throttle opening range up to 30%.

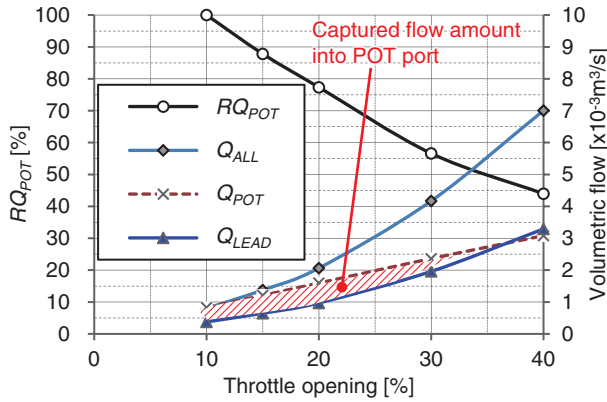


Fig. 16 RQ_{POT} , Q_{ALL} , Q_{POT} , and Q_{LEAD} vs. throttle opening

4. Effectiveness Verification in Actual Port Configuration

We checked whether the phenomenon of reverse flow capture in the POT port by installing a separator could be reproduced in an actual port configuration or not.

4.1. Analysis Model Having Actual Port Shape

Figure 17 shows a cross section of the tumble port without TCV. By setting RA_{POT} to 20%, in accordance with the straight pipe CFD analysis discussed earlier, we divided the inlet pipe into POT and WOT ports using a separator wall. The shape of the POT port exit is the same as that of the tumble port with TCV. The cross-section area of the POT port from entrance to exit at the cylinder head remains virtually unchanged. The diameter of the throttle valve is 22 mm, while the center position of the throttle valve shaft and the direction of valve rotation are the same as those of the original test engine.

4.2. Flow Analysis in Actual Port Shape

Figure 18 shows a flow analysis result of the tumble port without TCV. The flow out of the upper opening of

the throttle valve is shown in blue and the flow out of the lower opening is shown in red. Note that the flow shown in the figure is one when the inlet valve lift is 6 mm. From the analysis results, we can see that a merging of the reverse flow generated on the WOT port side with the leading edge flow is reproduced even with a curved port configuration downstream of the throttle valve. Furthermore, the flow ratio of the POT port RQ_{POT} is 91%, which is higher than

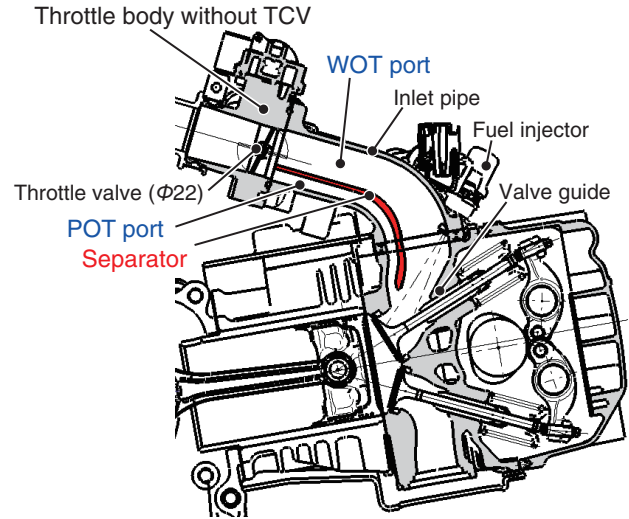


Fig. 17 Tumble port without TCV

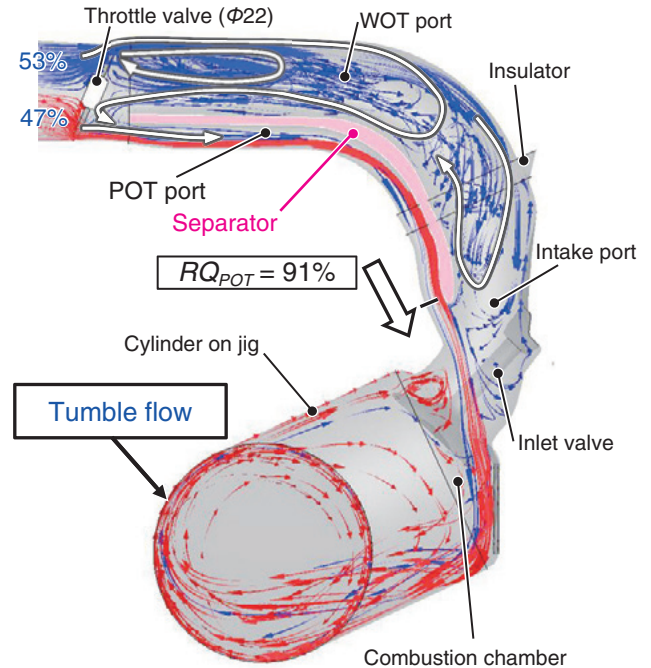


Fig. 18 Result of CFD analysis for flow of tumble port without TCV (throttle opening: 15%)

the 88% of the straight pipe, as shown in Fig. 14. This is considered due to the existence of the valve guide, which increases the ventilation resistance of the WOT port and increases the flow on the POT port side. Furthermore, we can see tumble generation by the intake air in the cylinder.

From the above results, we confirmed that the tumble port without TCV in an actual port configuration can also capture the reverse flow in the POT port to improve the POT port flow ratio RQ_{POT} .

As the RQ_{POT} value of 91% obtained without TCV exceeded the target value of 83% shown in Fig. 7, we felt that the targeted lower limit tumble ratio of 1.5 was achievable. However, as shown in Fig. 5, the tumble ratio of a conventional port increases as the throttle opening increases from 15% to 30%. Considering this effect, we surmised that the tumble ratio could exceed the upper limit of 2.0 with the tumble port without TCV in the above throttle opening range.

To reduce the RQ_{POT} value, we thought that moving the separator away from the throttle valve could reduce the amount of reverse flow capture. Therefore, we conducted a CFD analysis to determine the amount of shortening in the separator and found that a 10 mm contraction can reduce RQ_{POT} to 83%⁽⁶⁾.

Figure 19 shows a cross section of the tumble port without TCV when the separator is shortened along with the analysis results.

From the above results, we conclude that the target tumble ratio characteristics are achievable in the tumble port without the TCV.

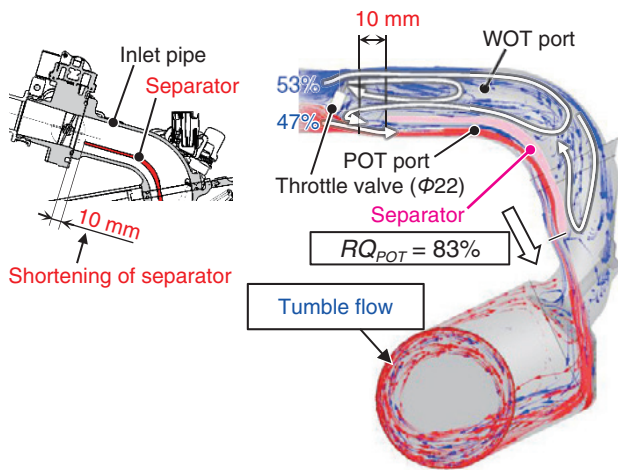


Fig. 19 Result of CFD analysis for flow of tumble port without TCV using short separator (throttle opening: 15%)

5. Verification Tests with Actual Unit

Described hereafter are the results of tests using actual engine.

5.1. Tumble Ratio Measurement

Figure 20 shows the tumble ratio measurement results. In the tumble port without the TCV, the measured tumble ratio at a throttle opening of 15% meets the targeted minimum value of 1.5. Also, at a throttle opening of 20% and 25%, the measured tumble ratio of 1.8 and 1.9, respectively, do not exceed the targeted upper limit value of 2.0. From these results, it was confirmed that a tumble port without TCV can achieve the targeted tumble ratio.

5.2. Verification of Improved Fuel Consumption at Lower Limit Tumble Ratio of 1.5

Figure 21 shows BSFC measurements of an engine unit made at BMEP of 250 kPa (equivalent to a throttle opening of about 15%) using a conventional intake port, a tumble port with TCV, and a tumble port without TCV. For the tumble port with TCV, we adjusted the TCV opening to set the tumble ratio to the lower-limit target of 1.5. For measurement conditions, we used an engine speed of

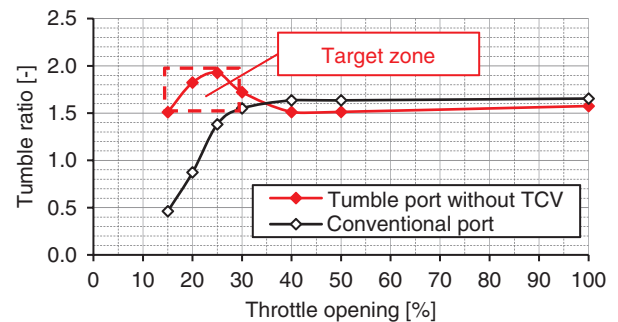


Fig. 20 Characteristic of tumble ratio

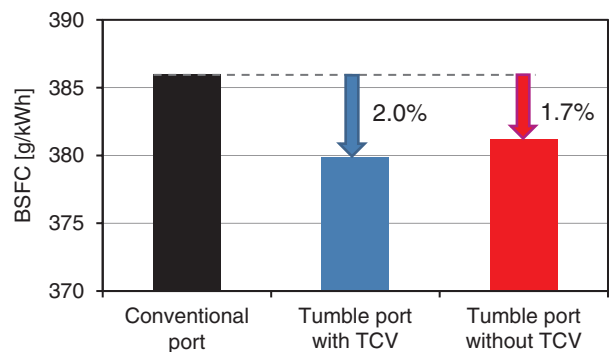


Fig. 21 BSFC results at BMEP of 250 kPa

4,000 rpm, a stoichiometric air-to-fuel ratio of 14.7, and an ignition timing of MBT for all types of port. The BSFC values of the tumble port with TCV and tumble port without TCV were improved by 2.0% and 1.7% from that of a conventional port, respectively. From the above results, we confirmed that increasing the tumble ratio to 1.5 or higher can effectively improve fuel consumption.

5.3. Verification of Engine Noise at Upper-limit Tumble Ratio of 2.0

Figure 22 shows the results of sensory evaluation for engine noise. Although both tumble ports are rated lower than a conventional port with a throttle opening of up to 30%, it is still within an acceptable range. At the fully loaded (WOT) condition, it is rated “very good” for all three ports. This is considered because the tumble ratio in a fully loaded condition is about the same as that of the conventional port as Fig. 20 shows.

From the above results, we conclude that the targeted maximum tumble ratio of 2.0 in low load range satisfies our in-house noise assessment criteria.

5.4. Verification of Effective Port Opening Area

Figure 23 shows the Z characteristics obtained from steady flow measurements at various inlet valve lifts. We

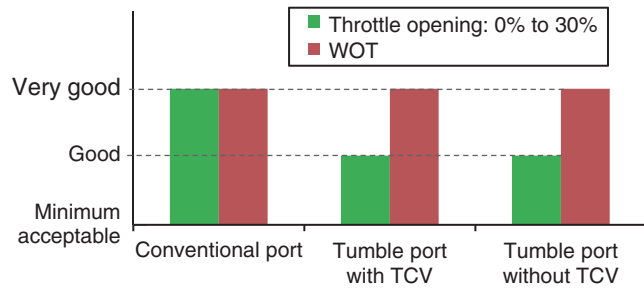


Fig. 22 Crank-noise evaluation (in-house standards)

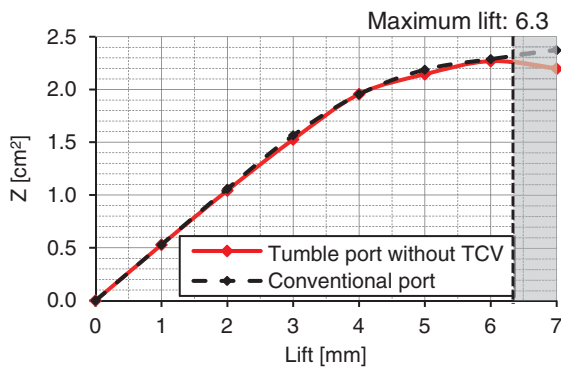


Fig. 23 Characteristics of effective opening area

found that the effective opening area Z of the tumble port without TCV is equivalent to that of a conventional port for the valve lift range of 1 mm to 6 mm. We also noted that the effective opening area Z starts to decrease after the lift exceeds 6 mm. The reason we supposed was that the flow out of the POT port collided with the flow from the WOT port, generated some vortex, causing a reduction in the effective opening area at the valve seat. The maximum lift of the inlet valve of the engine tested is 6.3 mm. Therefore, in terms of practical use, the Z characteristics of this port are equivalent to that of a conventional port.

5.5. Verification by Combustion Pressure Measurement

We verified the degree of constant volume, the initial combustion period (IG-MFB 10%), and the main combustion period (MFB 10%-90%) at various loads in the tumble port without TCV and in the conventional port. Figures 24-26 show the results at an engine speed of 4,000 rpm, A/F of 14.7 and the ignition timing at MBT.

The test results indicate that in the tumble port without TCV, the combustion period is shorter in the low loads, and about the same level in the high loads when compared to

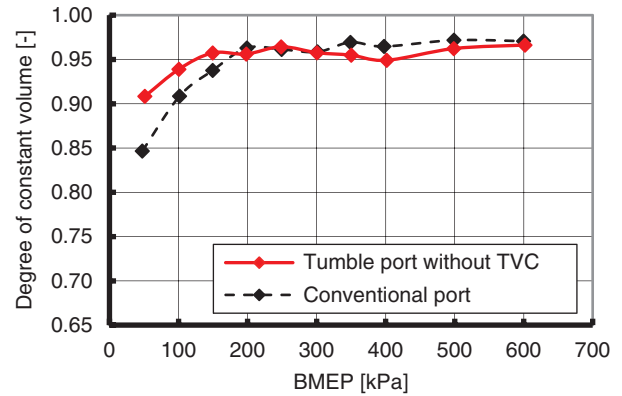


Fig. 24 Characteristics of degree of constant volume

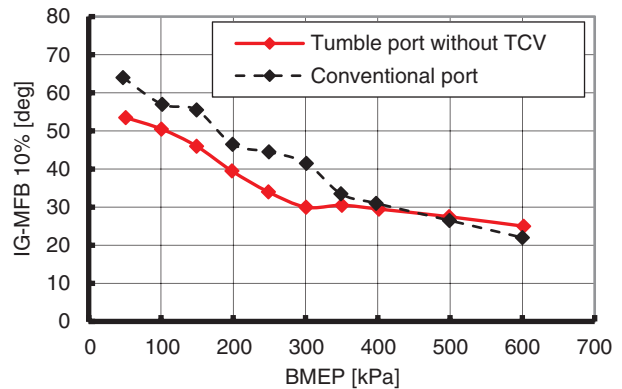


Fig. 25 Relationship between IG-MFB 10% and BMEP

Table 2 Improvement rate of fuel economy compared to conventional port

WMTC Class 1	Idle-stop on	Idle-stop off
Tumble port without TCV	+1.7%	+1.8%
Ref. Tumble port with TCV	+2.0%	+1.7%

Table 3 Results of emission measurements

EURO5/India's BS-VI WMTC Class 1	CO [mg/km]	THC [mg/km]	NOx [mg/km]
Emission regulations	1000	100	60
Tumble port without TCV	293	34	11
Conventional port	274	54	12
Ref. Tumble port with TCV	268	34	16

the conventional port, which proves that the target tumble effect has been achieved.

5.6. Verification in Complete Motorcycle

The fuel consumption in the WMTC mode and the exhaust emissions were measured from the complete motorcycle. Tables 2 and 3 show the results respectively. In the WMTC mode, a reduction of fuel consumption by 1.7% when using the idle stop system, and 1.8% when not are seen. The exhaust emissions are also compatible with the EURO5 and India's BS-VI, which is comparable to the conventional port.

From the above results, we have confirmed that the tumble is enhanced only in the low load range, contributing to a reduction of fuel consumption by 1.7% in the WMTC mode while meeting the EURO5 and India's BS-VI norms. The effective port opening area and the engine noise area are at the same level as in the conventional engine.

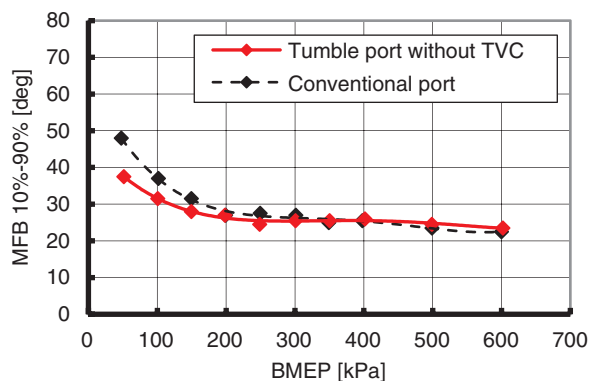


Fig. 26 Relationship between MFB 10%-90% and BMEP

6. Manufacturing of Tumble Port with Separator

Examples of practical applications of the tumble port with a separator wall to the mass production are seen in the fields of automobiles such as the one having a separate flat plate inserted in the port and another one having a flat plate cast together⁽³⁾. However, such methods are inapplicable to small motorcycles due to the restrictions from the curvature of the intake port as well as from the standpoint of cost. In addition, there is an issue in the use of existing production equipment. We have therefore set a target at establishment of a casting method that allows casting of the separator wall as an integral part of the inlet port without modifying the existing production equipment.

6.1. Construction of Port Core Molding Die

An option for integral casting of the separator is to separately mold cores for WOT and POT ports, and bond them together. In that case, two sets of dies are required for core molding. An increase of man hours for bonding of cores and lowering of dimension preciseness from misalignment are conceivable issues.

Our solution is to change the core molding die construction from the conventional horizontal split to the vertical split so that the WOT and POT ports can be created in a single molding operation. The separator wall is formed as a slit in the core. Figure 27 shows the conventional port and the tumble port with a separator. The dotted lines in the picture indicate the parting line of the core molding die. The arrow mark shows the direction of die split.

In the port core, there is a depression in the proximity of the valve guide as in Fig. 28. Such a depression does

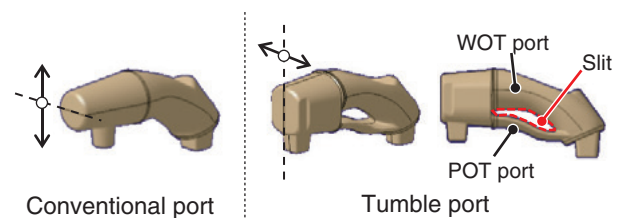


Fig. 27 Core shape of conventional port and tumble port



Fig. 28 Place of depression in valve guide

not allow vertical splitting of the die. To deal with this issue, the slide core has been added to form the valve guide depression. Figure 29 shows image pictures of the core molding.

The pictures indicate cross sections when die is closed, when the core sand is filled, and when die is opened. The construction is such that the angular pin held in the fixed die serves as a guide when the movable die opens and closes to move the sliding core up and down. The direction of sliding core movement is vertical while the movable die travels horizontally.

6.2. Verification of Manufacturability

We analyzed moldability of the tumble port core and castability of the cylinder head under the general processing conditions. The sand core is made of the resin-coated sand (RCS) in which the sand grains are coated with the phenolic resin as a binder at a rate of 1.4 wt.%.

Figure 30 shows the specifications of RCS and the molded tumble port core.

It has been confirmed that there is no detriment in the POT port of the core.

Figure 31 shows the cut separator wall in the cylinder head after undergoing a dye penetrant test.

It has been confirmed that there is no issue in the fillability of aluminum, and the cast product is free of internal casting detriment.

6.3. Removal of Sand Core

An incomplete removal of the sand core in the casting process may cause an increase of inspection in the latter

process, causing an increase of cost. General decoring methods are the hammering, which breaks the core by applying vibrations or the baking which heats the sand core in a heat treatment furnace⁽⁷⁾. Although the baking is an effective way of decoring, there are issues such as heat deformation of the cast product, the need of extra equipment, time, and energy⁽⁷⁾. It is therefore necessary to completely remove sand in the decoring process. Figure 32 shows the production processes. The decoring comes after the casting, and then the cast product is transferred to the heat treatment.

As there is a small-diameter POT port in the tumble port system unlike in the conventional port, we checked if there was any issue in the decoring of tumble port core. The decoring was verified using the existing hammering machine.

6.3.1. Sand removal by hammering

Figure 33 shows an overview of the hammering machine. It can be observed that the core sand in the port is taken out by the vibrating impacts from the hammer.

The following tests were conducted to determine optimum hammering conditions. The oscillation acceleration and the sand removal rate at various air

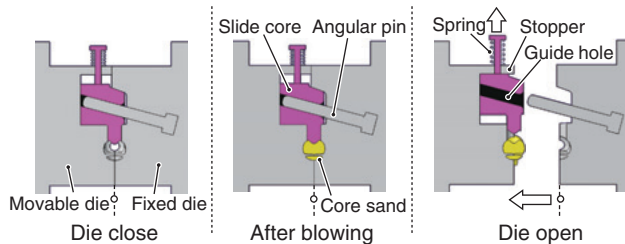


Fig. 29 Schematic diagram of tumble port core mold

Resin [wt.%]	1.4
Bending strength	405
Melting point [°C]	102
Grain size [AFS]	69

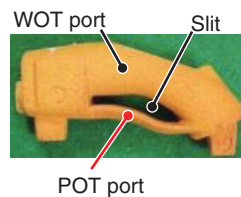


Fig. 30 Specification of RCS and appearance of tumble port core

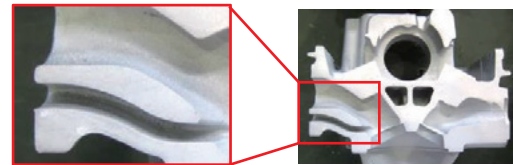


Fig. 31 Fillability and internal quality (dye penetrant test)

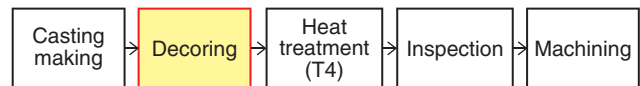


Fig. 32 Process chart

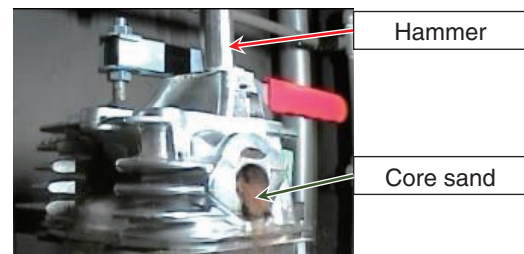


Fig. 33 State of decoring

pressures which is applied to hammer were measured. Note that the sand removal rate is defined by the percentage of the weight of the removed core sand against the weight of the intake port core. Figure 34 shows the test results. It has been confirmed that when the air pressure is above 0.3 MPa, the oscillation acceleration becomes more than 44 g, where the sand removal rate becomes 100%.

6.3.2. Collapsibility of sand core by heat treatment

Presuming a rare case of sand core remaining in the POT port after the chipping, we checked collapsibility of the sand core by heat treatment. The sand core is made of the RCS in which the sand grains are coated with the phenolic resin as a binder at a rate of 1.4 wt.% as Fig. 30 shows. The heat accelerates oxidative decomposition of the phenolic resin, and turns the resin to gases. In an attempt to clarify the temperature that causes the oxidative decomposition to occur, we conducted Thermogravimetry/Differential Thermal Analysis (TG-DTA) for the RCS⁽⁸⁾. Figure 35 shows the results. The DTA curve shows exothermic peak indicating oxidation at 428°C. The oxidative decomposition finishes at 500°C, which is the solution treatment temperature of the cast product. As a result, the phenolic resin serving as a binder disappears completely, which is an

indication of collapse of the sand core as Fig. 36 shows.

It is presumable that if the end of POT port on the combustion chamber side is closed by burr, the POT port sand core is exposed to the atmosphere only on the inlet pipe side, causing the oxidative decomposition of the phenolic resin not advancing far inside of the core. We have therefore tested collapsibility of the sand core by heating using the test piece in which the closed POT port is simulated in a simplified manner. Figure 37 shows the image picture of the test piece. The cross-sectional area of the opening that is exposed to the atmosphere is adjusted equal to that of the POT port. Figure 38 shows the relationship between the heating time and the collapse

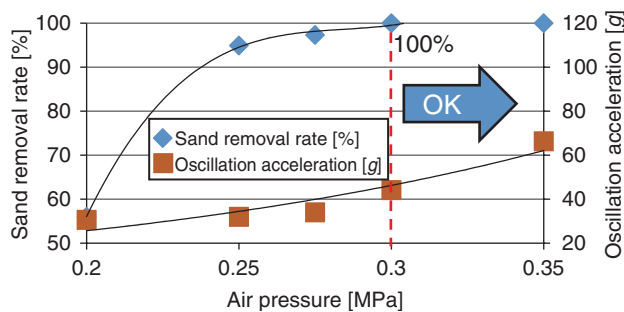


Fig. 34 Sand removal rate of intake port (after decorating for 30 seconds)

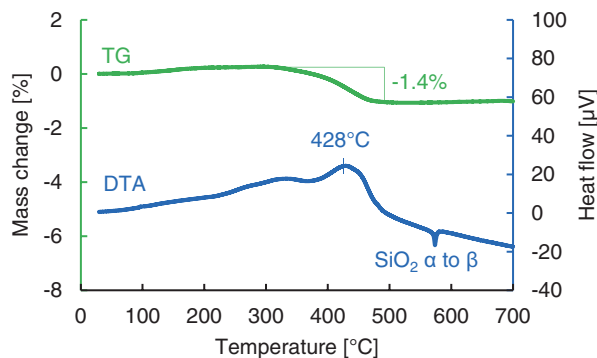


Fig. 35 TG-DTA curves at heating rate of 10°C/min

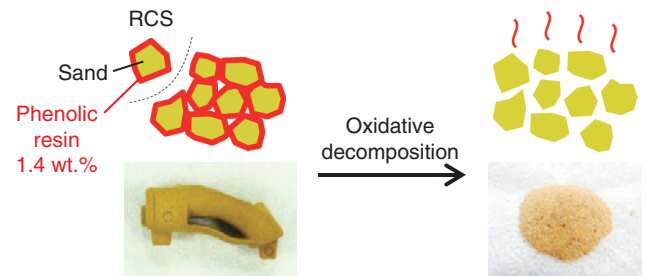


Fig. 36 Sand core collapse

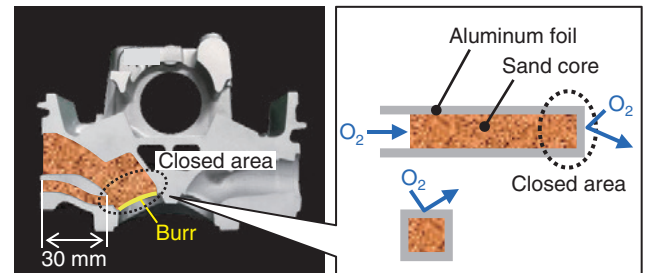


Fig. 37 Schematic diagram of test piece

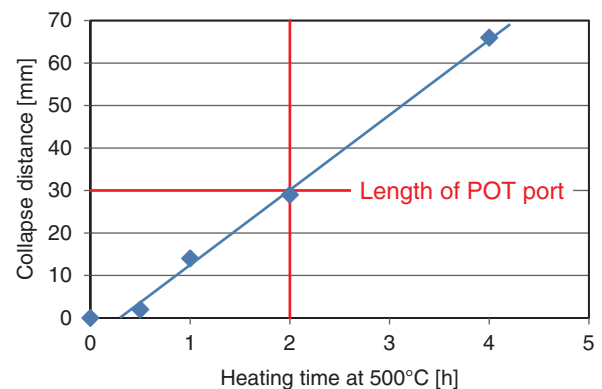


Fig. 38 Effect of heating on sand core collapsing

distance of sand core. The collapse advances proportionally to the heating time. After 2 hours of heating, the length corresponding to the 30 mm-long POT port has collapsed. Accordingly, we conclude that adequate collapse within the heat treatment time is prospective.

We have thus established the manufacturing method for integral casting of the separator in the intake port, allowing practical applications of the newly designed tumble port without modifying existing casting equipment.

7. Conclusion

We have established an inexpensive technology that can enhance tumble in a cylinder only when the engine is low loaded without using any flow path switching mechanisms.

The technology is based on the following findings:

- (1) In the intake port downstream of the throttle valve, the trailing edge side of the throttle valve produces a slow diffusing flow, while the leading edge side produces a fast converging flow.
- (2) The slow diffused flow on the trailing edge side is pulled by a low-pressure zone generated behind the throttle valve to produce some reverse flow.
- (3) By installing a separator in the port on the leading edge side of the throttle valve shaft, the reverse flow is guided along the separator wall to the low-pressure zone behind the throttle valve. It then merges with the converging flow on the leading edge side. As a result, more than 80% of the total flow is captured in the POT port⁽⁹⁾.
- (4) It has been confirmed from the combustion pressure analysis of actual engine that the combustion period is shorter in the low load range than in the conventional port, proving that the target tumble effects are achieved.
- (5) The emission norms of EURO5 and India's BS-VI are satisfied as well as improving the fuel economy of the motorcycle by 1.7% in the WMTC mode.
- (6) Using the vertical split construction for the intake port core molding die, the slit is made in the core to create the separator wall. This core enables the integral casting of the separator wall in the intake port.

By using this technology, we can improve fuel consumption performance at a practical operating range of an engine without sacrificing quietness or power performance. This technology also allows practical applications without adding extra parts or modifying existing production equipment.

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Development of High-efficiency CVT for 2020 Model Year CITY

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ABSTRACT

A CVT has been developed for use in the 2020 model year CITY with the aim of realizing a good balance between fuel efficiency and power performance.

As new mechanisms, the developed CVT employs a belt with a modified rocking position, pulleys with multiple V-surface shapes, and mechanical and electric oil pump systems in series connection. The application of these technologies has made it possible to reduce the main sources of loss in a metal pushing V-belt CVT and to increase power transmission efficiency. When these new mechanisms were combined, CVT control was optimized in order to help ensure a reduction of loss in the CVT itself.

In addition, the driver's intention in accelerating the vehicle is realized by switching CVT control in order to help ensure that there is no decline in power performance, due to the application of control that optimizes fuel efficiency. By setting drive power as the target parameter for CVT shift control, it has been possible to help avoid decline in drive power. Furthermore, the application of stepped shift has meant that vehicle speed follows engine speed linearly, and vehicle occupants experience an increase in drive power.

As a result, the CVT has realized a reduction of 5.7 g/km in CO₂ emissions against the previous unit in the New European Driving Cycle mode. In addition, the 2020 model year CITY meets the 100 g/km or below CO₂ emissions standard for the second phase of Thailand's eco-car project.

1. Introduction

Today, countries throughout the world are increasing the stringency of their environmental regulations as a response to global environmental issues. This global trend is accelerating the transition toward electrification of automotive powertrains. However, in nations in which increasing the utilization of electric vehicles is not an easy matter, for example emerging nations, realizing increased fuel efficiency in conventional vehicles that use internal combustion engines as their sole source of drive power is an urgent matter. Against this background, the application of continuously variable transmissions (CVT) is increasing, given that they are a transmission type able to operate internal combustion engines in the zone of high thermal efficiency. In addition to Honda, automakers in Japan and overseas are applying CVT in a wide range of vehicle types, from light vehicles to small and medium-sized vehicles. Figure 1 shows a breakdown of loss in a metal pushing V-belt CVT in JC08 mode⁽¹⁾. As this figure indicates, loss

resulting from the metal pushing V-belt and the oil pump accounts for more than 60% of total loss. Given this, a variety of measures are being applied to the mechanical parts that are responsible for major loss. Measures including

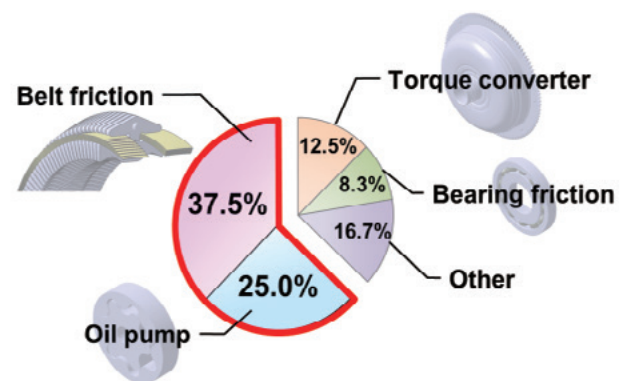


Fig. 1 Breakdown of power consumed in CVT

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the use of CVT provided with starting gears⁽²⁾ are being employed as a response to belt loss. Measures employed to respond to oil pump loss include the application of coaxial two-port oil pump systems⁽³⁾. As this indicates, while CVTs offer good automotive fuel efficiency performance, there remains considerable margin for increasing their power transmission efficiency as transmission systems.

The development discussed in this paper set out to reduce the major losses in metal pushing V-belt CVTs in order to comply with various national environmental regulations, in particular the regulations associated with the second phase of Thailand's eco-car project (Eco2). In addition, the goal for the new CITY was to balance a level of fuel efficiency producing CO₂ emissions of 100 g/km or less in the New European Driving Cycle (NEDC) mode with good power performance.

2. Development Aims

In a metal pushing V-belt CVT (Fig. 2), the belt is sandwiched between a fixed pulley and a movable pulley, and friction force transmits power from the primary (drive) pulley to the secondary (driven) pulley. Because the position of the movable pulley can be changed steplessly on the drive side and the driven side using hydraulic thrust,

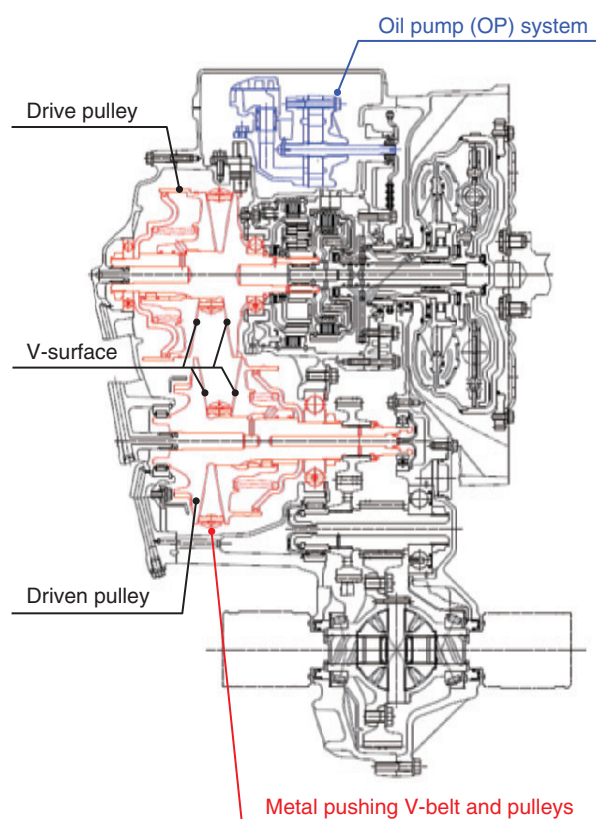


Fig. 2 Main sections of new CVT

the position of the belt wound around the pulleys can also be changed steplessly, making it possible to realize stepless shift. The ability to steplessly select the pulley ratio makes it possible to maintain the zone of high thermal efficiency in an internal combustion engine. As a result, the application of this transmission type is expanding as it increases automotive fuel efficiency.

Due to the component configuration of metal pushing V-belts, there are numerous slipping sections, and as a result, loss occurs in the interior of the belt, which is dependent on the winding diameter of the pulleys⁽⁴⁾. A single oil pump responds to the differing hydraulic oil conditions demanded by components, including the pulleys, the torque converter, and the clutch, in addition to demands for lubrication. Because of this, there is a constant demand for high-pressure and high-flow-rate work from the oil pump, and oil pump loss increases as a result⁽⁵⁾. The belt and the pulleys transmit power via friction, and this necessitates a high clamping pressure on the pulleys. This high level of force affects loss in the metal pushing V-belt, which has a large number of slipping sections, as a slipping load. In addition, oil pump work increases in proportion to the level of clamping pressure on the pulleys, and this increases loss. In order to increase fuel efficiency, the engine employed in the new CITY has been changed from the previous 1.5 L naturally aspirated unit to a 1.0 L turbocharger-equipped unit. To respond to the change in the output characteristic due to this change in the internal combustion engine, cooperative powertrain control (G-design shift) that sets drive power as a target value has been applied.

Based on the above, the following three points were set as the orientation for reduction of loss.

- (1) Reduction in friction loss originating in slipping in the interior of the metal pushing V-belt.
- (2) Optimization of the oil pump work necessary for the CVT by means of dividing work between hydraulic pressure and oil flow rate.
- (3) Optimization of CVT control in order to realize reduction of loss without a reduction in power performance.

3. Applied Technologies

A new belt and pulley assembly and a new oil pump system (Fig. 2) were applied in order to reduce the main losses in the metal pushing V-belt CVT.

3.1. Belt and Pulley Assembly

A metal pushing V-belt is made up of elements and rings. When the belt is wound between the pulleys, a geometric difference between the radius of rotation of the elements and the ring within the pulleys is generated. Because the elements and the ring do not mutually constrain each other, this difference in the radius of rotation generates a difference in rotational speed within the interior of the metal pushing V-belt. Due to slipping as a result of

this difference in rotational speed, the elements and ring generate friction loss in the interior of the belt. Friction loss per unit of time is given by the product of the coefficient of friction of the slipping sections, the vertical load generated on the slipping sections, and the relative speed. Based on this loss relationship, friction loss was reduced by reducing the slipping distance and load of the slipping sections. Table 1 shows the main specifications of the belt and pulleys employed in the new CVT. The reduction of these friction losses made it possible to increase power transmission efficiency by 0.9% in relation to the average pulley ratio range⁽⁴⁾.

3.1.1. Change in rocking position

Metal pushing V-belts transmit power by means of the action of the elements pushing against each other. By reducing the size of the elements at the position at which they push against each other (rocking position) and the difference in the radius of rotation between the elements and the rings within the pulleys, it was possible to reduce the slipping distance by means of the mutual difference in rotational speed. The slipping distance of the slipping sections of the belt is proportional to the difference in radius.

As shown in Table 1 and Fig. 3, the reduction of the size of the elements at the rocking position from 1.00 mm to 0.55 mm made it possible to geometrically reduce the amount of slipping by 45%.

3.1.2. Multiple V-surface pulleys

CVTs determine the pulley ratio in response to the transmitted torque while varying the clamping pressure on the pulleys in accordance with the operating status of the vehicle. The relationship between the clamping pressure on the drive and the driven pulleys also changes each time this happens. By narrowing the angle of the smaller-diameter side of the pulley V-surfaces at this time, it is possible to reduce the pulley clamping pressure necessary for the transmission of torque. This makes it possible to reduce the load on the slipping sections of the metal pushing V-belt.

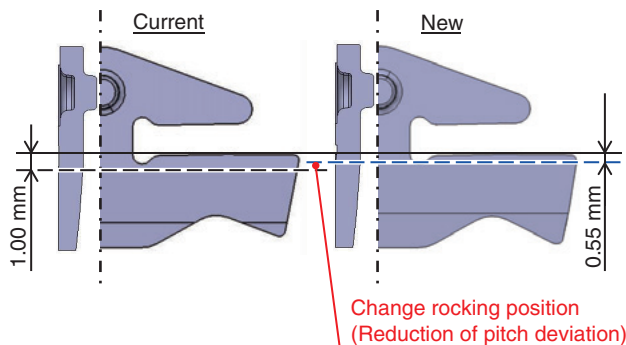


Fig. 3 Comparison of current and new elements

Table 1 Specifications of pulley and belt

Item		Current model	New model
Pulley	Distance between pulley axes	156 mm	156 mm
	V-surface	Single angle 11 deg	Multiple angle 9 deg / Round
Belt	Element width	24 mm	24 mm
	Rocking position	1.00 mm	0.55 mm
	V-surface	Single angle	Multiple angle
		11 deg	9 deg / Grooved
			Curved / No groove
	#1 ring diameter	208.8 mm	208.8 mm

Conversely, by increasing the angle of the larger-diameter side of the pulleys, it is possible to reduce the pulley clamping pressure that determines the pulley ratio. As a result, the maximum system hydraulic pressure necessary for the CVT (P_H) can be reduced. In the development under discussion, these characteristics were made use of in order to realize a multiple V-surface shape for the pulleys. The V-surface shapes of the elements were formed into a composite shape the same as the shape employed in the pulleys to help ensure the stability of power transmission when the pulleys are changed (Fig. 4). Because reducing P_H also makes it possible to reduce oil pump work, this contributes to the reduction of oil pump loss.

3.2. Mechanical and Electric Oil Pump Systems in Series Connection

Oil pump work is determined by the product of the hydraulic pressure and the oil flow rate demanded to generate the necessary drive force. Unlike other automatic transmissions, two types of work are necessary for a CVT. In addition to the low-pressure, high-flow-rate necessary for the torque converter and lubrication, high-pressure, low-flow-rate is also necessary for belt-clamping pressure and the connection of the clutch. Because of this, it is necessary

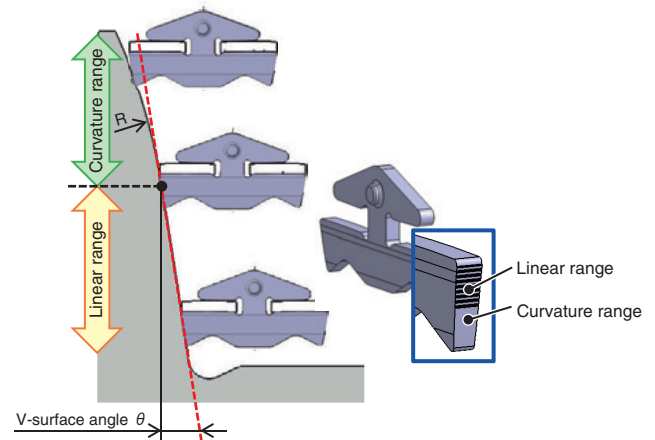


Fig. 4 Pattern diagram of pulley and belt

to realize the high pressure necessary for belt-clamping pressure and the high flow rate that makes it possible to maintain the state of lubrication using a single oil pump. Work is therefore demanded from the oil pump within the greatest scope that realizes both of these demands, and as a result oil pump work in the high-pressure, high-flow-rate zone becomes oil pump loss (Fig. 5).

However, the work of mechanical oil pumps (mechanical OP) depends on engine speed. In order to optimize oil pump work, it is necessary to employ a drive system that is independent of engine speed, making it possible to realize efficient rotation under a variety of operating conditions. An electric oil pump (electric OP) was therefore employed in addition to the mechanical OP⁽⁵⁾. The use of two different oil pumps has made it possible to divide the two types of work and reduce oil pump loss. In configuring the oil pump system, it was decided to employ a hydraulic circuit that would not hinder operation even if the electric OP malfunctioned (Fig. 6). The use of two oil pumps in a series configuration helps to ensure that the reference hydraulic pressure is constantly provided by the mechanical OP. The electric OP provides

high pressure and a low flow rate by increasing the pressure of the oil sent from the mechanical OP.

As a result, there is no necessity for the oil pump system to produce high pressure and a high flow rate, thus making it possible to reduce loss. In addition, because the drive system is motor driven and therefore does not depend on engine speed, the amount of oil pump work can be freely determined, making it possible to optimize oil pump work (Fig. 7).

The size of the motor that drives the electric OP was determined with consideration of the work of the alternating current generator (ACG) necessary for the reduction of oil pump loss. In the developed CVT, fuel efficiency was prioritized, and a 100 W motor was selected based on the amount of work necessary for the transmission employed in the CITY (Fig. 8). The main specifications of the oil pump system that was applied are shown in Table 2. The application of these technologies increased power transmission efficiency by 0.7% in relation to the average pulley ratio range.

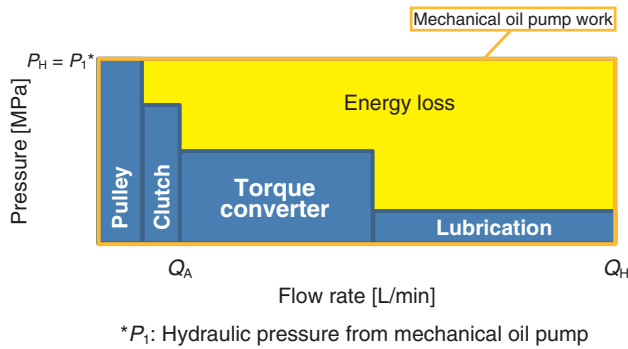


Fig. 5 Oil pump work in CVT

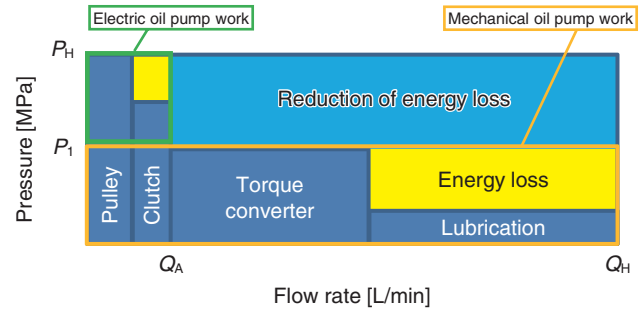


Fig. 7 New oil pump system for CVT

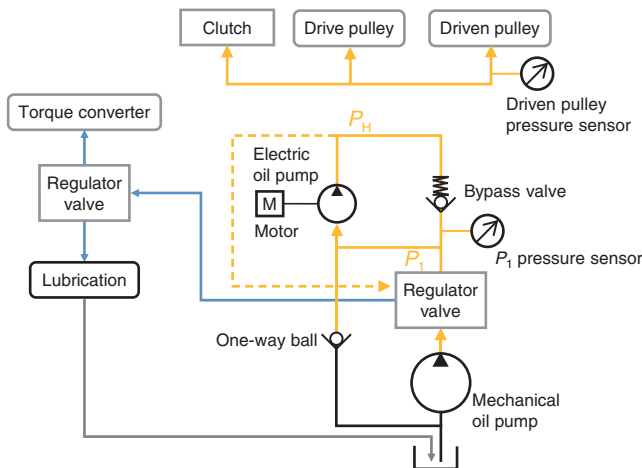


Fig. 6 Hydraulic circuit

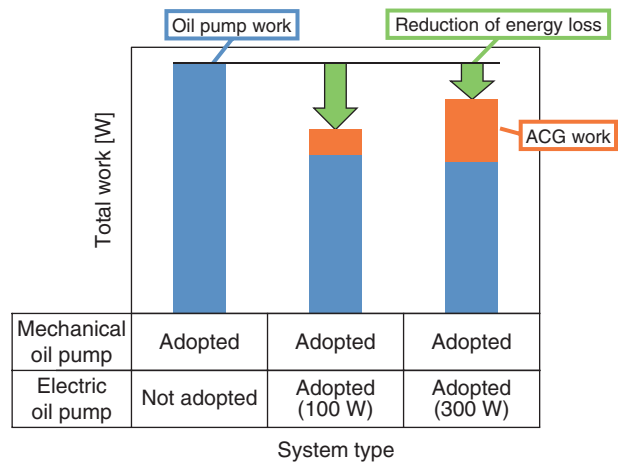


Fig. 8 Effect of reduction of energy loss

Table 2 Specifications of new oil pump system

Item		Current model	New model
Drive system	Mechanical	Adopted	Adopted
	Flow rate	Up to 72 L/min	Up to 72 L/min
	Discharge pressure	0.2 - 4.9 MPa	0.2 - 4.9 MPa
	Electrical	Not adopted	Adopted (100 W)
	Flow rate	—	Up to 5.8 L/min
	Discharge pressure	—	0.2 - 1.8 MPa

4. CVT Control

The developed CVT employs new technologies in two mechanisms: the belt and pulley system and the oil pump system. In addition to these technologies, other constituent components were redesigned in order to reduce loss. In relation to each of the loss reduction results achieved in this development, CVT control was optimized in order to realize power transmission efficiency in the unit as a CVT. In addition, the application of G-design shift in order to balance fuel efficiency with power performance made it possible to realize a linear acceleration feel.

4.1. Fuel Efficiency

The pulleys employed in the CVT are at once rotating bodies and hydraulic mechanisms. The drive and driven pulley shafts are connected by the metal pushing V-belt, and a mutual pulling force acts between the two shafts. As a result, a high load is applied to the bearings. In addition, the movable pulley is provided with a hydraulic chamber, and the metal pushing V-belt is sandwiched between the pulleys by hydraulic pressure supplied by the oil pump. In other words, at the same time as the oil pump work changes due to the necessary pulley clamping pressure, the load on the bearings and other components also changes. In the newly applied belt and pulley system and oil pump system, an electric OP was employed with the aim of boosting the pulley clamping pressure. Because electric OP drive consumes power, drive control that maintains efficiency in relation to the status of vehicle operation has been applied. The use of a multiple V-surface shape in the belt and pulley system has reduced the necessary pulley clamping pressure (i.e., the maximum hydraulic pressure, P_H). The reduction of the belt clamping pressure has had the effect of reducing friction loss between the belt and the pulleys. The adoption of mechanical and electric oil pump systems in series connection have made it possible to support high-pressure, low-flow-rate work via the electric OP. In other words, the higher the maximum hydraulic pressure, P_H ,

in the system, the greater the effect in loss reduction.

Based on consideration of the differences between the loss reduction methods employed in each of these mechanisms, the aim was to drive the system more efficiently as a CVT. The fact that the operation of the electric OP could be stopped in accordance with vehicle operating conditions made it possible to control power consumption. Utilization of the advantages provided by these choices of mechanism was reflected in CVT control.

Figure 9 shows the operation of the oil pump system during actual vehicle operation, in addition to power transmission efficiency and the effect of each mechanism in reducing loss.

(1) Idle stop (When the vehicle is stopped)

When the vehicle is idling, there is no change in fuel efficiency even if some engine power is used for the mechanical OP drive. The electric OP therefore does not operate as was previously the case. In addition, an idle stop system has been employed in the new CITY based on considerations of fuel efficiency. When the idle stop system is in operation, the electric OP is driven in order to compensate for the delay in the recovery of pulley clamping pressure when the engine is restarted. Driving the electric OP results in work for the ACG, but makes it possible to control fuel consumption when the vehicle is idling.

(2) Vehicle take-off

When the vehicle takes off, the torque converter amplifies torque, and the necessary pulley clamping pressure increases. In addition, when shifting from a low pulley ratio, the oil flow rate associated with shift is demanded. The electric OP realizes the flow rate for shift while also increasing pulley-clamping pressure, P_H , making it possible for the mechanical OP to reduce the hydraulic pressure generated to the level of lubrication pressure. As a result, it is possible to apportion oil pump work and realize a considerable reduction in drive loss in the oil pump system.

(3) Acceleration from take-off

For acceleration from take-off, drive force is reduced while the vehicle speed is increased. At this time, the pulley ratio is gradually shifted to the high side. In other words, both the transmitted power and the speed of shift are lower than when the vehicle takes off. In addition, the use of multiple V-surface pulleys made it possible to reduce the necessary clamping pressure, P_H , for the pulleys. It is therefore possible to maintain the work of the mechanical OP at lubrication pressure by increasing the drive speed of the electric OP. As a result, the increased work of the oil pump system only represents an increase in electric OP drive speed, and it is possible to maintain an effect of reduction in loss equivalent to that at vehicle take-off.

(4) Cruise

When the vehicle is cruising, the pulley ratio

is constantly maintained on the high side. High pulley ratios represent a zone in which the power transmission efficiency of the multiple V-surface pulleys and the belt with its change in rocking position are high, and this contributes greatly to increased fuel efficiency. In addition, because it is possible to reduce the necessary pulley-clamping pressure, P_H , and it is not necessary to change the oil flow rate for shift, it is also possible to control the electric OP drive speed. As a result, it is possible to realize loss reduction in both the belt and pulley system and the oil pump system. In addition, there has been a major effect in comprehensively reducing friction loss in a variety of components, such as the bearings. At this time, if it is judged that there is no loss reduction effect with consideration of electric OP drive power in relation to the total work of the oil pump system, the electric OP is not activated.

(5) Re-acceleration from cruise

When the vehicle re-accelerates after cruising, a low pulley ratio is employed in order to help ensure drive force. The necessary pulley-clamping pressure, P_H , increases as a result of the shift to a low pulley ratio. Because the amount of shift is small at this time, the necessary oil flow rate is also small. By using the electric OP to respond to the increased work of the oil pump system, it has been possible to reduce the work of

the mechanical OP, thus reducing drive loss in the oil pump system.

(6) Deceleration

When the vehicle brakes, fuel injection in the engine is stopped. Because no fuel is being consumed, the operation of the electric OP also stops. Although no fuel is being consumed, the effect of increased power transmission efficiency in the belt and pulley system and other components makes it possible to considerably reduce drag loss in the transmission.

As this indicates, it has been possible to implement CVT control that makes it possible to adequately utilize the loss reduction effect in increasing fuel efficiency.

4.2. Drive Power Design

In addition to the application of the new transmission, numerous modifications have been made to the new CITY in order to increase fuel efficiency. The engine employed in the vehicle has been changed from a naturally aspirated 1.5 L unit to a 1.0 L turbocharger-equipped unit in order to realize an internal combustion engine with increased fuel efficiency. The reduction in displacement has allowed fuel consumption to be controlled, while the use of a turbocharger has made it possible to maintain the previous level of maximum power. However, at times such as vehicle take-off, the engine maintains the characteristics of a naturally

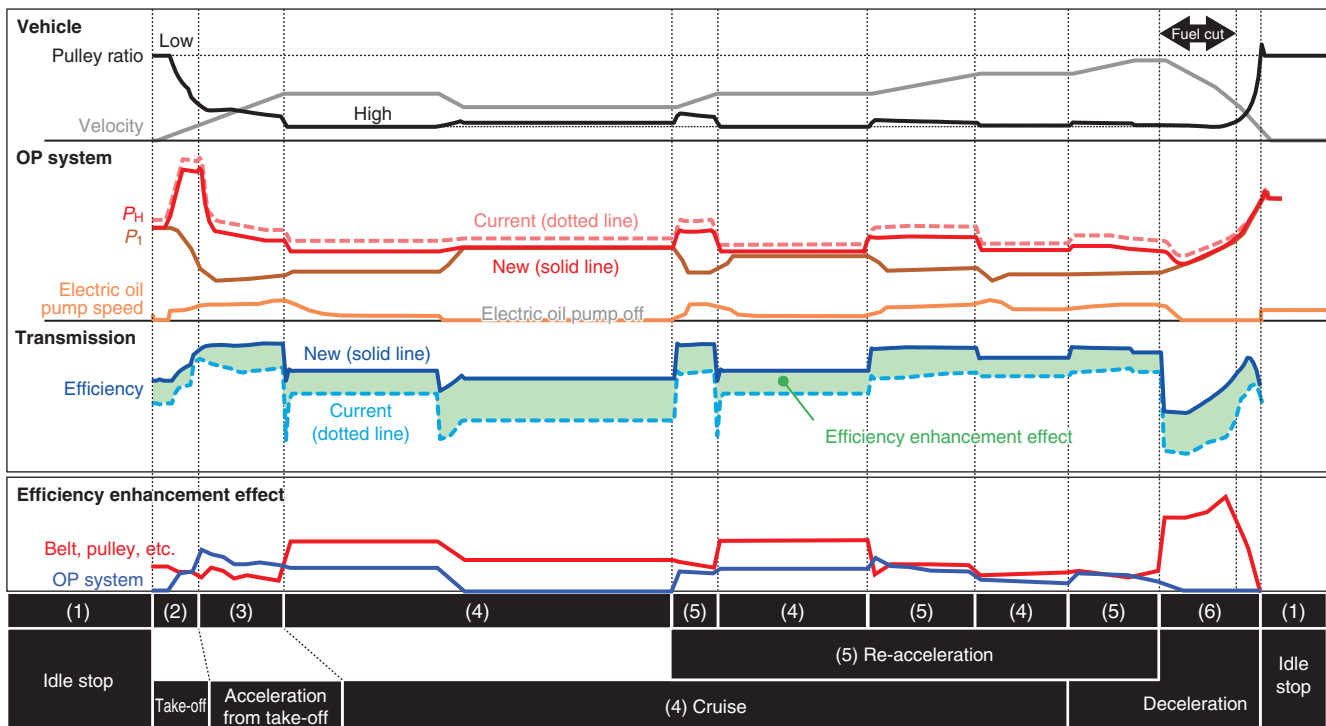


Fig. 9 Operation of new CVT

aspirated 1.0 L unit until the turbocharger commences operation. In other words, it takes a considerable amount of time until maximum output is realized. In response to this, the CVT balances fuel efficiency and power performance by switching shift control based on the driver's intention to accelerate. Determining the pulley ratio in response to the target drive force in order to maintain the drive feel has made it possible to realize control with no drop in drive force. As a result, it has been possible to realize a linear acceleration feel, with vehicle occupants experiencing no differences in the engine power characteristic. In addition, when the accelerator is fully depressed, fully open step-shift control that shifts like a stepped transmission is employed. As a result, vehicle speed linearly follows engine speed, and vehicle occupants experience an increase in drive power. Figure 10 shows a comparison of data measured during take-off and acceleration with the previous model. After the maximum drive power is generated, the target value is followed to help ensure that drive power does not fall, giving the new CITY a good drive feel.

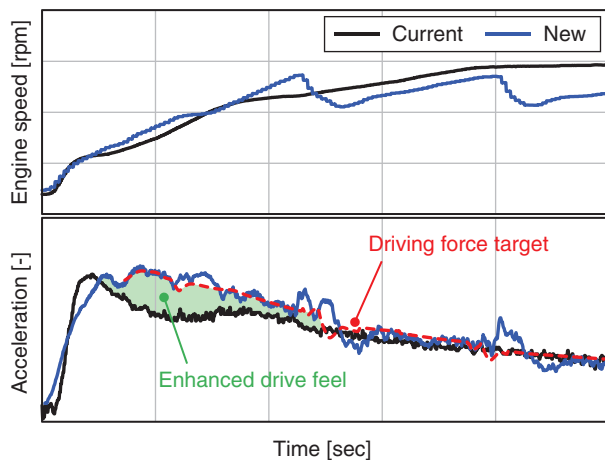


Fig. 10 Step-shift operation

5. Fuel Efficiency and Power Performance

The 2020 model year CITY in which the developed CVT is employed realizes CO₂ emissions of 100 g/km or less in NEDC mode. The reduction of loss in the CVT reduced CO₂ emissions by 5.7 g/km. In addition, as shown in Fig. 11, considerable increases in fuel consumption performance and power performance have been realized compared with the previous model.

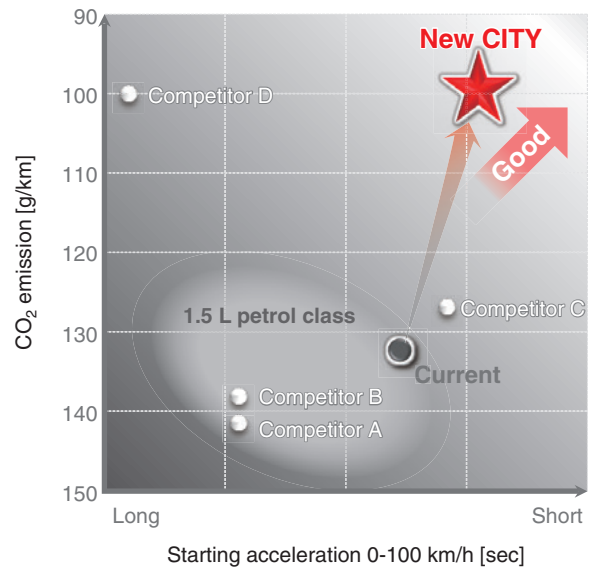


Fig. 11 Performance of new CITY

6. Conclusion

A high-efficiency CVT has been developed as the transmission for the 2020 model year CITY. The application of the developed CVT, which employs new technologies and a new control system, has balanced fuel efficiency and power performance. The CVT has reduced CO₂ emissions by 5.7 g/km compared with the previous model. In addition, the new CVT meets the Eco2 CO₂ emissions standard of 100 g/km or below.

- (1) As new technologies, a belt with changed rocking positions and pulleys employing multiple V-surface shapes were employed. In addition, mechanical and electric oil pump systems in series connection were employed. As a result, power transmission efficiency has been increased by 0.9% in the belt and pulley system and 0.7% in the oil pump system in relation to the average pulley ratio range.
- (2) In adopting the two new technologies described above, CVT control was optimized in order to make it possible to fully take advantage of the loss reduction effect.
- (3) Shift control that employs drive power as a target was applied in order to maintain the vehicle's drive feel while optimizing CVT control for fuel efficiency. In addition, the adoption of stepped shift has meant that vehicle speed follows engine speed linearly, and vehicle occupants experience an increase in drive power.

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Small Size Power Control Unit for 2020 Model Year FIT

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ABSTRACT

Honda has developed a third-generation power control unit for compact cars for the 2020 model year FIT.

Downsizing was achieved by employing RC-IGBTs in the power semiconductors used in the power module, which is the main component of the power control unit. This reduced the longitudinal length by 12%. The control boards that were divided into a motor ECU (control board) and a gate driver (drive circuit board) in the second-generation unit were integrated to reduce the wire harnesses that connect each board, achieving further downsizing. The capacitance of the capacitor was reduced by 50% by enhancing the current followability of voltage control unit control. The application of these technologies realized development of a PCU with output power up to 267 kVA that achieves a volume of 8.5 L even with the 12 V DC-DC converter incorporated into the PCU, which enables mounting in a compact car.

1. Introduction

Global warming and air pollution due to CO₂ emissions while driving continue to be issues associated with the spread of automobiles.

One means of addressing these issues is the electrification of automobiles to reduce exhaust gas. In 2013, Honda developed a two-motor hybrid system named the SPORT HYBRID Intelligent Multi-Mode Drive (i-MMD) system⁽¹⁾. The i-MMD system realizes the three drive modes of EV drive mode, which drives the vehicle by the motor mainly using electric power supplied from a high-voltage battery; Hybrid drive mode, which drives the vehicle by the motor using electric power supplied from the engine operating as a generator; and Engine drive mode. The power train consists of an engine, an electric coupled Continuously Variable Transmission (CVT) incorporating traction and generator motors, a Power Control Unit (PCU), and an Intelligent Power Unit (IPU).

The PCU functions to convert the electric power from the high-voltage battery, traction motor, and generator motor, and influences the motor output power and fuel

economy. The first-generation two-motor hybrid (GEN1) PCU was mounted on a frame fixed to the body inside the engine compartment.

A second-generation two-motor hybrid (GEN2) PCU was developed in 2016 to enhance ease of installation inside the engine compartment and support higher power density⁽²⁾. This GEN2 PCU was mounted directly on the transmission to achieve a compact layout within the engine compartment. This made it possible to mount a 12 V battery inside the engine compartment of various vehicles, thereby contributing to expanded cabin space.

A third-generation two-motor hybrid (GEN3) PCU was developed in 2018. This GEN3 PCU incorporated the 12 V DC-DC converter, which was built into the IPU mounted in the rear of the vehicle for the GEN2 PCU, into the PCU mounted in the engine compartment⁽³⁾.

Vehicles equipped with Honda's i-MMD system have conventionally been medium- and large-sized vehicles such as sedans and SUVs. In order to further expand electrification, Honda pursued development with the goal of mounting in compact models such as the FIT (Fig. 1). Honda also set vehicle development targets for compact

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² Honda Motor Co., Ltd.

³ Keihin Corporation

cars based on its original “Man Maximum, Machine Minimum” philosophy that seeks to maximize the space used by humans, and incorporated the 12 V DC-DC converter, which was built into the IPU mounted in the rear of the vehicle in the GEN2, into the PCU mounted in the engine compartment. Compact cars have little available mounting volume inside the engine compartment as shown in Fig. 2, so the GEN2 system could not be mounted as is.

This called for an even smaller third-generation two-motor hybrid (GEN3S) PCU for compact cars⁽⁴⁾.

The development target was set as a configuration that reduces the longitudinal length by 10% and achieves a mounting volume of 8.6 L while incorporating the 12 V DC-DC converter.

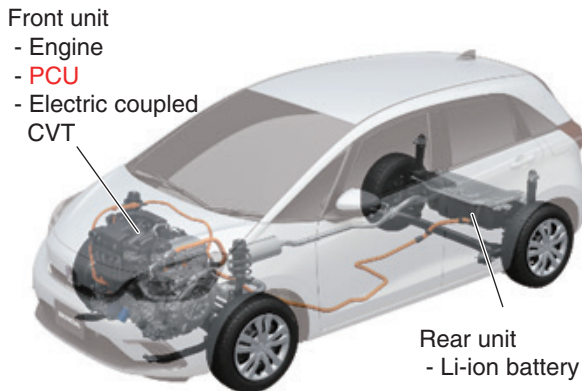


Fig. 1 Position of PCU in SPORT HYBRID i-MMD

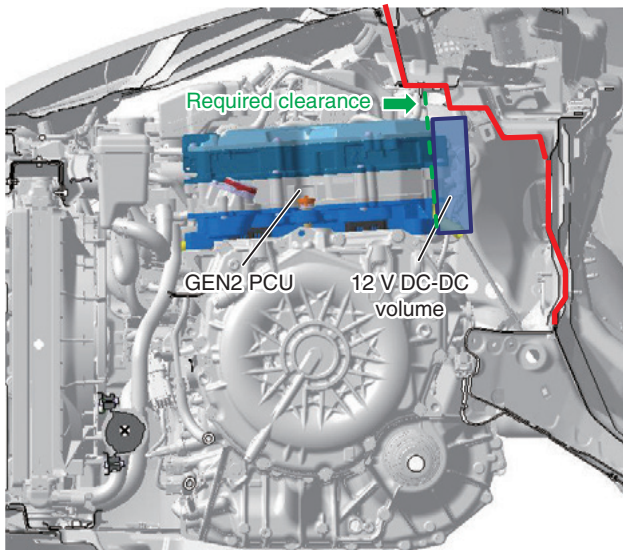


Fig. 2 Layout of PCU in SPORT HYBRID i-MMD

Table 1 Comparison of GEN2 and GEN3S specifications

Item	GEN2	GEN3S
Maximum total output power [kVA]	388	267
Maximum boost voltage [V]	700	570
Motor maximum output current [Arms]	320	270
Generator maximum output current [Arms]	155	155
DC-DC converter output voltage [V]	-	12
DC-DC converter maximum output current [Arms]	-	140
Volume [L]	8.9	8.5
Weight [kg]	14.3	13.4

2. Introduction of Small-size PCU for FIT

Figure 3 shows the PCU components.

The main component of the GEN3S PCU is an Intelligent Power Module (IPM) consisting of two inverters that drive the motors, a VCU that controls to the optimal voltages, and a control board (ECU) that performs integrated control of those parts. The IPM layout arranges the traction motor, generator motor, and VCU power semiconductors over the entire top surface of the water jacket, with the control board placed directly on top of those parts. A voltage smoothing capacitor, an inductor (booster circuit part), and a current sensor for detecting energizing current are also provided, and a 3-phase connector for direct connection with the motor built into the transmission is located close to the side surface. Also, the above-mentioned 12 V DC-DC converter is incorporated into the PCU.

As the goal is mounting in compact cars, the available mounting space in the vehicle is narrower than before. In addition, Table 1 shows that the demanded output power is less than that for GEN2.

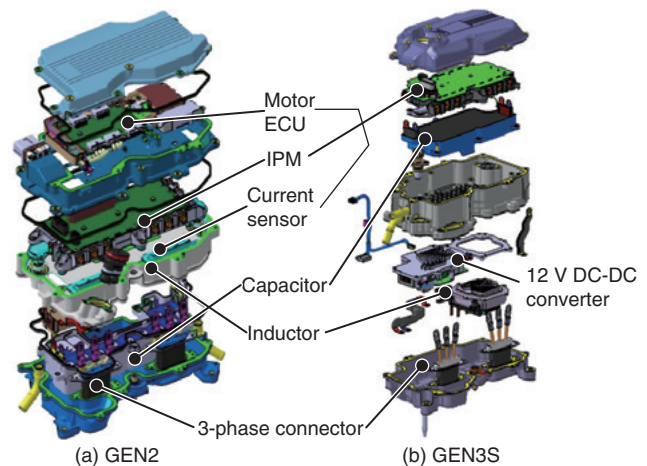


Fig. 3 Exploded view of GEN2 and GEN3S PCUs

The internal parts can be downsized in accordance with the demanded specifications, but further size reduction is needed for each part in order to newly incorporate the above-mentioned 12 V DC-DC converter. Therefore, the increase in parts incorporated into the PCU was supported by integrating components to reduce the number of parts. As a result, the longitudinal dimension was reduced by 12% and, even incorporating the 12 V DC-DC converter, the volume was reduced by 4.4% compared to the GEN2, which achieved the targets (Fig. 4).

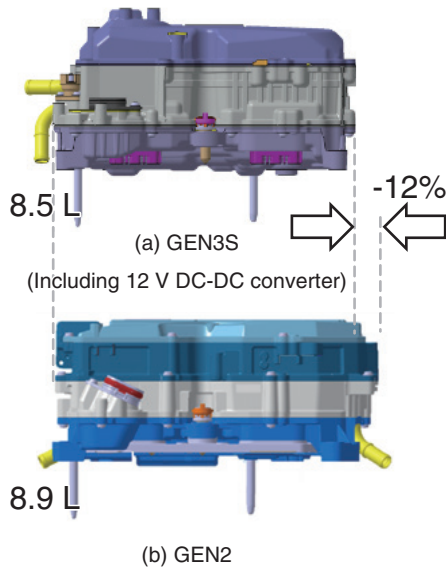


Fig. 4 Comparison of GEN2 and GEN3S sizes

3. Main Technologies

PCU components with a large space factor include the power module (PM), capacitor, control board, and the wire harnesses used to transmit the various signals.

The PM has semiconductors arranged in a plane, so, including the housing that comprises the circuit, this determines the longitudinal length of the PCU. In addition, the capacitor accounts for a large portion of the volume of the PCU lower part in the GEN2, so this volume was reduced in order to incorporate the 12 V DC-DC converter.

Furthermore, the control boards were divided in the GEN2, so these elements including the wire harnesses were reduced and parts were integrated to downsize the PCU.

The main technical developments are the following three points:

- (1) Adoption of reverse-conducting insulated gate bipolar transistors (RC-IGBTs) as the semiconductors mounted in the PM;
- (2) Integration of the control boards; and
- (3) Reduction of the capacitor capacitance.

3.1. Power Module Downsizing

High output power has been demanded of traction motors for hybrid systems, so IGBTs and diodes have been used as the silicon power semiconductors that function as the drive switching elements. The size of the PM in which these semiconductors are mounted determines the length of the PCU, so RC-IGBTs were adopted in the GEN3S PCU.

Figure 5 shows an overview of the RC-IGBT structure.

Conventional inverters for vehicles mount the IGBT and diode separately, with the temperature sensor that measures the semiconductor temperature mounted over only the IGBT.

The newly developed RC-IGBT is a new semiconductor device that has both IGBT and diode areas within the same semiconductor as shown in Fig. 5 (b). This enables the IGBT to also operate as a diode. By providing IGBT and diode areas within the same semiconductor, the breakdown voltage holding areas (guard ring) for each of the conventional IGBT and diode semiconductors can be shared, which reduced the semiconductor size.

In addition, the conventional configuration had a temperature sensor for overheat protection on the IGBT side but not on the diode side, so overheat protection for the diode was performed by estimating the temperature from the temperature sensor on the IGBT side. This method, however, has large estimation deviation compared to direct measurement of the semiconductor temperature using a temperature sensor. This made it necessary to limit the operating temperature range in consideration of this deviation relative to the upper limit operating temperature of the semiconductor, which called for a larger diode size than necessary. Use of an RC-IGBT extended temperature protection using the mounted temperature sensor to the diode area, which allowed reduction of diode size to the least size needed.

Figure 6 shows the effects. Sharing the guard ring needed by each semiconductor reduced the guard ring area by 33% and the diode area was also reduced by 64%, achieving a 30% reduction in the overall semiconductor area. This reduced the longitudinal length of the PM by 12%, which contributed to downsizing the PCU.

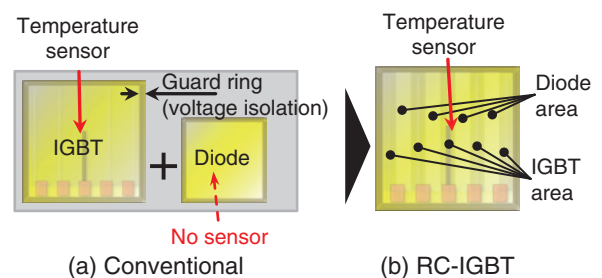


Fig. 5 Comparison of conventional chips and RC-IGBT chip structures

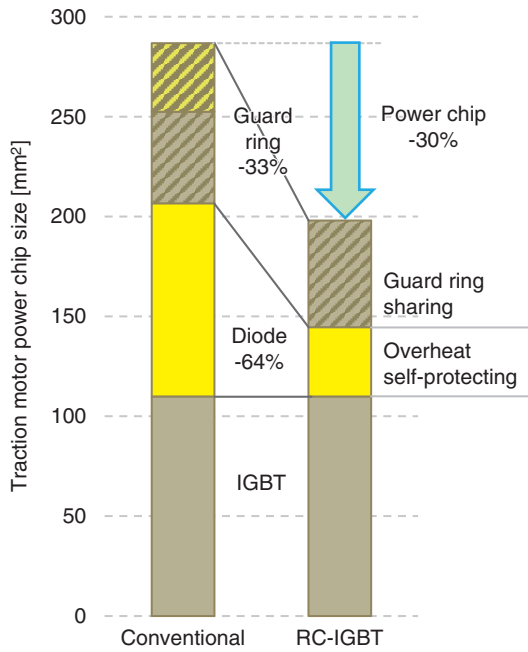


Fig. 6 Comparison of conventional and RC-IGBT semiconductor areas

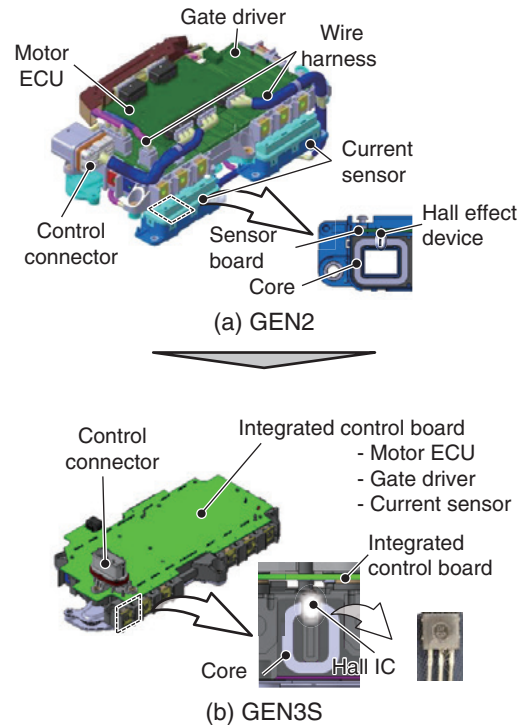


Fig. 7 Comparison of GEN2 and GEN3S circuit structures

3.2. Downsizing through Integration of Control Boards

The IPM sends commands from the motor ECU to the gate driver, and the VCU, motors, and generator inverter are driven according to those commands. In addition, current and voltage sensors for control are also connected to the IPM. In the GEN2 PCU, these parts were mounted on separate boards and connected to the motor ECU via wire harnesses. Connection with an external ECU consisted of connection to the PCU via a control connector, and then connection with the boards inside the PCU via wire harnesses. Figure 7 shows a comparison with the conventional structure.

When developing the GEN3S PCU, these parts were integrated to reduce the PCU volume.

The connector that receives external commands was mounted directly on the board to reduce the wire harnesses. This connector is connected to the integrated control board by signal pins.

The motor ECU and the gate driver were combined into an integrated control board. This board was achieved through such advances in circuit mounting technology as higher density compared to the conventional gate driver, and use of a single-package voltage sensor circuit. The previously divided motor ECU and gate driver boards were also integrated and mounted on the PM.

In addition, the conventional current sensor consisted of a magnetic flux core, a Hall element for measuring magnetic flux, and a board that controls these parts. However, this current sensor function is realized by the combination of

a magnetic flux core built into the PM case and a Hall IC mounted on the integrated control board. The structure has seven sensors as before, and was realized by the precision of collective assembly and development of technology for correcting the sensors post-assembly. This reduced the height by 50% (Fig. 8).

3.3. Reduction of Capacitor Capacitance

While the capacitor accounted for half of the overall height in the GEN2 PCU, enhancement of VCU control technology enabled a 50% reduction of capacitance. Thermal issues associated with capacitance reduction were addressed by modifying the cooling channel.

The capacitor functions as the VCU voltage source. It is

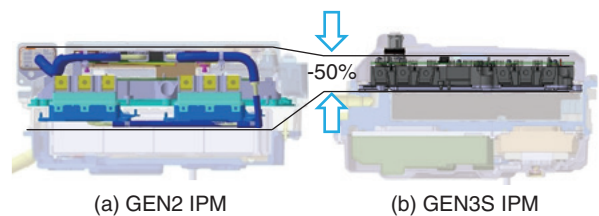


Fig. 8 Comparison of GEN2 and GEN3S IPM structures

not an ideal power source, however, and when the inductor current fluctuates, the voltage also fluctuates due to the influence of the internal impedance. This voltage fluctuation influences the control, with the result that the current fluctuation increases. The voltage fluctuation width is specified to help prevent an increase in the inductor current fluctuation, and a capacitor with a large capacitance was used in the GEN2 PCU to smooth the voltage.

To support the increase in voltage fluctuation, current control, cascade control of voltage control, a disturbance observer, a duty estimation calculator, and a duty cancel calculator were newly developed for VCU control. Use of these technologies suppressed the voltage resonance gain over a wide frequency range and reduced the AC component of the load current. This VCU control enabled capacitance reduction by 50% as shown in Fig. 9.

Reducing the capacitance of the capacitor, however, increases the internal impedance. This increases the self-heating value, but was addressed by modification of the cooling channel. The capacitor has a low heating value, so it is cooled by natural heat dissipation instead of water, and is susceptible to heat from the external environment. As the capacitor materials determine the heatproof temperature of the capacitor, the total of the temperature heated by the environment and the self-generated temperature due to energization, which are temperature rise factors, should be the heatproof temperature or less. Since the PCU is mounted in the engine compartment, it has a large temperature rise due to the environment.

In the structure used since the GEN2 i-MMD with the PCU mounted directly on the transmission, the capacitor was located below the IPM as shown in Fig. 10 (a), making it susceptible to transmission and engine heat. The GEN3S PCU uses a structure that surrounds the capacitor with a cooling channel as shown in Fig. 10 (b) to reduce the influence of this external environment heat.

In the GEN2 structure, cooling water entered from the vehicle front side, passed through the PCU interior, and was discharged from the vehicle rear side. In contrast, the GEN3S collects the cooling water inlet and outlet on the

vehicle front side, which allowed reduction of the cooling pipes inside the engine compartment and helped to reduce the occupied engine room space.

The capacitor is not directly water-cooled, but is surrounded by the cooling channel, which helps to prevent external thermal influence. Figure 11 gives an overview of the reduction in capacitance.

Capacitor self-heating increased by two times or more, but the external thermal influence was reduced by 46%, so the upper temperature reached could be reduced to less than or equivalent to that of the conventional structure.

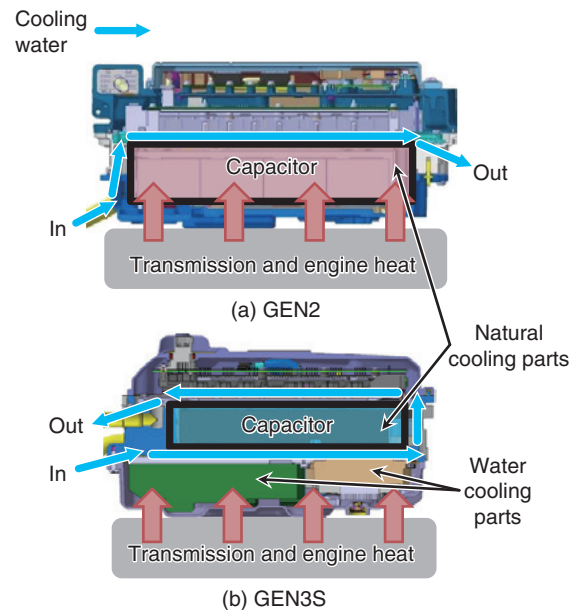


Fig. 10 Difference of capacitor structures

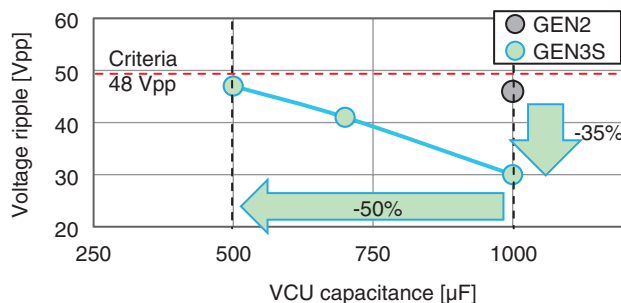


Fig. 9 Comparison of GEN2 and GEN3S VCU capacitance

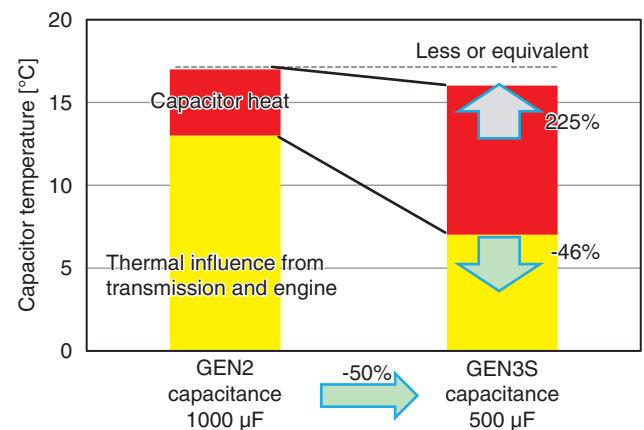


Fig. 11 Comparison of GEN2 and GEN3S capacitor temperatures

4. Conclusion

The following technical developments achieved the PCU downsizing targets with the goal of mounting the i-MMD system in a compact car.

- (1) Adoption of RC-IGBTs as the power semiconductors reduced the longitudinal PM length by 12%.
- (2) Integration of the control boards and current sensors reduced the IPM height by 50%.
- (3) Development of VCU control and adoption of a new cooling structure reduced the capacitance of the capacitor by 50%.

These technologies realized development of a PCU with output power up to 267 kVA that achieves a volume of 8.5 L even with the 12 V DC-DC converter incorporated into the PCU, thereby enabling mounting in a compact car.

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Development of One-piece Reverse Rim Aluminum Alloy Wheel Using Flowforming Process

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ABSTRACT

In an attempt to increase freedom of design in automobiles, a method of manufacturing aluminum wheels with a reverse rim configuration that realizes lower weight and lower cost has been developed. The configuration of the molds and the machining process for the rim in the GDC flowforming process were modified, and the machining method and machining conditions were optimized. This made one-piece manufacture of reverse rim wheels possible. CAE analysis verified that by converting wheels to reverse rim types, it would be possible to reduce the excessive thickness between the disk surface and the bead drop area of the wheel, reducing the weight of wheels of 18 inches or more in diameter by 5% or more. Next, a prototype of an 18-inch wheel was produced, and it was verified that its weight was reduced in accordance with CAE results. In addition, a prototype of a wheel employed in sports-type vehicles was produced, and it was verified that a weight reduction of 2% or more had been achieved despite the fact that the wheel had been designed to realize reduced weight.

1. Introduction

Aluminum wheels possessing a variety of designs are sold in large numbers by automobile accessory stores and the like as a product that boosts the exterior aesthetics of the vehicle⁽¹⁾. Seeking to customize their vehicles, many users increase (“inch-up”) the wheel size in order to boost freedom of design through the realization of increased diameter.

However, if the wheel is inched-up without changing the external diameter of the tire, the lateral force characteristic on the tire changes due to the tire’s flatness and high internal pressure, and vibration isolation performance also declines⁽²⁾. In addition, if the size of the wheel is increased by one inch, the weight of the wheel generally increases, and acceleration performance and fuel efficiency decline. The increased use of aluminum materials also increases materials costs.

The reverse rim wheel is one of the shapes employed in aluminum wheels. In the case of this wheel, the spokes can be made to appear longer by reversing the shape from the interior to the exterior of the rim and increasing the interior diameter of the exterior of the rim.

However, because it is necessary to manufacture

reverse rim wheels by first splitting and then rejoining the wheel and rim, they are heavier and more expensive than integrally molded aluminum wheels.

The authors therefore developed a method of integrally manufacturing reverse rim wheels by modifying the manufacturing method for mass-produced aluminum wheels.

Figure 1 shows a normal rim wheel and a reverse rim wheel of the same design. As the figure shows, reversing



Fig. 1 Appearance of normal rim wheel and reverse rim wheel

¹ Honda Motor Co., Ltd.

² KOSEI ALUMINUM Co., LTD.

the rim creates a design like an inch-up wheel. In addition, because it is possible to also reduce excessive thickness, despite the fact that the two wheels have the same design and are the same size, it has been possible to reduce the weight of the reverse rim wheel.

Below, the manufacturing method for reverse rim wheels will be introduced.

2. Overview of Reverse Rim Wheels

First, the structure of the wheel rims will be discussed. Figure 2 shows an external view of the machine that fits the tire to the wheel. Figure 3 shows the process of fitting of the tire, until the tire is mounted on the wheel.

In the process of fitting the tire, the wheel is first fixed to the rotary table of the tire changer machine, the tire is



Fig. 2 Tire changer machine

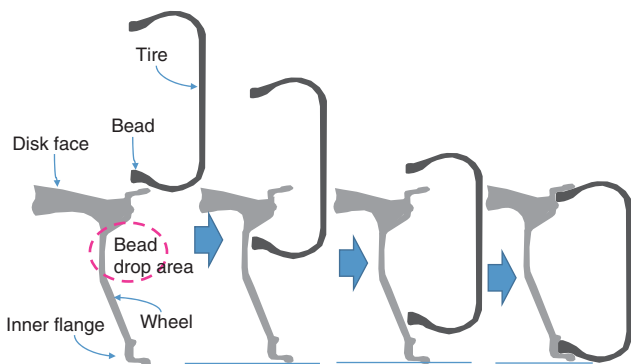


Fig. 3 Tire assembly procedure for normal rim wheel

positioned on it, and the work is performed. In order to allow passage for the tire bead, which is smaller than the external diameter of the wheel rim, a bead drop area with a narrower inner diameter is engineered into the wheel.

Wheels in which this bead drop area is positioned close to the disk surface are termed normal wheels. Wheels in which the bead drop area is positioned on the inner flange side, the side opposite to the disk surface, are termed reverse rim wheels. In the case of reverse rim wheels, the tire is fitted from the inner flange side, in the opposite fashion to normal wheels.

Figure 4 shows cross-sections of the structures of normal rim wheels and reverse rim wheels. In the case of (a), the normal rim wheel, the abovementioned bead drop area is positioned close to the disk that forms the design surface. This constricts the design section, and has an effect on freedom of design. By contrast, in the case of (b), the reverse rim wheel, by distancing the section of the rim with the lowest diameter from the disk, any effect on the design section is done away with, enabling the disk to appear larger.

However, because in reverse rim wheels an undercut is produced in the rim by the bead drop area, as shown in Fig. 4(b), the rims are manufactured by splitting parts into two or three and rejoining them by welding or bolting, which increases manufacturing costs.

It was therefore proposed to realize a manufacturing technology that would allow production of reverse rim wheels at the same cost as mass-produced normal rim wheels by modifying manufacturing equipment for mass-produced aluminum wheels to manufacture reverse rim wheels in a one-piece configuration.

In addition, as Fig. 5 shows, in a reverse rim wheel it is possible to reduce the excessive thickness between the disk surface and the bead drop area in a normal rim wheel.

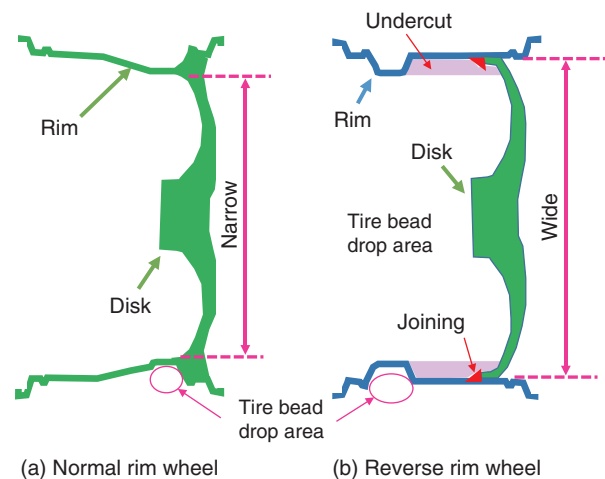


Fig. 4 Sectional view of normal rim wheel and reverse rim wheel

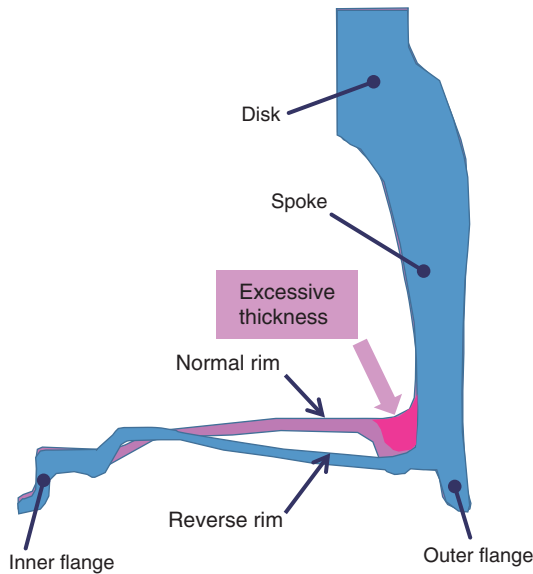


Fig. 5 Image of weight reduction

3. Manufacturing Method for Conventional Aluminum Wheels

The wheels are important parts that transmit input from the road surface to the vehicle body. The wheel and the tire make contact on both sides of the outer flange and the inner flange. Because the outer flange is close to the design surface, it displays a high level of stiffness. The stiffness of the inner flange, however, is low and load stress is therefore high, and because of this it is important to stabilize strength and quality.

The use of increasing wheel diameters in recent years has made the inner flange a section for which it is still more necessary to increase strength and toughness and give attention to quality management.

Aluminum wheels can be manufactured by both forging and casting processes. Forged parts are very strong, but their manufacture is high in cost. Because of this, casting is normally employed in the manufacture of aluminum wheels for mass-production vehicles.

There are two methods employed for this casting process: Low-pressure die cast (LPDC) and gravity die cast (GDC).

Figure 6 shows the LPDC manufacturing process. Because the inner flange, a part requiring strength, is distant from the gate through which the molten metal is introduced to the mold, the molten metal solidifies rapidly, producing fine grain sizes in the aluminum alloy, which increases strength.

Figure 7 shows the GDC manufacturing process. When employing GDC, casting can be performed using simpler equipment than LPDC, but because the molten metal is introduced from the inner flange, solidification is slow,

and the crystal grains increase in size. As a result, it is not possible to realize the same level of strength and toughness as LPDC⁽³⁾.

In the GDC manufacturing process, therefore, a flowforming machine is installed after the casting line. After the casting of the aluminum wheel material (preform), the material is again preheated, and the strength and toughness

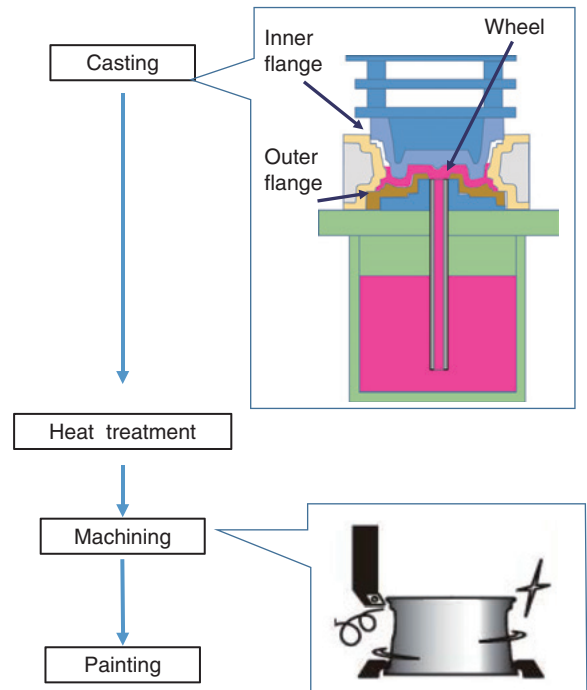


Fig. 6 LPDC production process

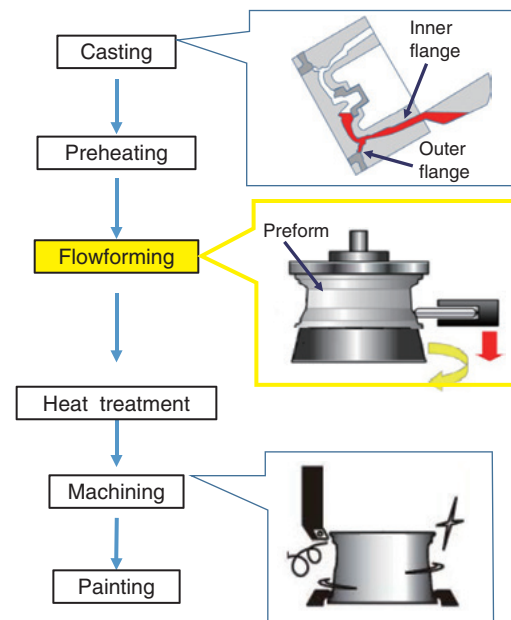


Fig. 7 GDC production process

of the inner flange are increased by deformation processing.

Figure 8 shows the flowforming manufacturing process. The preheated preform is molded by pressing the disk surface into the flowforming machine using the upper plate, fixing it in place, and rotating it using rollers that rotate from the exterior while pressing it against the mandrel. This process makes it possible to obtain the necessary strength and toughness in the inner flange.

In both manufacturing processes, following molding, a heat treatment is again applied, and machining and coating are performed in order to finish the product.

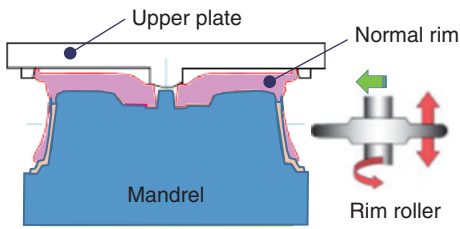


Fig. 8 Flowforming for normal rim wheel

4. Manufacturing Method for Reverse Rim Wheel

4.1. Rim Molding Method Using Flowforming

Because the reverse rim shape has an undercut section, the amount of machining increases when using LPDC, and the yield declines. In addition, in order to reduce cost increases, it is desirable to utilize standard equipment and processes without modification as much as possible.

The development discussed in this paper, therefore, selected GDC as the manufacturing method to mold the undercut section with a modification of part of the flowforming equipment and processes.

In order to mold a shape with a narrowed inner flange side on the same manufacturing line as conventional shapes, a method was considered in which a material that has the inner flange side open to the exterior is produced as usual at the casting stage, and a reverse taper is molded in the following stage using flowforming.

In conventional flowforming, because the section subject to ironing processing is constantly in contact with the mandrel, the center of the wheel does not deviate, enabling processing to be performed using a single roller on one side.

However, because in the case of a reverse rim wheel there is part of the section being processed that is not in contact with the mandrel, under a load from a single direction the rim becomes eccentric, hindering processing.

In order to reduce rim eccentricity during processing, a method employing two opposed rollers to apply a load to both sides simultaneously was proposed, as shown in Fig. 9.

Figure 10 shows the mandrel and rollers of the

prototype processing machine with the two opposed rollers positioned so as to be symmetrical in relation to the central axis of the mandrel.

Figure 11 shows the status of flowform processing using the prototype machine.

4.2. Setting of Optimum Processing Conditions

The control items for flowform processing conditions for mass-produced normal rim wheels include processing temperature and roller ironing conditions. In flowform

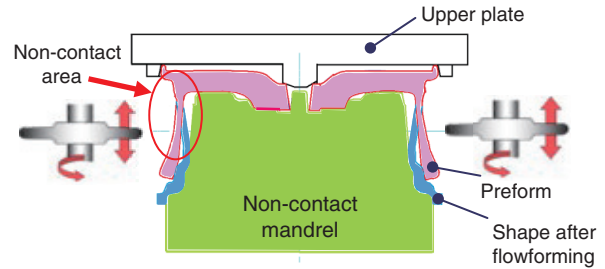


Fig. 9 Non-contact mandrel for reverse rim wheel

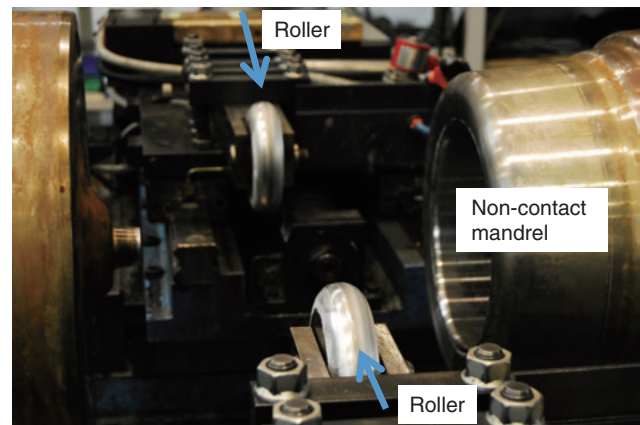


Fig. 10 Proposed test machine for flowforming

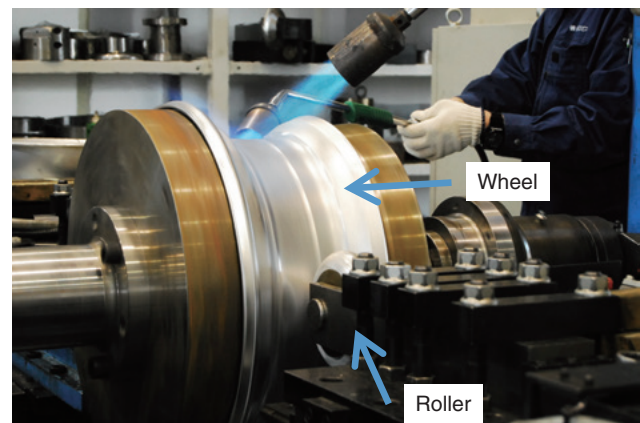


Fig. 11 Flowforming trial using two rollers

processing, costs can be reduced by using enormous loads during molding to reduce the number of roller applications. However, because there are areas that do not make contact between the reverse rim preform and the mandrel, if excessive loads are applied to the rollers, considerable strain is generated in the rim and cracks form in the part.

In order to respond to these issues, it is necessary, having taken into consideration the capacity of the equipment, to perform flowform processing while controlling the load.

The two related items, processing temperature and the number of roller ironings, were therefore focused on, and conditions were optimized.

First, the setting of processing temperature will be discussed. The preheating temperature of the casting material during flowform processing is an important factor in reducing the roller pushing load during processing. Figure 12 shows high-temperature material characteristics determined using a test piece cut from a JIS AC4CH (the aluminum alloy employed in wheels) aluminum alloy wheel. The yield strength of AC4CH aluminum alloy declines with increasing temperature, while elongation displays the opposite tendency⁽⁴⁾.

Because the flowform processing temperature for mass-produced normal rim wheels is around 300°C, a test using a flowformed prototype was conducted at this temperature. As shown in Fig. 13(a), cracks formed in the inner circumference of the rim. Based on the results of this preliminary test, flowform processing was conducted at 400°C, at which yield strength is approximately halved and elongation is doubled, and here, no cracks appeared in the rim.

In order to help prevent cracks from occurring and verify the optimum processing temperature range with consideration of mass production, processing tests were conducted at various temperatures. Table 1 shows test results for each temperature. At temperatures of 380°C and higher, no cracks occurred, but when the temperature became too high, there was a significant decline in material strength, and there was concern that the wheel material

Table 1 Test results of temperatures

Temperature	300°C	350°C	380°C	400°C	420°C	450°C
Result	Crack	Crack	No crack	No crack	No crack	No crack

would be deformed when retrieved from the preheating furnace or by transport robot chucking during transport or when set in the mandrel, which would be undesirable in terms of mass production; 400°C was therefore set as the temperature condition.

Next, tests were conducted in order to determine the optimum number of times for ironing of the rim by the rollers. In the case of flowform processing of mass-produced normal rim wheels, the roller responsible for forming the rough shape irons the rim one or two times and the roller responsible for forming the inner flange rolls the rim once, completing the process in a total of two or three ironings. By contrast, in the case of flowform processing for a reverse rim wheel, because it is necessary to process the abovementioned sections that do not make contact with the mandrel bit by bit, the number of ironings increases. Prototype tests were then conducted, varying the setting for the number of ironings. Figure 14 shows the trajectory of roller motion.

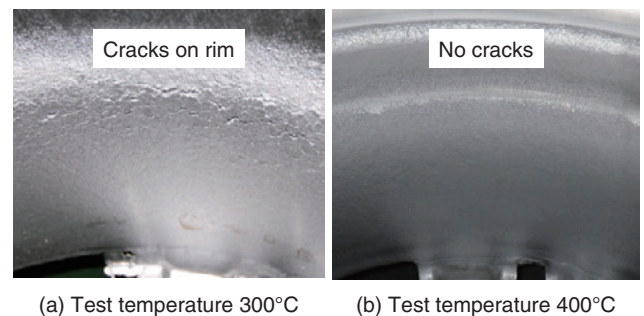


Fig. 13 Interior of rim after flowforming process

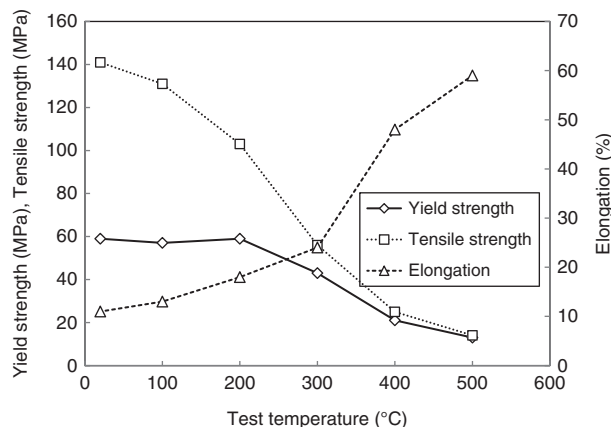


Fig. 12 Mechanical properties of JIS AC4CH

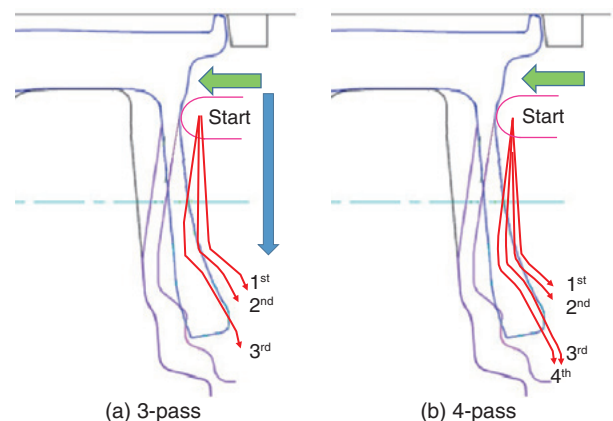


Fig. 14 Motion of roller while flowforming

The rollers applied loads from the start position in the direction of the green arrows, while moving in the direction of the blue arrows along the trajectories represented by the red lines. Processing was performed at various trajectories in order to disperse strain. At three ironings, the degree of processing per ironing was too high, and cracks appeared in the inner surface of the rim. By performing four ironings, however, it was possible to control the occurrence of cracks.

As the above results indicate, modifying the flowform processing method and optimizing the processing conditions enabled the creation of a production technology that would manufacture reverse rim wheels at the same cost as mass-produced normal rim wheels.

5. Verification of Effects

5.1. Prediction of Effect on External Appearance and Weight Reduction using CAE

Figure 15 shows the results of calculations, using 3D models, for the conversion of four wheels of differing sizes and designs into reverse rim wheels.

For all of the products, the conversion to a reverse rim type made the wheel look larger in diameter while reducing the weight of the wheel.

In the case of wheels A, B, and C, which had standard designs, the effect of weight reduction became greater as the size of the wheel increased.

For example, SUV tend to have large-diameter wheels due to their massive bodies. By using reverse rim wheels, the wheels will appear larger without inching up, and both

the weight reduction realized by inching up and the weight reduction realized by changing to a reverse rim wheel of the same size can be expected.

In addition, in the case of wheel D, a lightweight wheel developed with the aim of reducing weight, it was possible to realize a further reduction in weight by conversion to a reverse rim type.

5.2. Verification of Reverse Rim Wheels in Actual Vehicle

The CAE results for the effect of the reverse rim wheels were verified using models A and D in Fig. 15. Model A visually appeared larger in diameter, as shown in Fig. 1. In addition, the weight of the wheel was 650 g lighter than a normal rim wheel, matching the effect predicted by CAE results.

Wheel D, the lightweight model, is the wheel used in the 2015 model year Civic Type-R (size: 19 inches x 8.5 J). Figure 16 shows the reverse rim version of this wheel. In the reverse rim type, the spokes increased in length to 464 mm from the 440 mm of the normal rim type, and appeared approximately 1 inch longer.

The conversion to reverse rim types increased the interior space of the wheel, giving the wheel a sporty impression. Figure 17 shows the wheels mounted on an actual vehicle.

Size	Normal rim wheel	Reverse rim wheel	Weight reduction
Wheel A 18 × 7.5J	 12.40 kg	 11.75 kg	-0.65 kg -5.24%
Wheel B 19 × 8.0J	 13.56 kg	 12.48 kg	-1.08 kg -7.96%
Wheel C 20 × 8.5J	 15.08 kg	 13.95 kg	-1.13 kg -7.49%
Lightweight wheel D 19 × 8.5J	 11.91 kg	 11.66 kg	-0.25 kg -2.10%

Fig. 15 CAE results for appearance and weight

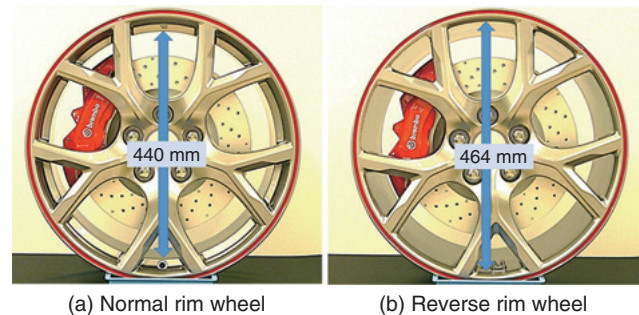


Fig. 16 Appearance of normal rim wheel and reverse rim wheel



Fig. 17 Reverse rim wheel on sport type car

It was possible to reduce weight by 250 g per wheel, matching the results of the CAE analysis.

Figure 18 shows the sections in which weight was reduced through the application of reverse rim wheels. The green section shows the section in which weight was reduced. Despite the fact that the weight of the wheel had already been reduced, conversion to a reverse rim type had the effect of reducing weight as a result of the removal of excessive thickness between the disk surface and the bead drop area.

As indicated above, the conversion to reverse rim wheels realizes increased freedom of design through the visual appearance of increased diameter equivalent to that of an inch up wheel when the design is the same as that of a normal rim wheel, and the reduction in excessive thickness makes it possible to reduce the weight of a wheel of 18 inches or more in diameter by 5% or more. It was also verified that it is possible to realize a weight reduction of 2% or more even in a wheel designed for reduced weight.

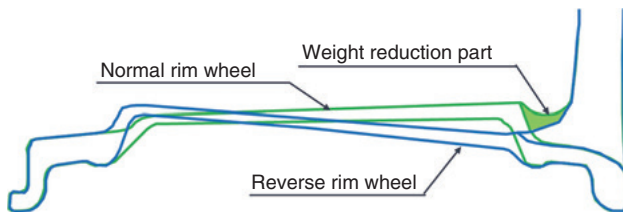


Fig. 18 Area in which weight is reduced in reverse rim wheel

6. Conclusion

The application of the manufacturing technology and method developed in the project discussed in this paper made possible one-piece manufacturing of reverse rim wheels, which simultaneously make the wheel appear larger in diameter while reducing its weight.

- (1) A type of flowform processing using opposed rollers was proposed, and a method of manufacturing reverse rim wheels as an inexpensive one-piece configuration using existing line equipment was developed.
- (2) For flowform processing, the preheating temperature was set at 400°C and the number of ironings by the roller was set at four, realizing optimum processing conditions that would not produce scratch marks such as cracks and micro-cracks.
- (3) It was shown that the shape predicted by CAE could be realized and that the target weight reduction effect could be obtained.
- (4) It was verified that the conversion to reverse rim wheels permits increased freedom of design through the appearance of increased diameter equivalent to that of an inch up wheel when the design is the same as that

of a normal rim wheel, and the reduction in excessive thickness enables reduction of the weight of a wheel of 18 inches or more in diameter by 5% or more. It was also verified that it was possible to realize a weight reduction of 2% or more even in a wheel designed for reduced weight.

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Modeling and Utilizing Expert's Knowledge, Experience, and Thinking in Automobile Development

Shigeto YASUHARA¹ Takeshi YOSHIMOTO¹ Hideyuki OKADA¹

ABSTRACT

Measures were taken to realize the structured knowledge and thinking of experts, personalized in the form of tacit knowledge, for the purpose of enhancing the development efficiency of design work.

In this approach, the words are extracted from procedure manuals, checklists, and so on, that are usually put into written form and managed. Those words are categorized as design information and work procedures, after which they are structured using two types of machine languages. By further extracting both the knowledge and thinking that are the tacit knowledge of an expert directly from statements, the newness and quantity of the information were assured within a short time. At the same time, the thinking that experts perform based on their own empirical values was structured and incorporated in a model. In order to verify the effectiveness of that model in operation, a system for obtaining suggestions not from other people but from machines was constructed and applied to design work on actual crash safety performance. The results confirmed that, by comparison with conventional cases in which only procedure manuals are referred to, cases in which the present model was used to perform work showed that it became possible to advance the work efficiently so that goals could be achieved in approximately one-half the time.

1. Introduction

Keeping up with new technology, as typified by connected, autonomous, shared, and electric (CASE) mobility, is a major challenge for automobile manufacturers. Moreover, regulations relating to environmental protection, as typified by CAFE, as well as safety requirements for the protection of vehicle occupants, grow more rigorous year by year. Engineers, therefore, have to think about such various aspects as safety, regulations, cost, mass productivity, and so on, when developing a vehicle. In order to carry out design work of high quality on a global scale, it is necessary for many engineers at different centers around the world to maintain the same level of design quality. Given this context, AI is used actively in a variety of fields, regardless of the industry, and solutions using big data are being proposed.

In development as it is currently practiced, most engineers actively use simulations as a substitute for actual testing. This shortens the time they spend on investigation. In recent years, however, increases in simulation accuracy have been accompanied by enlargements in model scale, so that the computation time taken for a single cycle has

also increased by the year. Engineers with less experience (beginners) end up needing more time because they go by trial and error, so that securing the time to turn to research and development of next-generation technology, and other such more creative work, becomes an issue. Experts, on the other hand, conduct their investigation very efficiently, without pursuing unnecessary procedures, on the basis of rational hypotheses and theories. They can do this because they have learned lessons from their vast experiences of malfunctions in the past, and they are able to act in an instant to select the appropriate, necessary, and sufficient method for success.

In order to make use of this kind of expert skill to heighten the efficiency of design work, an effort was made to record methods of investigation in design manuals and other such documentation using presentation and other such software employing imagery, graphs, and photographs. However, the thinking process of experts most often deals with tacit knowledge, which has not been put into writing and made into explicit knowledge, so that the structuring of that knowledge is an issue. One method for structuring the thinking and knowledge of experts is by the use of AI. Although there are many cases of the use of AI that

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employs deep learning, however, what these do is process enormous amounts of data by rules that are determined by computer. For that reason, the particulars of how a solution was reached, and what its grounds are, are not understood even by specialists, and there are concerns that the process itself would become a black box. There was MYCIN⁽¹⁾, an expert system for medical use that was developed in the 1970s at Stanford University. MYCIN held knowledge data comprising about 500 rules. When physicians posed questions, the system would respond with a yes or a no, and eventually it would be able to indicate a recommended medical treatment. However, it was not used in actual clinical settings. This was because, if the computer gave a mistaken response, the recommended medical treatment would be of uncertain traceability. When issues arose, it was not possible to look back at the grounds for the judgement, and this was an issue.

In order to make use of AI in the field of vehicle development, where guarantees of quality are important, the developer needs to indicate the basis for conclusions, as in medical, judicial, and other such fields where important conclusions are delivered.

In light of this background, and in order to deal with more issues using fewer resources in the future, it will be necessary to grow out of conventional handling of the experience and knowledge that constitutes an enormous development process based on verification results from the past. What is needed instead is a development-related organization that accumulates that knowhow and utilizes it not in a personalized manner but for the organization as a whole, thereby reducing man-hours of development on already known issues. The present research was, therefore, directed to the construction of a system capable of structuring the thinking and knowledge of experts and utilizing it in design work.

2. Aims of the Present Research

2.1. Overview

For the present research, the structured knowledge of an expert is defined as a knowledge model and a model structured with the thinking of an expert is defined as an expert model.

First, a method for combining the two machine languages of Goal Structuring Notation (GSN)⁽²⁾ and System Modeling Language (Sys ML)⁽³⁾ was verified as a method for structuring knowledge in design. Words extracted from information materials were structured by the two machine languages and the two were linked together in order to construct a knowledge model. Next, a method to enable structuring knowledge directly from an expert's statement even when information materials in documentary form are not available was investigated and steps were taken to speed up the construction of a model. Policy was then further extracted from the tacit knowledge possessed by an expert, and the expert's thinking was structured

using the concept of reward. Finally, the constructed model was applied to actual design work and its effectiveness in workload reduction was evaluated. Figure 1 shows the ideal state of an expert model being utilized globally. There are large numbers of people engaging in work while being transferred to and from large numbers of centers where they come and go. Therefore, the issue of passing on and accumulating technology becomes greater when considered on a global scale. The aim here, by contrast, is to aggregate structured knowledge and experience of experts at a single location so that anyone anywhere can make active use of that expert knowledge and experience.

2.2. Approach to the Ideal State

Figure 2 shows an approach to the ideal state. Beginners do not have the knowledge and experience needed for development work, so they tend to carry out extra tasks. The approach taken to make it possible for beginners also to advance their work effectively was to structure knowledge and thinking of experts in the form of a model. By making use of the model, beginners can reduce the time they need for development work, and with the extra time they create, they can pursue more creative work.

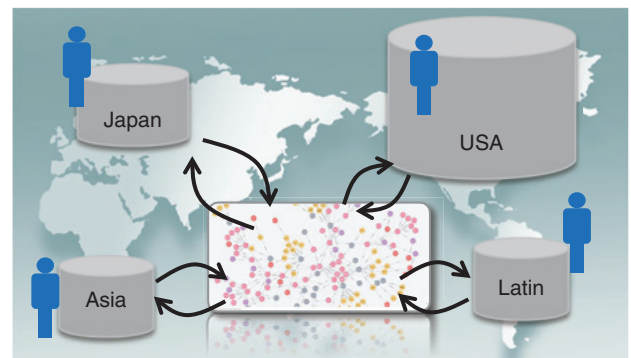


Fig. 1 Expert model utilized globally

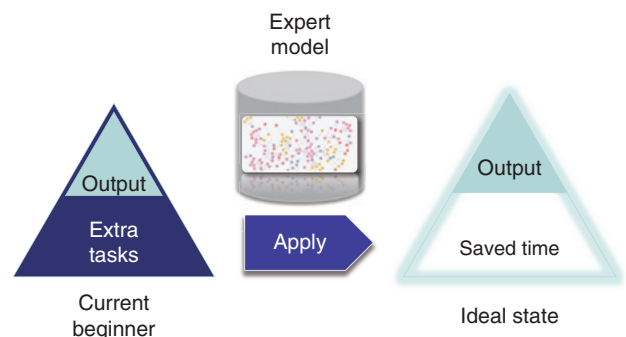


Fig. 2 Concept of expert model

Figure 3 shows the dialogue with an expert model. As shown in Fig. 3(a), the knowledge and experience in conventional work is personalized, so that the passing on of knowledge and experience and education in it is carried on from person to person by analog communication of information. The proposal here, as shown in Fig. 3(b), was conceived to have users engage in dialogue with the system to obtain the suggestions they need to promote development.

2.3. The Four Steps of the System

The system presented in this research is conceived as being implemented in four steps, as shown in Fig. 4.

“Educating”

Knowledge, experience, and thinking are extracted from experts and technical documents and structured in a language that can be input to machines. By providing that structured model to the system as sequential input, the system is placed in a state that allows engineers to obtain suggestions from it.

“Listening”

Users ask the expert model questions, using the system



Fig. 3 Interaction with expert's knowledge

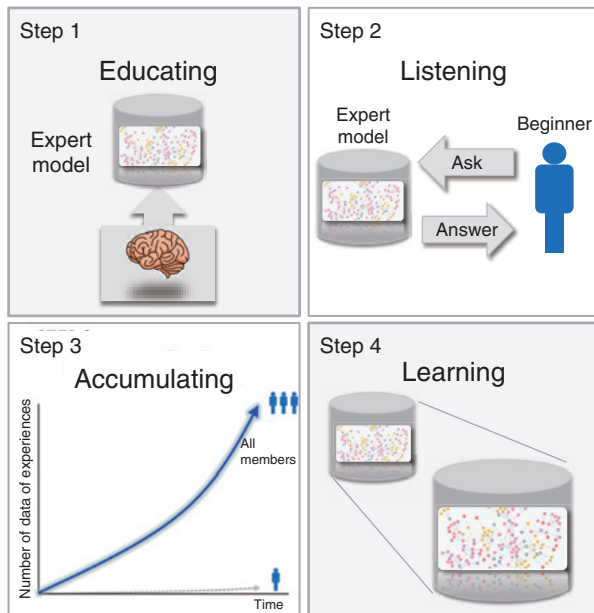


Fig. 4 Four step approach

as intermediary, and obtain suggestions from the expert model regarding investigation policy.

“Accumulating”

As the expert model is utilized more and more, so that history, including the responses, is accumulated in the model as empirical values. When it is utilized by more users, then it can accumulate a dramatically greater number of empirical values. This makes it possible to maintain a constantly up-to-date newness of information.

“Learning”

The model itself engages in self learning that uses knowledge together with cause-and-effect relationships, and in this way evolves into a model that goes beyond human experience.

The actual sites of design and development are spread around the whole world. As more users employ this model, the knowledge in it accumulates and the model undergoes further growth by engaging in self learning. The expert model can be thought of as evolving while going through the four steps described above. This paper will explain the structuring method used and the verification results obtained for the “Educating” of the expert model that becomes the core of this approach by means of the four steps.

3. “Educating”

3.1. The Modeling Process

Figure 5 shows the procedure for construction of the model. Tacit knowledge is extracted from information materials from the past that record knowledge and experience of experts, verification results, words spoken by experts, and other such sources, and the knowledge model is constructed. Next, policy is extracted from experts and combined with the knowledge model to construct the expert model.

Figure 6 shows the visualization and structurization of tacit knowledge.

The knowledge based on experiences contained in the brain of an expert is tacit knowledge that is invisible

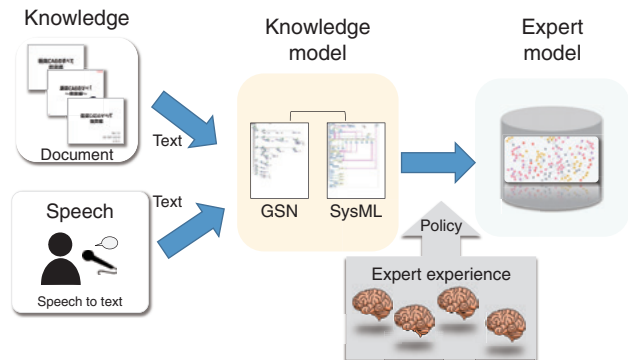


Fig. 5 Model construction process

and cannot be seen by other people (bottom left). That knowledge is extracted from procedure manual and statements in a state that is made visible using text data (top left). Then, it is further structured so that it can be interpreted by machine (top right) and a knowledge model is constructed. However, the work of creating procedure manuals takes considerable time, so it is possible that information will be updated during that interval. For present purposes, therefore, it was decided to construct the knowledge model directly from statements without going through the conversion of tacit knowledge into information materials. Following this kind of process makes it possible to create the model in a shorter time. The knowledge model constructed by extracting knowledge and experience directly from the expert's tacit knowledge is grounded in the expert's experience, and suggestions obtained from it can be formed so that they are based in past development experience and verification results as their grounds.

3.2. Modeling Knowledge

A design procedure manual used in actual work is easy for people to understand, but it is written down on the assumption that people will have the ability to comprehend some amount of specialized knowledge and the meanings of the words. It is also sometimes the case that the definitions of words and work procedures that are accepted as a matter of course in that field are omitted, in which case only people who have knowledge of that field will be able to understand the meaning of the what is written. The machine, however, has not been equipped with the meanings and definitions of the various words in that text, so it cannot readily interpret them. The written procedure manual, therefore, needs to be structured using a language that the machine is able to interpret. For that purpose, the writing in information materials is extracted in the form of text and broken down into words. A dictionary of specialized terminology is, then, used to categorize the words by their parts of speech.

The contents of the procedure manual have accounts

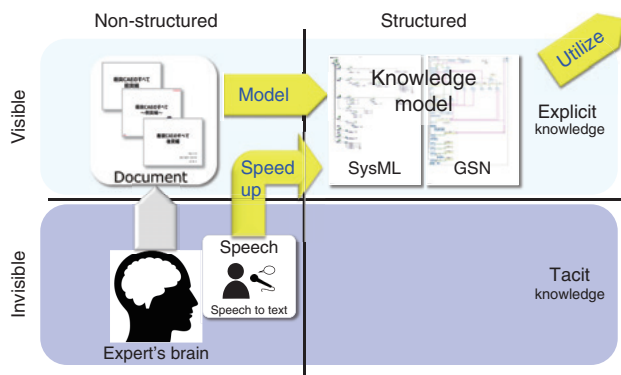


Fig. 6 Visualization and structurization of invisible knowledge

of design information and accounts of design procedures mixed together, so they need to be structured using different methods respectively. For the present research, therefore, the design information was structured using SysML. SysML has a syntactical construction used to express system structure, and it is capable of expressing components as a tree structure, expressing relationships between those components, and so on. For this reason, it is suited to structuring information for the purpose of designing parts. The structuring of design procedures, on the other hand, was handled using GSN. GSN is a syntactical construction that is used for visualization of design quality. GSN can express a top goal by breaking it down into sub goals. By using this GSN, the validity of sub goals can be explained on the basis of evidence regarding the goals they belong to, and the satisfaction of characteristic criteria for a top goal can be explained. For this reason, it is suited to structuring design procedures for the purpose of satisfying the goals for parts. When GSN and SysML are used in these ways for their respective structuring and then further linked together, it becomes possible for the first time to tie design procedures together with parts structure, and the structuring of knowledge becomes possible.

As a specific example, Fig. 7 shows the method for making crispy pizza of a kind only a first-rate chef can make, structured using SysML and GSN. In SysML, the makeup of the pizza is structured. The pizza is made up of dough, tomato sauce, and topping. The dough is further made up of flour, salt, dried yeast, and water.

In GSN, on the other hand, the design procedures for making crispy pizza are structured. With the dough, the top goal (1) is to make crispy pizza, and for that purpose (2) the flour, water, salt, and dried yeast are thoroughly stirred together. Next, the sub goal (3) is to beat the dough against a board until its surface is smooth. In SysML, the action of beating the dough until its surface is smooth becomes a

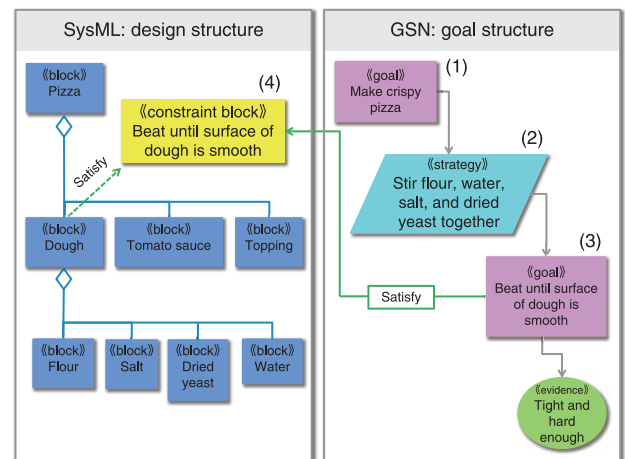


Fig. 7 SysML-GSN model of making crispy pizza

condition of constraint with regard to the dough, and this serves the purpose of (4) linking GSN and SysML together. When GSN and SysML are linked together in this way, the pizza makeup and procedure is clarified for the first time, and the recipe for pizza is completed. When the recipe is available, even beginners can successfully make crispy pizza, and this method can, therefore, be considered to have successfully structured the knowledge of a first-rate chef.

Figure 8 shows an example of this structuring method applied to the design of frame structure intended to achieve the stable absorption of crash energy as designed by an expert in charge of crash safety.

The vehicle body component parts in the engine room that absorb crash energy during a collision are structured in SysML. The engine room is made up of the side frame, lower member, and subframe. There are also component parts that make up the side frame, namely the main plate, back plate, patch, and bulkhead. In GSN, on the other hand, the design procedures for the purpose of stable absorption of crash energy are structured. The top goal (1) is the stable absorption of crash energy, and in order to achieve that, then (2) the side frame has to be made to collapse in a stable manner. Next, in order to cause stable collapse, the sub goal (3) is to configure three bending points where collapse is to occur, as shown in Fig. 9. The configuration of three bending points for collapse is a condition of constraint with respect to the side frame in SysML, and this serves the purpose of (4) linking GSN and SysML together. In other words, the procedure and structure needed to realize the stable absorption of crash energy are clarified, meaning that the recipe for achieving the top goal, which is the expert's knowledge, has been structured using GSN and SysML.

3.3. Increasing the Speed of the Modeling Method

There is a history of research that used to be carried out on expert systems to handle the knowledge of experts using

computers. That was during the second AI boom from the 1980s to the 1990s. From the 1990s on, however, this faded away. The rules for the if statements used at that time to solve complex issues are not easy to understand, and the programming itself was not a simple task. Consequently, the input work done in order to use that system could only be carried out by engineers who had learned those skills. Input, therefore, took huge amounts of time, and this combined with the challenges involved in acquiring those limited skills meant that the quantity and newness of the needed information could not be maintained. This was a factor in the decline of that approach.

Now that programming has advanced to its present level, it is possible to extract words from procedure manuals, as described in Section 3.2., in those fields that have procedure manuals and other such documentary data. It is, therefore, easier, by comparison, to create a model. In fields that do not have procedure manuals and other such documentary data presenting knowledge, however, the documentation has to be created before structuring can be done. Some of the work that has been done to date in creating documentation of certain functionalities took approximately three years, so that by the time it was published, the information already needed to be updated. Creating the documentation successfully achieved the goal of centralizing the knowledge, but it did not enable use of the most up-to-date information in development. Meanwhile, new knowledge is being generated day by day in the discussions conducted by experts at the sites where development is being done, in lectures, and so on. If it became possible to extract and structure the knowledge from those spoken words, therefore, then the newness of information could be maintained. For these reasons, the method adopted for the present research to speed up the process was to construct the technology to create models directly from statements without going through information

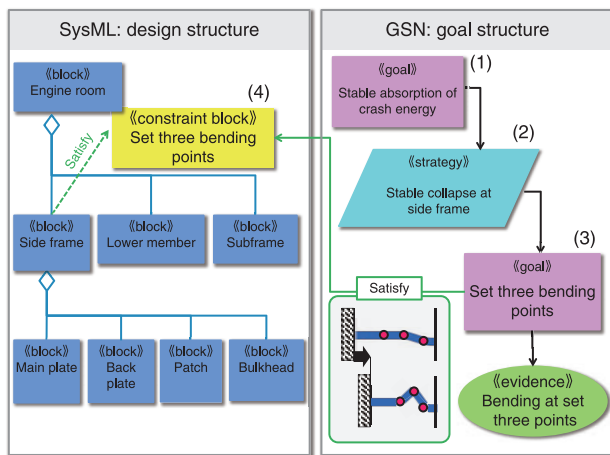


Fig. 8 SysML-GSN model of side frame design

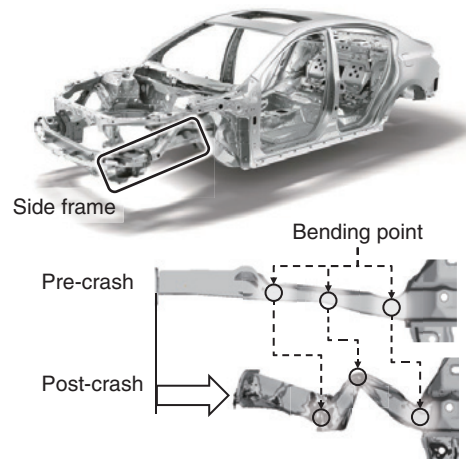


Fig. 9 Three bending points of side frame

materials, as shown in Fig. 10. The procedure followed was first to hold interviews with experts and have them talk about their knowledge. Their spoken statements would be recorded and converted to text by voice recognition. This differs from the procedure followed when extracting text from written documents because statements made in natural conversation involve some amount of ambiguity. The statements were, therefore, subjected to context analysis and anaphoric analysis in order to remove the ambiguities before structuring.

The content of natural conversation is often not understandable to a third party because, for someone who was not present at the time, it may not be clear what the statements are referring to. The knowledge cannot readily be structured in such cases. In order to identify the context of statements, therefore, context analysis was conducted as shown in Fig. 11.

When a statement with the content, “the force generated at the side frame did not reach the target,” is subjected to context analysis, it becomes clear that the words “did not reach the target” show that this is a statement about goals. As a result, the words making up this sentence can be properly structured according to their parts of speech in GSN, which records goals.

Next, the anaphoric analysis shown in Fig. 12 is carried out in order to deal with terms such as “it” and “that” that indicate correspondences between different parts of the text. With statements made in natural conversation, it is common for multiple sentences using anaphor to become broken off and disconnected. If those statements are structured just as they are, the structure will also become broken off and disconnected, and the result will end up inadequate as knowledge. In order to help prevent this, anaphoric analysis was used to make connections between antecedents and anaphors so that structuring could be done without causing the relationships between words to become broken

off and disconnected. In this way, anaphoric analysis and context analysis were included in the tools for generating knowledge structure, and structuring was successfully accomplished without going through the process of creating information materials from spoken utterances.

3.4. Structuring Expert Thinking

Figure 13 shows differences between the thinking of beginners and experts. Beginners, who have less knowledge and experience, tackle a task without knowing the pathway to achieving a solution. Experts, on the other hand, have structured their experience and thinking within their own brains. Therefore, not only do they possess it in the form of knowledge, but they can also build the pathway to achieving a solution appropriately for the circumstances. Experts possess this kind of thinking as the result of long years of experience. When they experience a malfunction, they identify the causes of it and remember them and make use of them in their brain in the form of a policy expressing their essence. A policy is a statement that can be expressed in the form “in other words...is what it means.” It is generalized, with specific attributes removed, so that it can be used as a choice for action to help prevent malfunctions

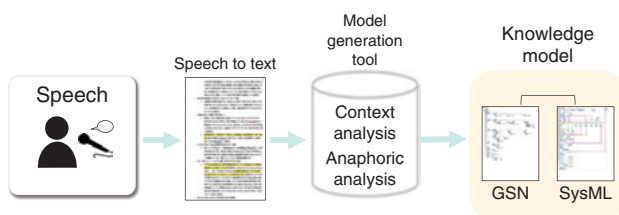


Fig. 10 Speech-to-knowledge model process

Speech	Context analysis
Force generated at the side frame did not reach the target.	➡ About goal
He was the president of this company.	➡ About person
Higher the deformation, higher the injury value.	➡ About collision

Fig. 11 Context analysis

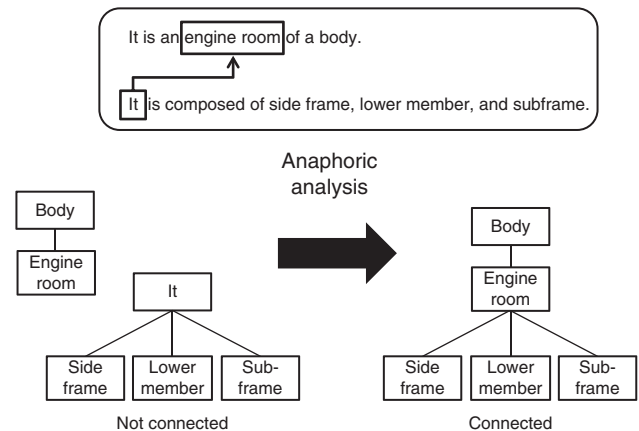


Fig. 12 Anaphoric analysis

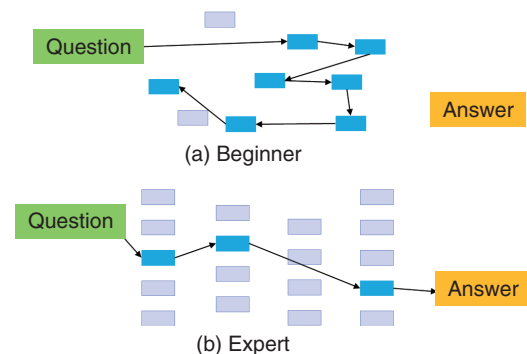


Fig. 13 Comparison of beginner's and expert's thinking

even in different cases. The science of failure⁽⁴⁾ was used for visualization of this policy. The science of failure is a systematized method for working from factor analysis of faults that occur to arrive at factors that present their essence. It is used for extracting policy. First, cases of faults from actual past work were gathered together and interviews were conducted with the people involved. Next, a collection of troubles in the past was created according to the science of failure, and policies were collected.

The policies extracted from malfunctions in this way constitute guidelines to help prevent faults before they can occur, or in other words, they are actions that experts would select. In order to suggest these actions to beginners, a method for reward scoring matched to the action was investigated. Figure 14 shows an example of reward scoring according to policy. The rewards were determined as point scores matched to actions. Action that is in accordance with policy is assigned a higher reward, and action that is instead counter to policy is assigned a negative reward. When users choose a procedure that gains them the highest reward, they are able to choose the procedure with the higher priority.

Figure 15 shows the concept of using reward to suggest priority. Here, what should be done first in order to achieve the crash performance target that is the goal is shown in an example using GSN. Next, in the case of tasks to be carried out that are presented in parallel, beginners will end up carrying out an incorrect task unless they receive suggestions about priority. When making use of rewards in this situation, the higher reward is assigned to the procedure that sets goals based on policy, and users are able to

Policy	Reward
Cause should be analyzed	+2
Set target	+1
Aimless consideration	-4

Humans have responsibility of setting reward

Fig. 14 Description of policy and reward

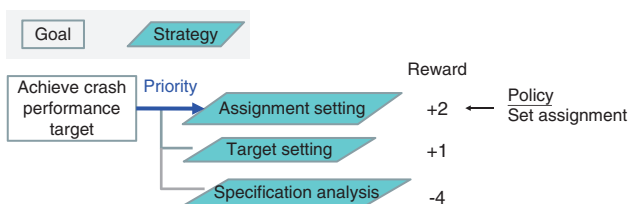


Fig. 15 Reward suggesting correct strategy

understand why that procedure has a higher priority.

The rules for this reward scoring shown in Fig. 14 constitute the grounds for the correctness of suggestions made by the expert model. Therefore, these grounds need to be valid in a way that human beings can understand, such as in terms of their experience, logic, and so on. Thus, the system is predicated on human beings taking responsibility for upholding the rules. The substance of the approach explained up to this point was used to incorporate knowledge and thinking in a structure, and an expert model was constructed that structures 29,429 items of design information relating to performance design of a vehicle frame.

3.5. Verification of Effectiveness

The following scenario was formulated for crash safety work in order to verify that using the expert model is effective in reducing man-hours: "In an offset deformable barrier crash mode where the vehicle has a weight 100 kg greater than the base vehicle, carry out a design whereby the force generated at the side frame is increased from 100 kN to 150 kN while achieving the target mode of collapse." For verification, two younger engineers at approximately the same skill level who were inexperienced in development were selected and a comparison was made of the extent to which they achieved the goal with and without use of the expert model. One engaged in the work while referring only to a procedure manual. The other used the expert model to obtain suggestions while engaging in the work. Figure 16 shows the results for verification of effectiveness by comparison of the extent to which the two subjects achieved their goal and the work time required to do so. Where the expert model was not used, it took 142 hours to achieve the target for the force generated at the side frame. However, the target for mode of collapse was not achieved. Where the expert model was used, on the other hand, the target for force generated and for mode of collapse were both successfully achieved in 62 hours. The effect was to shorten the work time by 56%.

	Result	Required time
Without model	Target missed	142 h
With model	Target achieved	62 h

-80 h
-56%

Fig. 16 Verification result of analysis time reduction effect

Figure 17 shows a breakdown of the reduction effect. It is clear that where the expert model was used, a smaller number of analysis cycles was executed. This is particularly notable in the more time-consuming analysis using a large-scale CAE model, where the number of cycles executed was held down to four cycles compared to seven cycles without the system.

Figure 18 shows the results from verification of the process. The engineer who used only a procedure manual did not succeed in defining phased aims for analysis and actions. Consequently, the work of investigating specific specifications for the side frame to be derived from that process was executed by an analysis using a large-scale CAE model. Many hours were, therefore, expended on the work, and the result did not succeed in achieving the target for mode of collapse.

On the other hand, the engineer who used the expert model was able to obtain suggestions for necessary and sufficient procedures. By means of those suggestions, a grasp of the current state of the base vehicle was obtained, on which basis targets were defined, each stage was configured for the issues involved, and investigation of specific specifications was successfully executed. This made it possible even for someone without experience of their own to successfully achieve all the set targets. The development time shortening effect of using the expert model was, therefore, confirmed.

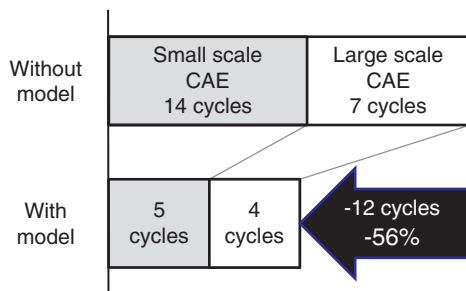


Fig. 17 Breakdown of analysis reduction

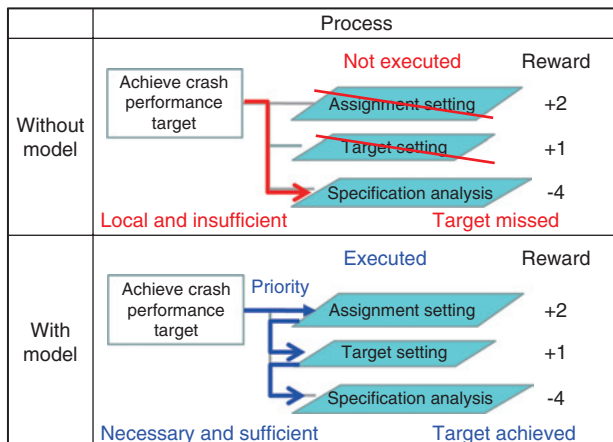


Fig. 18 Verification result of design process

4. Conclusion

A method was established for structuring the thinking and knowledge of experts, which had been in the form of tacit knowledge, and an expert model that is needed for the “Educating” step of an expert system was constructed.

- (1) Knowledge was constructed as a knowledge model by using GSN and SysML linked together.
- (2) A method of rapidly structuring the knowledge model from statements without going through information materials was constructed.
- (3) An expert model was constructed that is capable of reproducing an expert’s thinking process by assigning higher rewards in the knowledge model to actions that are accordance with the expert’s policy.
- (4) It was confirmed that use of the expert model constructed in the present research had the effect of shortening the work time.

The methods established in the present research will be used in the future to engage in accumulating and collecting recorded data with the aim of expanding the scale of the expert model. System development for the purpose of utilizing the model in regular work on the basis of “Listening” and “Accumulating” steps will be promoted. Compatibility with analysis, mining, accumulation, and machine learning technologies for the purpose of linking with “Learning” will also be considered within the scope of this effort in order to continue the research with a view to enabling use of the model across a broader range of application.

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Search for Alloy Catalyst for Automobile Exhaust Gas by Means of Integrated Flow of Experiments, First-principles Calculation, and Materials Informatics

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ABSTRACT

A new integrated flow has been developed that makes it possible to efficiently search for alloy catalysts that reduce the amount of precious metals employed in catalysts for the purification of automotive exhaust gases. The distinctive feature of this flow is that it functionally integrates the properties of the conventionally performed test methods such as catalyst activation tests and X-ray photoelectron spectroscopy with those of first-principles calculations and materials informatics, performed using computers. First, experiments and first-principles calculations were used together in order to conduct an analysis of the nitrogen monoxide reduction reaction, and a density of state was set to function as an index of material performance. Next, the performance rank of binary alloy catalysts was predicted using first-principles calculations and materials informatics, with this density of state as the target variable. More than 10 binary alloy catalysts calculated as displaying performance in the top rank were actually synthesized and their performance was confirmed. The results showed that it was possible to create an alloy catalyst that displayed a higher level of performance than a catalyst using palladium, the main active metal in use in current catalysts, demonstrating the usefulness of the integrated flow.

1. Introduction

Increasingly urgent demands in relation to the preservation of the global environment in recent years have made it necessary to achieve further reductions in the quantities of CO₂, CO, HC, and NO_x present in exhaust gas emitted while vehicles are in operation. Effective responses to the reduction of CO₂ emissions during automobile operation are being promoted through automotive electrification, as exemplified by the use of hybrid vehicles⁽¹⁾. By contrast, the need to reduce emissions of CO, HC, and NO_x is being acknowledged by means of after-treatment using three-way catalysts⁽²⁾. Catalyst materials are employed in a form in which minute particles of precious metals such as platinum (Pt), palladium (Pd), and rhodium (Rh) are widely dispersed and loaded on the surface of an oxide such as alumina (Fig. 1). The inherent rarity of these precious metal resources makes them substances with a high procurement risk⁽³⁾. A reduction in the amount of use of precious metals is thus demanded in order to respond to future increases in the stringency of global automotive

exhaust gas regulations and increases in the number of automobiles sold in developing nations.

A variety of approaches have been taken from the perspective of effective use of the precious metals that have conventionally been used as the active species in catalysts, a typical example being the modification of the oxides that support the precious metals⁽⁴⁾. One of the aims of this is to maintain the precious metal particles on the surface of the oxide in a highly dispersed state even in environments such as automotive exhaust gas, in which temperatures are high and there is considerable fluctuation in the redox

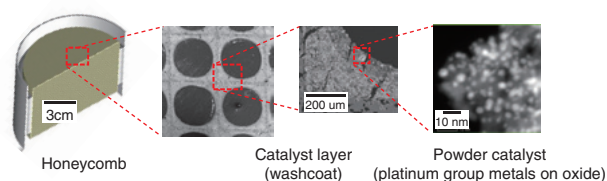


Fig. 1 Layout of catalyst material in exhaust system

¹ Innovative Research Excellence

atmosphere. However, there is considered to be a theoretical limit to realizing increases in dispersibility. Another aim of these measures is to boost purification performance by means of the mutual interaction between the loaded metal and the oxide, known as the support effect⁽⁵⁾. There are, however, numerous unclear points regarding the mechanism to realize this function, and at present the effect also remains unclear. It will be challenging to further reduce the total amount of precious metals employed in exhaust gas purification catalysts through such catalyst oxide modification approaches alone.

Another approach that can be considered is to modify the active species themselves. While it is well known empirically that only precious metal elements are highly effective as active species, there has not been sufficient elucidation of the mechanism that causes only precious metals to function effectively. In addition, the development of materials has also not progressed in comparison to oxides, the reason being that because the catalytic reaction proceeds extremely rapidly, it has been considered that there were limits on the potential for elucidation of the mechanism through experimental methods alone. Thus, the search for new active species has, rather than basing itself on theory, mainly employed test methods that rely on previous experiments and findings, resulting in time-intensive material development.

The dramatic increase in computing power in recent years, however, has greatly changed the material research and development environment.

One of these changes has been the vigorous implementation of an approach to the elucidation of the reaction mechanism between gases and active metals involving the application of electronic structure analysis using first-principles calculations⁽⁶⁾⁻⁽¹²⁾. However, at present, the simulation of all of the complex catalytic reactions that occur simultaneously with redox reactions in gases in which there are numerous reaction gas components, such as automotive exhaust gas, necessitates enormous computation costs, making the process unrealistic. A means of restricting the targets of the computations is, therefore, necessary.

Another change is the burgeoning use of a method termed materials informatics, which uses machine learning (able to easily handle enormous amounts of information) to enable effective searches across wide ranges^{(13), (14)}. Using this method, it is possible to search for materials that are beyond the range of previous experience and findings if appropriate target and explanatory variables are prepared. In order to apply the method to the search for catalyst active species, however, it would be necessary to set target and explanatory variables that accord with the reaction mechanism.

Making use of the recent rapid developments in the materials research and development environment, the research discussed in this paper thus sought to create a search flow that integrated experiments, first-principles calculations, and materials informatics, while focusing on

the modification of catalyst active species, an area in which comparatively little progress can be considered to have been made. The research also sought to efficiently search for and verify alloy active species that would simultaneously allow the reduction of the amount of precious metals employed and maintain or increase purification performance.

2. Concept of Materials Search and Integrated Flow

The concept of the materials search under discussion was to utilize computing power to the greatest possible extent in order to realize the greatest potential reductions in the number of experiments, and conduct materials searches efficiently using first-principles calculations and materials informatics. The following integration flow was examined in order to realize this goal.

First, using experiments and first-principles calculations, densities of state are set as indices for materials searches. Next, repeated iterations of first-principles calculations and materials informatics are employed in order to narrow down the materials able to realize high performance. Finally, the candidate materials are actually synthesized, their performance is confirmed, and they are selected.

Because the number of standards that can be synthesized at one time in normal experiments is limited, when the range of a search is broadened, the number of synthesized materials and performance tests increases, necessitating more time. This represents an issue for experiments-based searches. Conducting the greater part of material screening using computers in this way helps to address this issue. In addition, with regard to the setting of calculation conditions, an issue for first-principles calculations, the reactions that correspond experimentally with purification performance are set as calculation conditions. For the setting of target and explanatory variables that accord with the reaction mechanism, an issue for materials informatics, densities of state linked to actual catalyst performance confirmed by experiments and first-principles calculations are set as target variables, and the basic chemical parameters of the elements are set as explanatory variables. By supplementing the issues of experiments using calculations and their issues in this way, the aim of the research was to attempt to help avoid divergence between experiments and calculations, and create a functionally integrated search flow.

Figure 2 shows a comparison of search flows. In the conventional search flow, high-performance materials are searched for by repeating material synthesis and catalyst activity tests. As a result, the time necessary for the search can increase in proportion to the increase in the search range [Fig. 2(a)]. By contrast, in the integrated flow under discussion, the materials search is conducted using calculations based on conditions restricted through the use of already synthesized materials, and only materials showing prospects for the realization of high performance are actually synthesized and tested for confirmation of

performance. As a result, it is possible not only to conduct searches over a wide range in a comparatively short period of time, but to reduce the number of materials that are actually synthesized to the greatest possible extent [Fig. 2(b)].

NO, which is said to be resistant to purification because the NO purification reaction is a reduction reaction and thus more thermodynamically disadvantageous than CO and HC oxidation reactions⁽¹⁵⁾, was made the subject of the research, and the NO-CO reaction, important to three-way catalyst performance, was focused on. In addition, the reaction was analyzed by applying experiments and first-principles calculations to the NO dissociative adsorption reaction, which is considered to be the most important reaction in the NO reduction reaction pathway^{(16), (17)}. It was decided that the density of state, the target variable for the materials search, would be controlled by alloying with an active metal as a method of actually changing and realizing this parameter. This research conducted a search for a binary system composition that would form the basis of the alloy.

Below, the details of concrete efforts implemented following the integrated flow proposed in this research are discussed.

- (1) Understanding the correlation between catalytic reactions and density of state in active metals through experiments

The correlation between NO reduction performance and the density of state of catalyst metals was experimentally confirmed using catalyst activity tests, adsorbed species analysis and electronic structure analysis.

- (2) Analysis of density of state in reactions using first-principles calculations

Using first-principles calculations, the density of state that contributed to the reaction was analyzed, and a

local density of state (LDOS) index was established as a target variable for a materials search using materials informatics.

- (3) Alloy search using materials informatics

With the LDOS index as the target variable, binary alloys that allow the realization of high performance were searched for through repeated iterations of smart materials informatics (SMI)⁽¹⁸⁾, which has a high predictive accuracy based on comparatively low amounts of data, and first-principles calculations.

- (4) Synthesis and characterization of binary system alloy catalysts

The binary alloy compositions shown by the calculations to be in the top range of performance were actually synthesized as alloy catalysts, and the state of alloying and the electronic structure were confirmed in tests.

- (5) Evaluation of performance of binary alloy catalysts

The actual performance of the binary alloy catalysts was evaluated in catalyst activity tests.

The following sections will discuss the research details of each of the five steps described above.

3. Materials Search Method and Results

3.1. Understanding the Correlation between Catalytic Reactions and Electronic Structure in Active Metals through Experiments

3.1.1. Test method

- (1) Catalyst synthesis method

Six types of single-metal catalysts were created using the impregnation method employing a normal aqueous solution. γ - Al_2O_3 was employed as the support oxide for all of the catalysts (Table 1).

- (2) Evaluation of catalyst performance

Catalyst activity tests were conducted using an atmospheric-pressure fixed-bed reactor employing a model gas. Catalyst weight was 100 mg, and the total gas flow rate was 400 ml/min. With regard to pretreatment, following reduction treatment at 500°C, catalyst performance was evaluated at 50°C-increments descending from 500°C. Evaluations were conducted using two reaction gas conditions: simulated exhaust gas conditions (Table 2), and NO-CO conditions that enabled evaluation of the typical reactivity of the NO reduction reaction for exhaust gas (Table 3).

- (3) Adsorbed species analysis

The adsorbed amount of isocyanate (NCO species), an index of the dissociation properties of NO, was measured. These measurements were conducted in a NO-CO consecutive reaction format using diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS). With regard to pretreatment, following reduction treatment at 500°C, the measurements were conducted at 200°C. The gas flow sequence was as follows: Following a flow of NO, a purge was conducted using N_2 ; next, following a

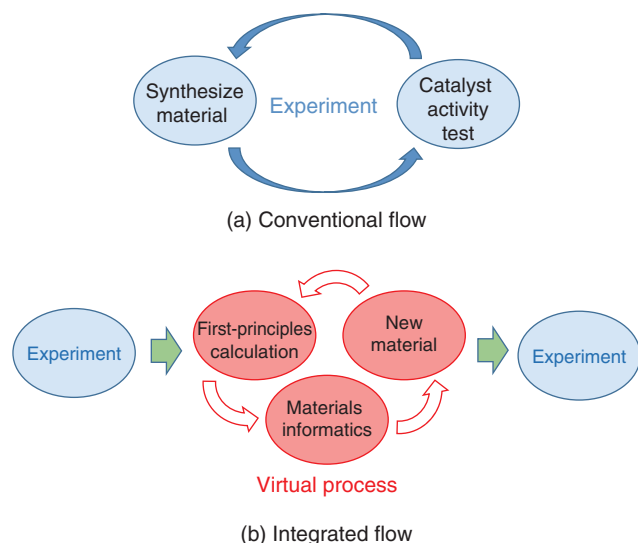


Fig. 2 Comparison of material search flows

Table 1 Sample catalyst

Catalytic active metal	Support oxide
Pd, Pt, Rh, Cu, Ag, Nd	γ -Al ₂ O ₃

Table 2 Simulated exhaust gas composition

Gases	Concentration
NO (ppm)	500
CO (ppm)	5000
C ₃ H ₆ (ppm)	400
H ₂ (ppm)	1700
O ₂ (ppm)	4900
CO ₂ (%)	14
H ₂ O (%)	10
N ₂	Balance

Table 3 NO-CO gas composition

Gases	Concentration
NO (ppm)	1000
CO (ppm)	1050
N ₂	Balance

flow of CO, a purge was conducted using N₂; peak strength measurements of NCO species were conducted at close to 2210 cm⁻¹.

(4) Analysis of catalyst electronic structure

X-ray photoelectron spectroscopy (XPS) was employed in the analysis of catalyst electronic structure. Measurements were conducted in a vacuum. The measurement conditions were as follows: MONO (Al) radiation source; voltage: 15 kV; current: 10 mA; the measurement energy band was from -15 eV to 40 eV. Samples were subjected to reduction treatment at 500°C as pretreatment, following which they were introduced to the measurement device in an inert gas environment without exposure to the atmosphere.

3.1.2. Experiment results

Because the material would ultimately be employed in an exhaust gas environment, it was first confirmed that there was no divergence between NO reduction performance under simulated exhaust gas conditions and NO-CO conditions in catalyst activity tests (Fig. 3). The results indicated that there was a correlation between the inclinations of the NO-reduction ratios under simulated exhaust gas conditions and NO-CO conditions. Given this, it was decided to proceed from this point on with the analysis under NO-CO conditions.

Next, Fig. 4 shows an image of the reaction pathway generated by dissociation, indicated as being an important reaction pathway in NO reduction. The dissociation

properties were evaluated using DRIFTS in order to experimentally investigate the correlation between the NO dissociation reaction and reduction performance. Because it was not possible to directly observe N atoms and O atoms, the adsorption strength of NCO species formed by the bonding of CO to dissociated and adsorbed N atoms was evaluated as the dissociation properties.

The results indicated a high correlation between the NO dissociation properties and the NO reduction ratio (Fig. 5).

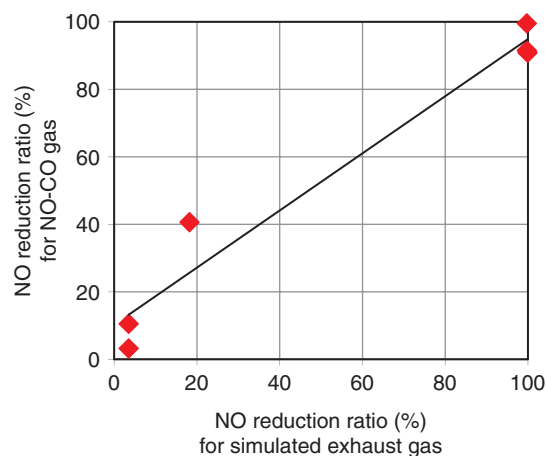


Fig. 3 Correlation between purification ratio for NO-CO gas and simulated exhaust gas

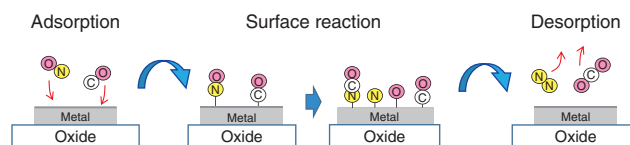


Fig. 4 Image of reaction path for NO reduction

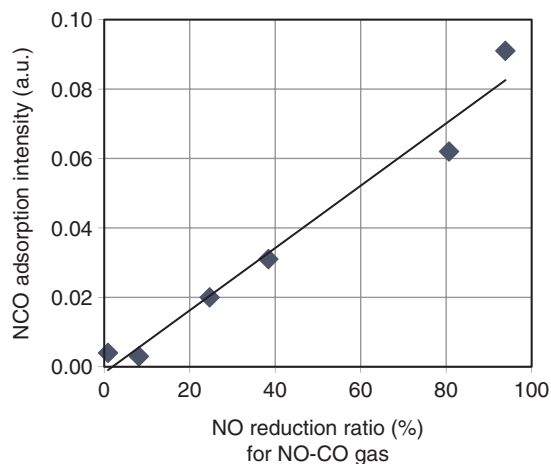


Fig. 5 Correlation between NO reduction ratio and NCO adsorption intensity

It was therefore confirmed that the NO dissociation reaction is an important reaction for the NO reduction reaction.

In the case of molecules that do not have paired electrons, such as NO, the driving force of the phenomenon of molecular dissociation is generally considered to be destabilization due to electron donation to antibonding orbitals (Fig. 6)⁽¹⁹⁾.

It is reasonable to assume that the source of these donor electrons is the catalytic metal into which the NO molecules are adsorbed. It was, therefore, considered that the dissociation reaction occurs as a result of electron donation from the catalytic metal to the NO molecules, and that the ease or lack thereof of this electron donation is dependent on the electronic structure of the catalytic metal. It was, therefore, conjectured that there would also be differences in the NO dissociation properties as a result of differences in the electronic structure of the catalytic metal (Fig. 7). The electronic structure of the catalyst valence band was therefore analyzed using XPS. The influence of the catalyst oxide was then subtracted, and the correlation between the electronic structure of the valence band of the catalytic metal alone (indexed valence value) and the dissociation properties of NO was investigated.

The results indicated a high correlation, as shown in Fig. 8, suggesting that electrons were donated from the catalytic metal to NO molecules.

Summarizing the results concerning NO reduction obtained in the series of experiments conducted up to this point:

- A correlation was obtained between the NO reduction ratio under simulated exhaust gas conditions and the NO reduction ratio under NO-CO conditions.

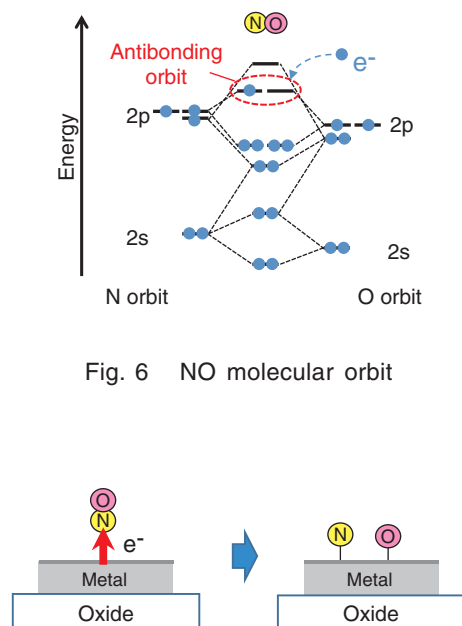


Fig. 6 NO molecular orbit

Fig. 7 Model of NO dissociation by electron donation

- It was confirmed that the NO dissociation reaction is an important reaction pathway for NO reduction, and that a correlation exists between the dissociation properties and reduction performance.
- A correlation between the dissociation properties of NO and the indexed valence value of the catalytic metal was confirmed.

Based on the results discussed above, it was considered that there was a correlative relationship between the electronic structure of the catalytic metal and NO reduction performance. It was therefore decided to conduct a detailed analysis of the density of state using first-principles calculations.

3.2. Analysis of Reaction Density of State Using First-principles Calculations

In order to provide theoretical backing for the observation that the NO dissociative reaction, which is important in the reduction of NO, occurs as a result of the donation of electrons from the catalyst metal, and to establish a search index for density of state in materials informatics, the electronic structure was analyzed using first-principles calculations.

3.2.1. Calculation method

The density of state in the NO dissociative adsorption process was analyzed using density functional theory (DFT), a representative first-principles calculation method⁽²⁰⁾. Table 4 shows the conditions for these calculations. The nudged elastic band (NEB) method⁽²¹⁾ was employed in the analysis of the process of transition. Table 5 shows the calculation conditions.

3.2.2. Density of state calculation model

Pd was employed as the representative metal in the calculation model. With regard to atomic position, NO

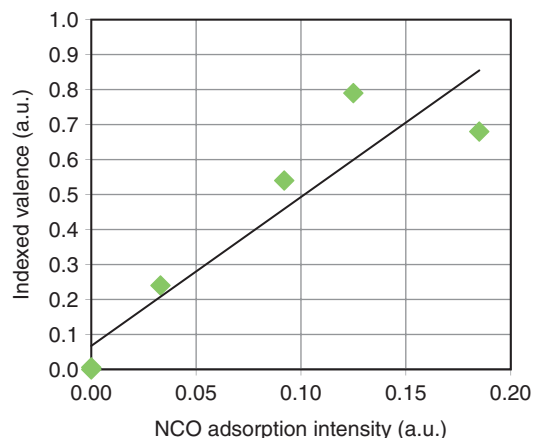


Fig. 8 Correlation between NCO adsorption intensity and indexed valence of catalytic active metal

Table 4 First-principles calculation conditions

Item	Detail
Software	Quantum espresso
Functional	PBE -GGA
Cutoff energy	35.0 Ry
K-points	$3 \times 3 \times 1$
SCF conv.	1E-07
Magnetism	Spin-unpolarized

Table 5 NEB calculation conditions

Item	Detail
Number of images	11
Optimize scheme	Quick-min
Path threshold	0.05 eV/Ang
Spring constant	0.1 a.u.

molecules were positioned on the outermost surface of the Pd (111) three-layer slab model as the initial state of the reaction, and N and O atoms were positioned as the final state of the reaction (total number of atoms: 38). For each positioning, the position in which adsorption would be stable was determined after conducting geometry optimization calculations. As a result, the state in which the NO molecule was adsorbed vertically into an fcc hollow site with the N atom and the Pd in contact was set as the initial state of the reaction (Image 0), and the state in which the O atom was dissociated and adsorbed into the adjacent fcc hollow site was set as the final state of the reaction (Image 10) (Fig. 9).

3.2.3. Calculation results

Figure 10 shows the distance between the N atom and the O atom from Image 0 to Image 10, following geometry optimization based on the NEB method.

These results indicate that the vertically adsorbed NO molecule collapses into the Pd surface, and from Image

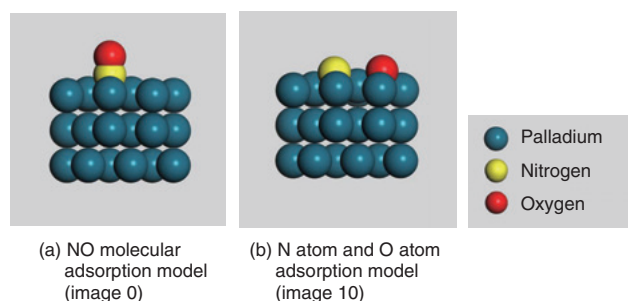


Fig. 9 NO adsorption model

5 onwards the distance between the N atom and the O atom gradually increases until dissociation finally occurs. The density of state during this process of transition was analyzed. The O atom was focused on in this analysis, as it was considered that because the O atom was at the furthest distance from the Pd surface in the initial state of the reaction and had been adsorbed into the Pd surface in the final state of the reaction, the change in density of state due to hybridization of orbitals would be greatest for this atom. Figure 11 shows a color map of the degree of change in LDOS in the p orbital of the O atom from Image 0 to Image 10. It was confirmed that there was a rapid increase in LDOS at close to 0 eV (in the white broken lines) from Image 6 onwards. This is considered to indicate that during the NO dissociation process, electrons were donated from the Pd to close to the Fermi level of the O atom (NO molecule).

Based on the results discussed above, it was considered from the changes in the position of the N atom and the O atom and the changes in density of state, that density of state close to the Fermi level contributed to the NO dissociation reaction. It was also considered that an alloy catalyst in which the density of state was high close to the Fermi level would promote more active electron donation to NO, boosting the dissociation properties of NO, with the result that it could be expected that NO reduction performance would ultimately increase. In this research, therefore, a particular energy band close to the Fermi level was specified, and LDOS within that range was employed as an index for the materials search.

3.3. Alloy Search Using Materials Informatics

The LDOS index value specified in Clause 3.2.3. was set as the target variable, and a binary alloy that would increase that value was searched for using SMI⁽¹⁸⁾, which offers good predictive accuracy even when the amount of data is

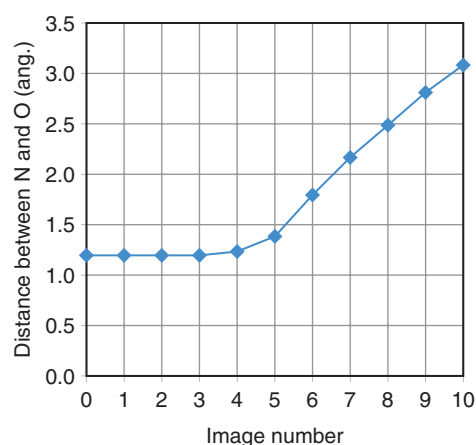


Fig. 10 Distance between N atom and O atom for each image

comparatively low. Because the purpose of calculations in the research under discussion was to reduce search time, and performance would ultimately be confirmed by testing, the calculation model for density of state was a face-centered cubic-based complete solid solution model. The composition ratio was a 1:1 atom ratio.

3.3.1. Density of state calculation model and calculation conditions

With regard to the positioning of the atoms, a bulk model [Fig. 12(a)] was formulated in which heteroatoms were uniformly arrayed in a complete solid solution. The calculation procedure was as follows: following the application of geometry optimization calculations using the bulk model, a six-layer slab model (total number of atoms: 24) was cut out of the (111) plane [Fig. 12(b)]. Geometry optimization calculations were then reapplied. Next, the LDOS for the two heteroatoms on the outermost surface in the specified energy band close to the Fermi level was calculated, following which the values that had been standardized by the value for Pd were set as indexed LDOS. The calculation conditions are shown in Table 6⁽²²⁾⁻⁽²⁴⁾.

Table 6 First-principles calculation conditions

Item	Detail
Software	DMol ³
Functional	PBE -GGA
Basis set	DNP basis set
Core treatment	DFT Semi-core pseudopotential

3.3.2. Formulation of prediction model for LDOS index values

SMI was employed to formulate a prediction model with the LDOS index values for the two heteroatoms on the outermost surface as the target variable and the basic chemical parameters of the elements as the explanatory variables (Fig. 13).

In the first round of formulation of prediction models, LDOS index values for 48 single metal and 42 binary alloys (total: 90 types) were employed. Dozens of types of binary alloy predicted to have high LDOS index values based on the results were calculated and confirmed using DFT, after which the prediction model was updated by adding these as learning points. This active learning was conducted a number of times, increasing the accuracy of the prediction model. Ultimately, a prediction model was formulated based on LDOS index values for a total of 164 types of single metal and binary alloys.

3.3.3. Results of formulation of binary alloy prediction model

Figure 14 shows fitting results and leave-one-out cross-validation (LOOCV) results for the prediction model.

Given that the model was formulated using basic chemical parameters as the explanatory variables, the fitting results and LOOCV deviation are basically acceptable. Among the 2048 single-metal and binary alloys, excluding combinations with radioactive elements, gaseous elements and the like, the three precious metals Pd, Rh and Pt, which are already used in exhaust gas purification catalysts, each had an LDOS value in the top 30. Even when compared with empirical findings in this way, the LDOS calculation model and prediction model formulated in this research were demonstrated to possess a high degree of validity.

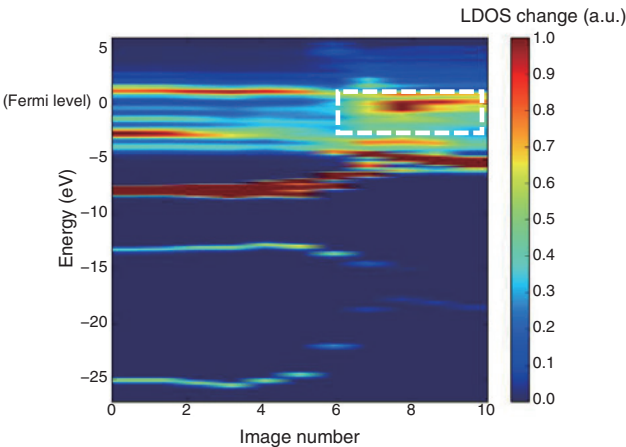


Fig. 11 Change in LDOS of oxygen p orbital during NO molecular dissociation process

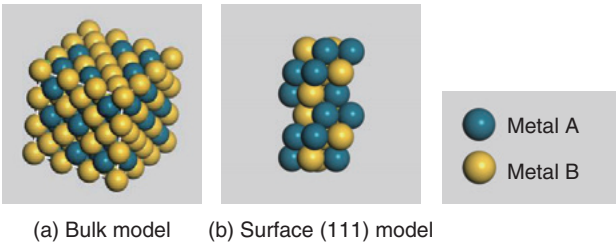


Fig. 12 First-principles calculation model

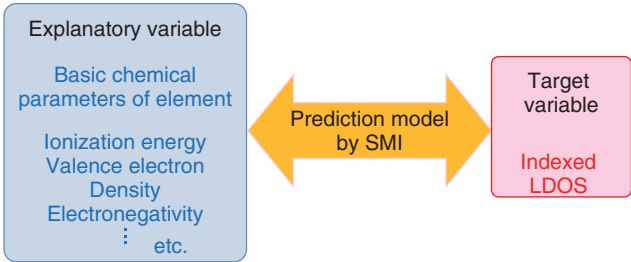


Fig. 13 Prediction model for indexed LDOS

3.4. Synthesis and Characterization of Binary Alloy Catalysts

Among the binary alloy compositions with high LDOS index values as indicated by the prediction model discussed in Clause 3.3.3., alloy catalysts that were considered synthesis candidates were synthesized, and the state of synthesis was confirmed.

3.4.1. Method of synthesis of binary alloy catalysts

In order to help preclude the extreme segregation of dissimilar metals in the alloy synthesis process or the phase-separated deposition that occurs in core-shell structure⁽²⁵⁾, particles that had been alloyed using the liquid phase reduction method⁽²⁶⁾, which creates the possibility for simultaneous deposition of dissimilar metals, were loaded onto γ -Al₂O₃. In the case of systems in which the reduction potential difference of the metallic elements was high and it was predicted that simultaneous deposition would not be easy, and systems which included elements with a higher reduction potential than the reducing agent, the alloys were synthesized by direct sputtering onto γ -Al₂O₃ using arc plasma⁽²⁷⁾.

3.4.2. Characterization of binary alloy catalyst

In order to confirm that alloy particles were present on the γ -Al₂O₃, structural analysis was conducted using X-ray diffraction (XRD), particle distribution was measured using scanning transmission electron microscope-energy dispersive X-ray spectroscopy (STEM-EDS), and an elemental analysis was performed for comprehensive judgment of the success of forming an alloy catalyst.

Figure 15 shows XRD measurement results for a PdCo alloy catalyst synthesized using the liquid phase reduction method as a typical example. The results of diffraction peak analysis showed that peaks do not appear at the diffraction angles that indicate Pd (111) and Co (111), while at the

same time, a peak indicating a PdCo solid solution alloy appears between those diffraction angles (shown by the arrow).

STEM-EDS analysis was applied to samples for which XRD structural analysis had confirmed the formation of a solid solution alloy. Figure 16 shows the results of electron microscopic observation and elemental analysis of the PdCo alloy catalyst.

From the high angle annular dark field (HAADF) image, in which contrast difference is obtained as a result of the atomic number, it was confirmed that metal particles were widely dispersed on the γ -Al₂O₃. Analysis of the state of elemental distribution using EDS mapping showed that Pd and Co are present in basically the same positions. Therefore, based on the results of XRD measurements and STEM-EDS observations, it was judged that PdCo was present on the γ -Al₂O₃ as alloy particles. The successful synthesis of a variety of alloy catalysts was judged in the same way. In addition, electronic structure measurements using XPS and measurements of indexed valence per concentration of loaded metal were conducted for the samples that were judged as alloy catalysts.

Table 7 shows the methods employed to synthesize the binary alloy catalysts that had been narrowed down as candidates by calculations, an indication of the success of synthesis, and the indexed valence values for the alloy catalysts.

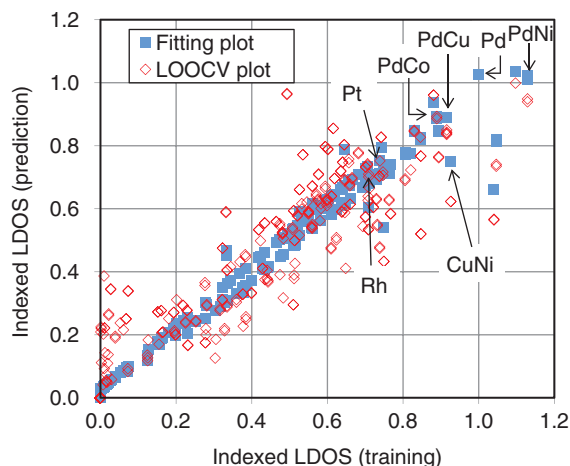


Fig. 14 Fitting result and LOOCV result

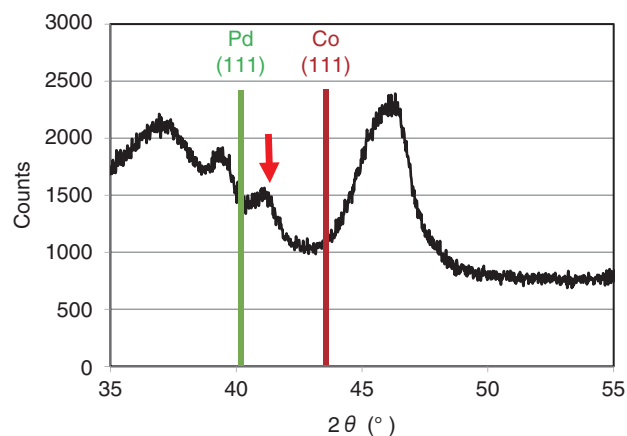


Fig. 15 XRD profile of PdCo alloy catalyst

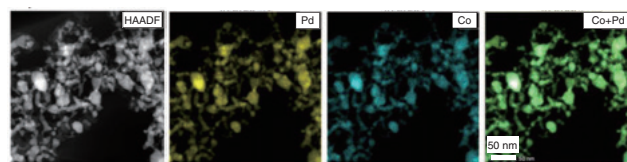


Fig. 16 STEM-EDS analysis of PdCo alloy catalyst

Table 7 Results of synthesis of alloy catalyst

Alloy system	Synthesis		Indexed valence (a.u.)
	Method	Success or failure	
Pd (Ref.)	Liquid phase reduction	S	26.1
PdNi	Liquid phase reduction	S	30.2
PdCu	Liquid phase reduction	S	12.2
PdCo	Liquid phase reduction	S	36.0
PdAu	Liquid phase reduction	S	6.2
PdAg	Liquid phase reduction	F	-
AuNi	Arc plasma	S	11.9
CuNi	Liquid phase reduction	S	9.1
CoNi	Liquid phase reduction	S	5.1
CoRe	Arc plasma	F	-
CoGe	Arc plasma	F	-
NiSn	Arc plasma	F	-
MoNi	Arc plasma	F	-
NiW	Arc plasma	F	-
CoMo	Arc plasma	F	-
NiRe	Arc plasma	F	-
CoCu	Arc plasma	S	11.2

4. Evaluation of Performance of Binary Alloy Catalysts

The performance of the alloy catalysts when new was evaluated under the NO-CO conditions employed in Clause 3.1.1. (2), and the correlation between the indexed valence value and catalyst performance at 300°C was evaluated (Fig. 17). Turnover Frequency (TOF), as expressed by Eq. (1) below, was employed as the index of catalyst performance. Note that the reaction surface, S , was calculated from the actual amount loaded and the average particle size for each alloy catalyst.

$$T.O.F. \text{ (mol/sec} \cdot \text{m}^2\text{)} = A \text{ (mol/sec)} / S \text{ (m}^2\text{)} \quad (1)$$

A : Reaction molecule amount per second

S : Reaction surface

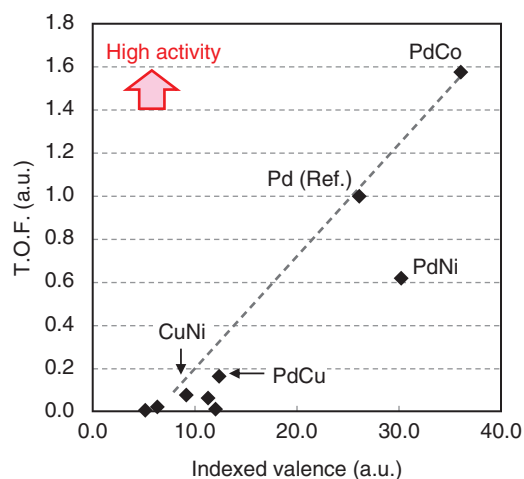


Fig. 17 T.O.F. against indexed valence for various alloy catalysts

The results showed that, as predicted, reduction performance tended to be greater in alloy catalysts with higher indexed valence values. In particular, the PdCo alloy catalyst displayed a level of performance approximately 1.6 times greater than a Pd catalyst (Ref.). The performance of the synthesized PdCo catalyst was therefore also evaluated under the simulated exhaust gas conditions employed in Clause 3.1.1. (2). The results are shown in Fig. 18.

Despite the fact that its Pd content was approximately two-thirds that of a Pd catalyst (Ref.) by weight ratio, its reduction performance exceeded that of the Pd catalyst in the 300°C-400°C range. This indicated that it had been possible to search for and verify the performance of an alloy catalyst that used a reduced amount of precious metals while also maintaining or increasing reduction performance, as per the initial target.

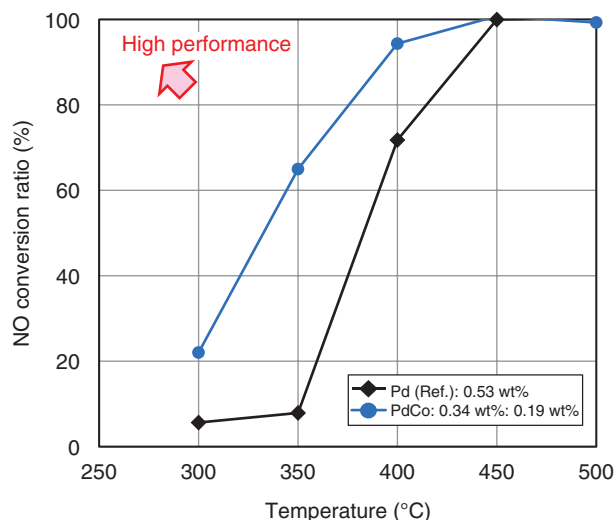


Fig. 18 Results of performance evaluation on condition of simulated exhaust gas composition

5. Conclusion

(1) A materials search flow that functionally integrates experiments, first-principles calculations and materials informatics was created, and its effectiveness was confirmed. The main points of this research are as follows:

- Experiments showed that correlations exist between NO reduction performance and NO dissociation properties, and between NO dissociation properties and the electronic structure of the valence band of the catalyst metal.
- Using first-principles calculations, an analysis of the density of state that contribute to the NO dissociation reaction was conducted, and LDOS in a specified

energy band close to the Fermi level was established as an index for materials searches.

- It was possible to efficiently search for binary alloy compositions that could realize high performance by conducting repeated iterations of materials informatics and first-principles calculations with indexed LDOS as the target variable.
- (2) A binary alloy identified by the materials search flow developed in this research falling in the top level of performance was synthesized, and a PdCo catalyst using 30% less Pd while realizing a higher level of performance than a Pd catalyst was created.

The basic concept of the integrated flow employed in this research is not restricted to catalyst materials but can be broadly applied, and its use in relation to a variety of materials searches can be expected in the future.

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Material Database for Efficient Development Using Materials Informatics

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ABSTRACT

A comprehensive material database that enables the storage, management and export of material data and related information in a standardized format has been constructed to promote the use of materials informatics to achieve highly efficient materials research, such as the application of information science to predict physical properties in order to reduce experimental trial and error.

Usability and user differences such as expertise were taken into account when selecting the database tools and creating the internal structure. As a result, storage of around 10,000 test data and standard properties in various material fields has been completed.

It was confirmed that this enables a reduction in the work time required for data cleansing, which is an issue for use of materials informatics. It also facilitates the acquisition of data needed for design and CAE, etc., and helps to increase operations efficiency and reduce development costs.

1. Introduction

Due to factors such as economic globalization and the rapid progression of global warming, there are growing needs for the enhancement of automotive parts, including weight and cost reduction and higher functionality. Material and manufacturing process development has also been promoted for the materials that comprise automotive parts in order to achieve replacement with aluminum and resin materials that have lower density than steel materials⁽¹⁾⁻⁽³⁾. This type of development process typically adopts the empirical method, in which various prototype materials with different composition and manufacturing conditions are synthesized, and the basic properties are obtained using test pieces. However, functional materials such as adhesives, catalysts, and magnets, and new manufacturing processes such as additive manufacturing (AM)⁽⁴⁾ have a wide range of factors that influence material properties, and this entails enormous cost and work time to acquire the basic properties for analysis of those factors. Therefore, methods that use materials informatics (MI), which integrates materials science and machine learning to predict material properties from test results, are attracting attention⁽⁵⁾.

MI uses material properties as target variables and factors such as composition and manufacturing conditions as explanatory variables, performs statistical processing to derive the relationships between these variables, and

optimizes the material composition and manufacturing process based on those relationships. Therefore, prerequisites for use of MI include not only a certain amount of material property measurement data, but also the necessary related information and an integrated data format. In practice, however, there are individual differences in the expertise, roles, and skills, etc., of data owners, so information such as data distribution, test conditions, and units may be missing, and there may be variations in notation, such as the use of trade names or abbreviations as material names. Therefore, in cases such as when there are multiple data owners, first the owner is identified, and then the data is aggregated, data with the necessary related information is selected, and a data list is created with an integrated format such as data arrangement, unit, and notation of terms. Further processing, such as data conversion according to the purpose, is then performed, enabling the start of data analysis. This type of data cleansing work to collect, convert, and organize data is said to account for 70% of the work time needed for machine learning, including MI, and is a major issue for the use of MI^{(6),(7)}.

2. Development Goals

Efficient material development using MI calls for swifter data cleansing by storing material test data structurally, together with manufacturing conditions and other incidental

¹ Honda Motor Co., Ltd.

Table 1 Comparison table of DB software

	Requirements	DB Software		
		Software [A]	Software [B]	GRANTA MI
Input	Material name, standard name and product name can be input together	+++	+++	+++
	Attributes can be added easily, and input template is created automatically	+	++	+++
	Unit can be converted automatically	+++	+++	+++
	Links between data can be created easily	+	++	+++
Display	Display items and layout can be changed according to the purpose	+	+++	+++
	Graphs can be superimposed easily	+	+++	+++
	Graphs can be created from the results of search and statistical processing	+	++	+++
Search	Complex search including process and test conditions can be performed	+	++	+++
Export	Data can be exported in Excel, PDF, CSV format, etc.	+	+++	+++
	Works with Abaqus, LS-Dyna, FEMFAT, Nastran, Enovia, CATIA, etc.	++	+++	++
Administration	Access can be controlled by data, folder or database	+	+++	+++
	Revision and release history remains	+	+++	+++
	Easy modifications for large amounts of data	+	+	+++
	Reliability rank of data can be displayed	+	+++	+++
Cost	Reasonable purchase price and maintenance cost	+++	+	+++

information in a material database (DB) and exporting these data in a fixed format. Furthermore, if representative material properties used for design and CAE can be centrally stored and shared in a material DB together with material test data, various operational efficiency enhancements such as standardization of data, reduction of inquiry work time, sharing of know-how, and leveling of workload can be expected in addition to reduction of development costs.

Therefore, the authors decided to construct a new material DB with the following two goals.

- (1) Swifter data cleansing for efficient MI use.
- (2) Centralized management of material data for enhancement of operational efficiency and reduction of development costs.

3. Material DB for Use of MI

When using material DB that are publicly accessible such as via the Internet in this development, it is a challenge to store in-house data in a flexible manner that maintains confidentiality^{(8), (9)}. In addition, many material DBs operated within companies list specific material properties such as Young's modulus and density, and storage of other material properties and detailed test data would entail large system renovation costs. Furthermore, in order to construct a material DB and maintain long-term functionality, it is necessary to not only store the information sought by users, but also to take into account convenience by enabling easy data registration, modification, search, and utilization in accordance with changing needs.

Therefore, commercially available DB software that enables DB construction without specialized skills such as programming languages and that also enables flexible

modification was used to design a highly convenient DB structure, and data was accumulated.

3.1. Selection of DB Software

When selecting the DB software, multiple software with proven records both in-house and outside the company were evaluated beforehand in terms of input, display, search, export, administrative functions, and usage cost, etc. Table 1 summarizes these results. Software B and ANSYS, Inc.'s GRANTA MI received nearly the same rating, but importance was placed on features such as automatic creation of input templates, search and export with complex conditions, and batch modification of data, and in the end GRANTA MI was selected.

Figure 1 shows an overview of the GRANTA MI system. Like a typical Web application, each user and DB

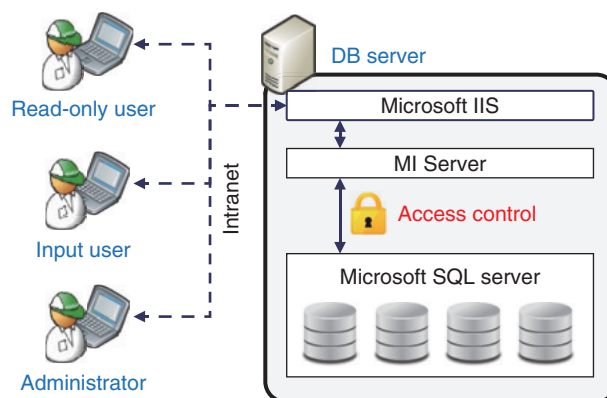


Fig. 1 System configuration of GRANTA MI

administrator logs in to Microsoft IIS from a client PC via an intranet, the GRANTA MI core system MI Server determines the access rights and performs data processing, and multiple DBs within Microsoft SQL Server can then be accessed. Administrators can also limit the data viewing, input and export ranges according to differences in user responsibilities and expertise.

3.2. DB Structure Design

Figure 2 shows various automotive parts and the corresponding required properties for each material type. As shown here, the material properties to be handled differ for each material field, such as strength and rigidity for metals, weather resistance and viscosity for resin materials, and magnetic properties for magnetic materials. This results in a correspondingly diverse range of test methods and registration items. In addition, there are also various manufacturing methods such as casting, rolling, sintering, injection molding, and AM, and each method uses different parameters, so it is more efficient to manage these using separate DBs.

However, representative property values and judgment criteria values for a wide range of materials are used in design work and CAE analysis, but those values are also based on large amounts of test data from different suppliers and test environments, etc. For example, when setting fatigue strength criteria for a material, 10 to 30 tests are conducted at each temperature in the anticipated operating temperature range, and the influence of strength variation due to factors such as surface roughness, hardness, and quality is also taken into account. This calls for separate management of representative values and actual data.

Therefore, the DB structure was separated into a Design and simulation DB that manages representative properties and DBs, such as a Metal DB and Resin DB that manage

the test data for each material field as shown in Fig. 3. The Design and simulation DB structure is further divided into mutually interlinked areas that manage physical property values, together with supplemental information such as representative values and guaranteed values (Design table), manage property values by CAE purpose (Simulation table), and manage applied materials by part (Application table). Meanwhile, it is presumed that material tests are conducted under multiple manufacturing conditions even for the same material type. Therefore, each DB for managing test data was designed with mutually interlinked areas that manage material name lists (Material list table), manage related information such as compositions and manufacturing conditions (Pedigree table), and manage various test conditions and data (Test data table).

This lets design and CAE staff swiftly access the representative material properties needed for operations even if they have little materials expertise, and raw data can also be checked retroactively as needed. It also enables flexible input and export of special test data and manufacturing conditions that differ for each material field, which makes it easier for materials staff to accumulate and reuse data.

3.3. Addition of Data Input Assist Functions

One feature of the above-mentioned GRANTA MI is that the input template is automatically created when the input items are set. However, at the default setting there are no restrictions on the input contents, so when unspecified multiple users freely enter data, differences occur in the material classification method and the degree of data completeness, which does not lead to a reduced data cleansing load. In the case of resin materials, for example, it is necessary to accurately input various classification information such as the base resin, ISO standard, in-house

	Metals	Polymers	Magnetics and catalysts	Chemical
Parts	 Body, cylinder block, gear, etc.	 Bumper, tire, oil, engine cover, etc.	 Rotor, stator, converter, etc.	 Door, color, seat, etc.
Material	Steel, aluminum, magnesium	Resin, rubber, oil, long life coolant	Ceramics, magnet, precious metal	Adhesive, paint, fabric
Demanded properties	Fatigue strength, elongation, rigidity, weldability, heat resistance, etc.	Environmental resistance, wear resistance, fluidity, etc.	Core loss, flux density, conversion efficiency, etc.	Adhesion strength, anti-corrosion performance, viscosity, etc.

Fig. 2 Material classification and required properties

standard, and supplier grade name. In the case of metal materials, it is necessary to keep load conditions such as axial and bending directions together with fatigue test results. However, if this information is missing or incorrect, not only does data correction become necessary, but it can also lead to inconvenience such the inability to find the needed data.

Therefore, input assist functions such as the following were added to the input template to help correctly search for the needed data.

- (1) Item description: Descriptions and actual examples of items are shown in order to minimize differences in interpretation of item names.
- (2) Selection list setting: Items with limited entry contents such as classification are selected from pull-down menus in order to achieve consistent input word notations.
- (3) Image file name input: A function that automatically enters image file names to the template was added in order to streamline the input of large numbers of images.
- (4) Automatic entry: Items such as ID that are to be entered in accordance with administrative rules are entered automatically.
- (5) Contents check: Prior to import, it is possible to check that the data format of items such as text, values, and date are correct, and that required fields are entered.

3.4. Centralized Management of Material Data

When using MI, the more experimental data that can be prepared, the better. However, material data involves the synthesis of prototype materials and creation of test pieces, so it is not an easy task to obtain thousands or

Table 2 Number of records

Material categories	Databases	
	Design and simulation	Metal, resin, etc.
Metals	755	7104
Resins	304	363
Rubbers	87	495
Magnetics	121	785
Fluids	49	66
Catalysts	0	394

tens of thousands of data. Therefore, the Smart Materials Informatics method⁽⁵⁾, which enables the prediction of properties even with a small number of data, was used to investigate the number of data that enables prediction. In the referenced study, artificial data was used to understand the relationship between the number of data and prediction error, and verification was performed using actual catalyst, magnet, and thermoelectric material data. As a result, it was stated that at least several tens to hundreds of data are needed per case for prediction to function effectively⁽⁵⁾. Based on this, the target number of accumulated data in this DB was set as a total of 10,000 records for the 500 main material types used in automobiles, and activities to promote input such as hands-on in-house seminars were conducted. As a result, registration of records equivalent to the target number was completed over the approximately three-year period through April 2020, as shown in Table 2. This is an amount comparable to the 1,130 records of the aerospace material DB (MMPDS) and 6,600 records of the metal material DB (MI-21).

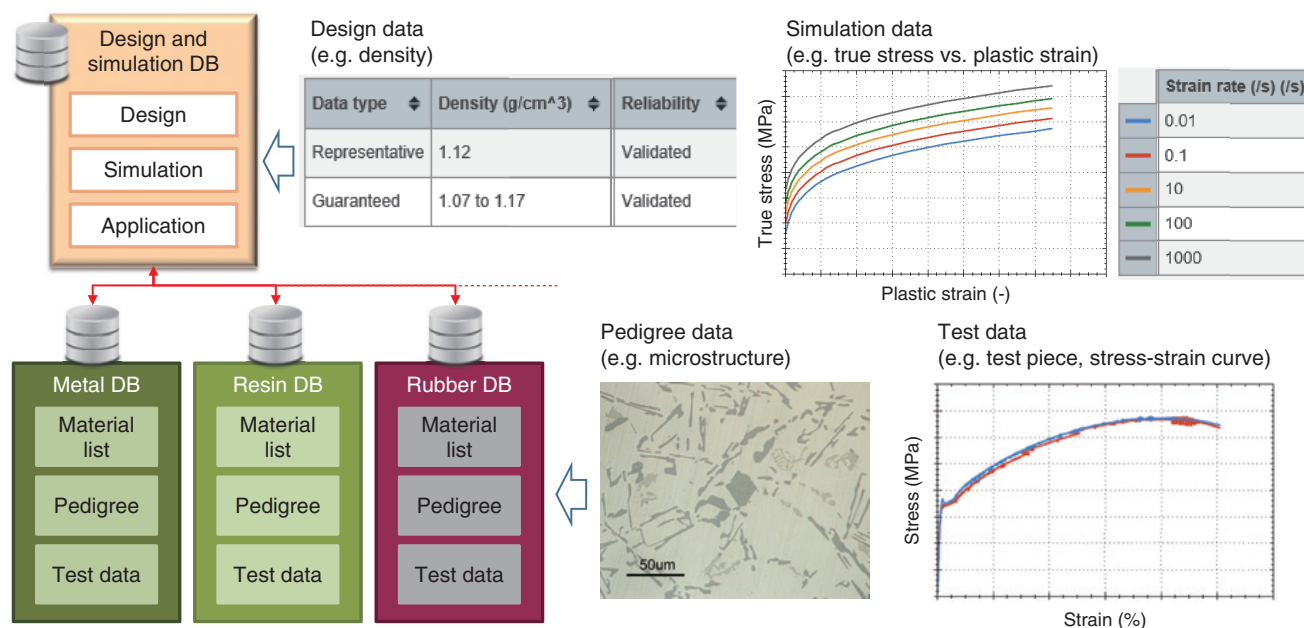


Fig. 3 Structure of database and example data

4. Introduction of Cases of Technical Application

4.1. Use of MI to Promote New Material Development

In order to use MI, it has been necessary to spend much work time on data cleansing, such as collection and selection of test data with clear material manufacturing and test conditions, and integration of data formats. However, the accumulated test data can be stored in this DB and exported in a standardized format together with related information, which enables the use of MI with greatly reduced data cleansing. Figure 4 shows an example of the results for storage and export of chemical material test data. In this example, the measurement results for adhesion strength and viscosity are stored in a linked format with information of the combination of compounds that constitute the chemical materials. In addition, the results of 25 different tests are exported in list format. Although it is still necessary to convert the data as before, the time needed for data collection and selection and format integration was greatly reduced by inputting it in accordance with the input template, which reduced the total data cleansing time by 80% or more as shown in Fig. 5.

Next, Fig. 6 shows the material property prediction results obtained by applying MI to these test results. Here, the correlation between each component and each material property was obtained from 25 test results exported from the DB, and the unknown adhesion strength and viscosity for 400,000 different combinations of components was then predicted based on those correlations and plotted. This figure

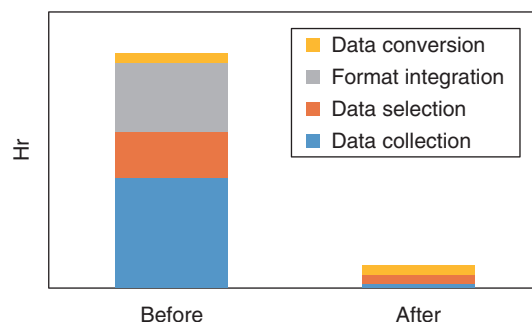


Fig. 5 Change in data cleansing time

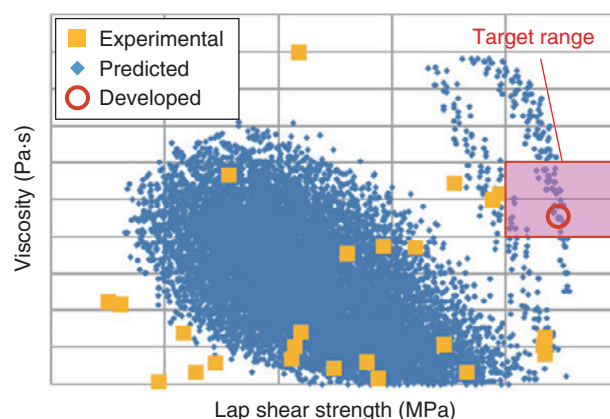


Fig. 6 Property predicted results of adhesive materials

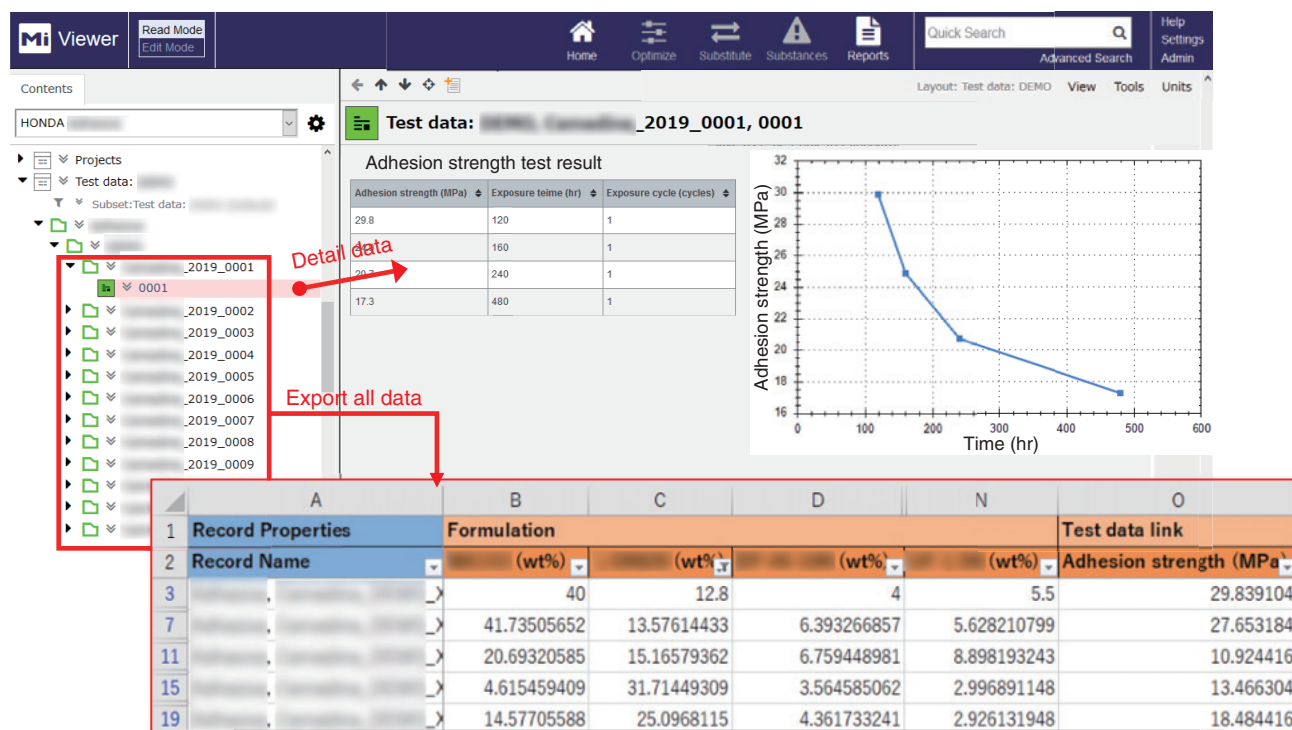


Fig. 4 List output of adhesive test data

shows that combinations of components that can provide high adhesion strength within the viscosity range demanded by automotive production lines can be efficiently extracted. As an example, Fig. 7 compares the measured and predicted values of the material properties of the developed material shown in the red circle in Fig. 6. Thus, the use of data accumulated in this DB together with MI enabled the prediction of unknown material properties with high accuracy, and provided a direction for the development of new materials.

4.2. Enhancement of Operational Efficiency

As part of their duties, materials staff verify functions in consideration of the operating environmental load of each part. For example, the functional life of rubber materials differs according to the operating temperature and the material type, so life verification is performed for each individual part, and alternative materials are investigated from among a large number of material types as necessary. In this case, it was previously necessary to collect heat resistance data for all of the materials to be compared and to compare them by drawing on Excel. However, this DB enables a superimposed display of the heat resistance properties of each material obtained from the accumulated data, as shown in Fig. 8, so materials suited to the operating environment can be investigated from among a wide range of materials in a shorter time. Furthermore, approximate properties can also be estimated from past data even for materials with unknown material properties. Figure 9 shows an example of low- and high-frequency core loss values extracted from 160 separate magnetic property measurement data for electric steel sheets and expressed in an X-Y graph. This figure shows that differences in the correlation of each property according to the sheet thickness can be quantitatively expressed, which enables more accurate estimation even for materials with a thickness for which the properties have not yet been measured.

Use of this DB can be expected to increase design work efficiency when selecting material types based on material properties. Figure 10 shows an example of the results of extracting materials with a yield strength of 80 MPa or more and a tensile strength of 100 MPa or more as representative

properties at 800°C from over 200 types of registered steel material data. This DB also enables a search for the required property value range in this manner, and also a search for materials by incidental information such as guaranteed values and representative values, which lets designers narrow down the material candidates without inquiries to specialist materials staff. In addition to increasing the work efficiency of designers, this is expected to promote the in-house spread of design studies with standardized physical property values, leading to higher design quality and reduced development reworking.

This DB also stores material models by CAE purpose, so for example, material properties for crash analysis used in domestic automobile development can be used for the same application at overseas development sites. This is expected to increase CAE work efficiency, and also enables a reduction in the cost of material testing, which has been duplicated by each department in order to construct material models. As a result, even adding in license, server administration and other costs related to material DB introduction, it is estimated that material property acquisition costs can be reduced by approximately 41% as shown in Fig. 11.

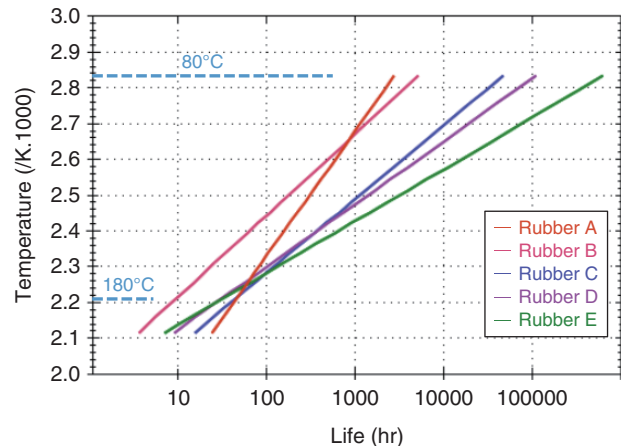


Fig. 8 Temperature and lifetime of rubber materials

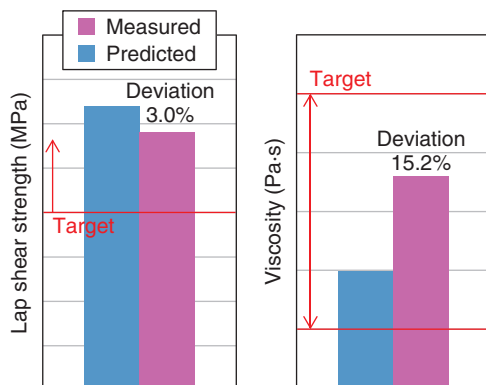


Fig. 7 Properties of developed material

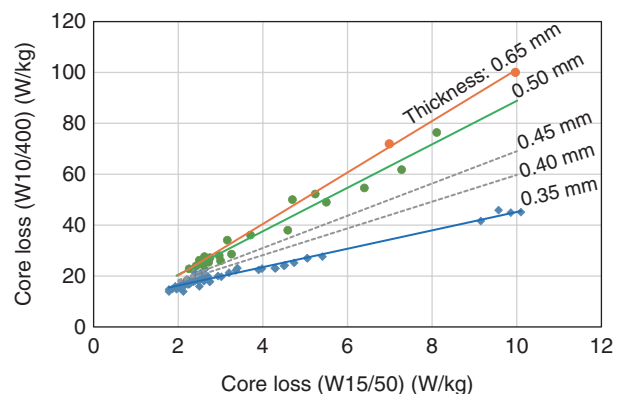


Fig. 9 Relationship of core losses by frequency of electrical steel sheet

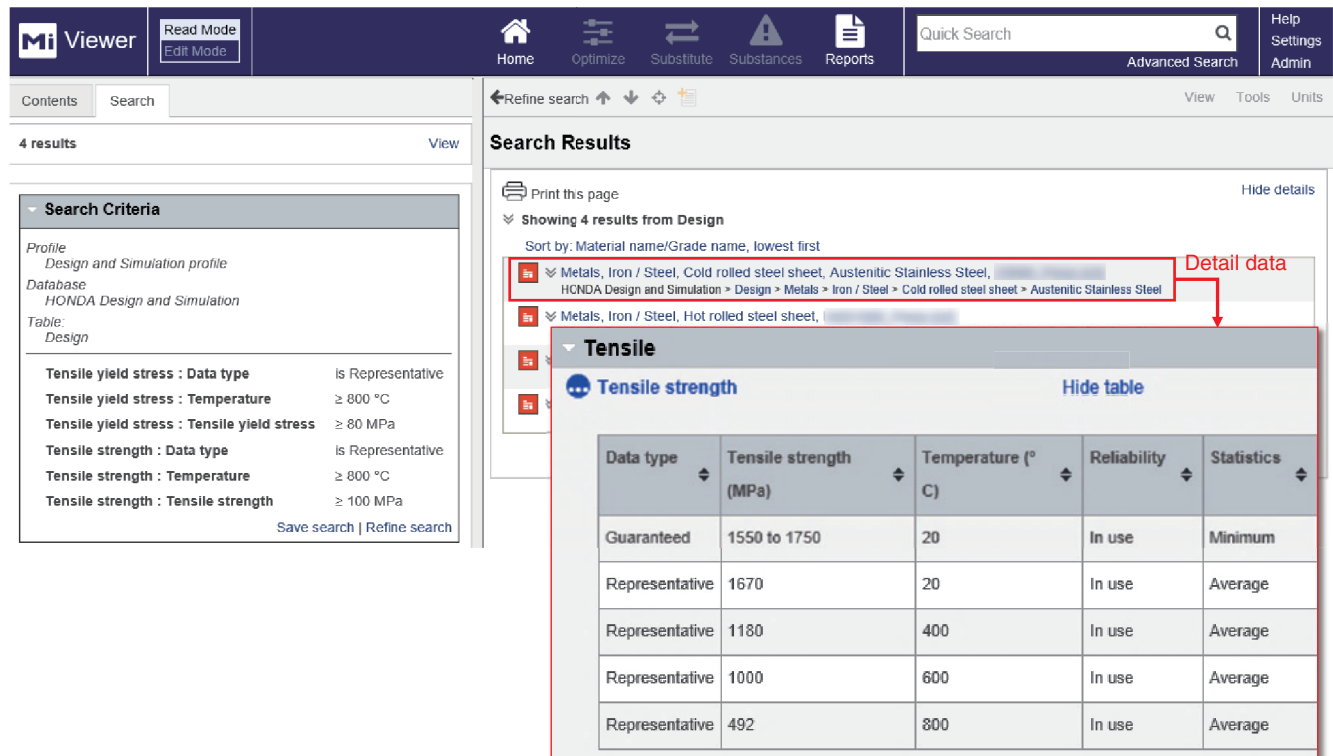


Fig. 10 Search results by material properties

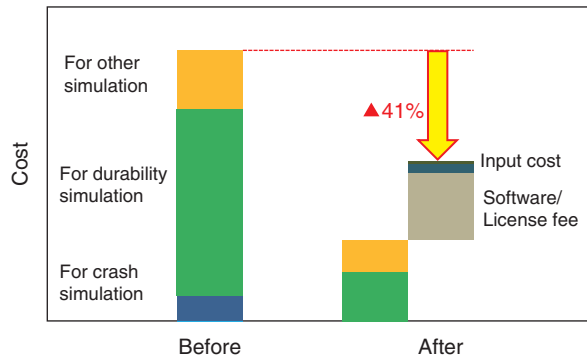


Fig. 11 Material property measurement cost for simulation model

5. Conclusion

A material DB that can store, manage, and export various in-house material data structurally, together with incidental information, has been designed and constructed to increase the efficiency of development operations by utilizing MI. The following effects were obtained as a result.

- (1) The use of data accumulated in this DB together with MI enabled the prediction of unknown material properties with high accuracy, and provided a direction

for the development of new materials.

- (2) By storing and exporting the test data for each material field structurally, together with related information, the work time for data cleansing was greatly reduced, which was an issue when using MI.
- (3) Use of a structure that manages the standard material properties used for design and CAE separately from material test data enables each staff to access the needed material properties by themselves. In addition, it was shown that the cost of acquiring material properties for the construction of material models can be reduced by sharing data between domestic and overseas development departments.

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3D-structured Cathode Electrode for High Capacity Lithium-ion Battery

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ABSTRACT

A study was made of 3D structuring applied to electrode collectors for the purpose of heightening lithium-ion battery performance.

It was confirmed that loading, which is the electrolyte composite coating amount per unit area, could be increased to 150 mg/cm² on the cathode. The results from the calculation of energy density when that electrode was applied clearly showed that energy density could be increased 10% with respect to the foil-coated cathode.

The results from comparison of the foil-coated cathode and 3D-structured cathode with the cathode loading fixed at 90 mg/cm² confirmed that increasing the contact area of the active material and the collector can reduce the initial resistance by 17% with respect to the foil-coated cathode. It was also confirmed that, while the resistance increase during cycle testing was 149% for the foil-coated cathode, this amount was held to 29% for the 3D-structured cathode because of the suppression of structural change.

It was verified that application of the 3D-structured cathode in a lithium-ion battery could achieve a balance between enhancing energy density and addressing the issue of suppressing the increase in resistance and the decrease in durability.

1. Introduction

Reducing automobile CO₂ emissions is a crucial issue in moving toward realization of a low-carbon society. Enhancing fuel economy by electrification of automobiles and achieving full, widespread adoption of electric vehicles are key measures to address that issue^{(1),(2)}. For that purpose, increasing the energy density of lithium-ion batteries becomes a crucial issue^{(3),(4)}.

As shown in Fig. 1, the internal section of a lithium-ion battery consists of the cathode, anode, separator, and electrolyte. The electrodes (cathode and anode) consist of the active material, conductive agent, binder, and collector. The energy density (Wh/L) is calculated as the product of capacity (Ah) and voltage (V) divided by volume (L). The capacity of a battery is determined by the capacity per unit volume of active material in the electrodes and the filling amount of that material.

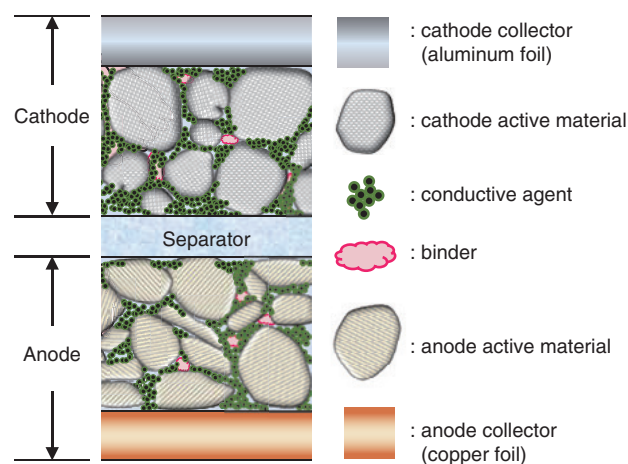


Fig. 1 Schematic section drawing of lithium-ion battery

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The electrodes for lithium-ion batteries in general are manufactured by the processes shown in Fig. 2. As shown in Fig. 2 (a), each of the materials is mixed with a solvent to adjust the composite slurry. Next, as shown in Fig. 2 (b), a coater is used to coat the surface of the metallic foil collector with the composite slurry. After that, it is dried and the solvent is caused to vaporize. Then, as shown in Fig. 2 (c), it is pressure-formed by roll pressing and the electrode is completed.

There are active initiatives to increase the energy density by giving the active material higher capacity or higher voltage. However, these involve such issues as decreases in durability and safety⁽⁵⁾⁻⁽¹⁰⁾.

On the other hand, increasing the coating amount per unit area (hereafter the loading) of electrodes without changing the active material causes a reduction in the number of electrode layers. As a result, the amount of separator and collector used can be reduced. That can raise the energy density of the battery by increasing the proportion of active material in the cell. It is necessary to coat the surface of the collector foil with a large amount of composite slurry in order to increase the loading, but as the amount of composite slurry is increased, an even surface becomes less readily retainable. There is, therefore, an upper limit on the loading⁽¹¹⁾⁻⁽¹³⁾. The increase in loading is further accompanied by an increase in the electrode coating thickness. This can lead to an increase in the internal resistance of the battery and deterioration of the structure, resulting in the issue of reduced durability⁽¹¹⁾⁻⁽¹³⁾. The approach of adopting a composite structure for electrodes in order to increase the loading has been studied in recent years⁽¹⁴⁾⁻⁽²⁴⁾. Applying porous nickel collectors in nickel-hydrogen batteries is another way of realizing enhanced loading⁽²⁵⁾⁻⁽²⁷⁾.

A 3D-structured collector made of aluminum has a thickness of 500 μm or more combined with a 90% or higher porosity. Consequently, filling those voids with active material can increase the loading and raise the energy density. The high conductivity of aluminum also reduces the resistance while the 3D frame structure can be expected to enhance the properties of durability, so that this can be considered a technology that addresses the issues associated with increased energy density.

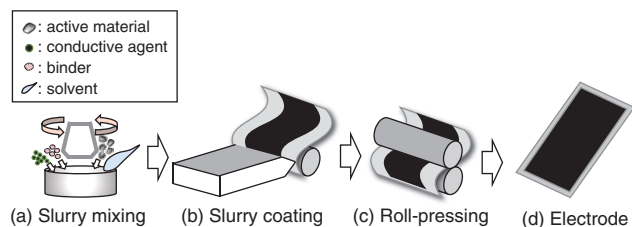


Fig. 2 Schematic view of lithium-ion battery electrode processes

2. Collector Design Guidelines

As indicated in the previous chapter, in order to raise the cell energy density in a lithium-ion battery under the conditions of a constant cell size and fixed active material, it is necessary to increase the amount of active material filling within the cell. The design guidelines for the electrodes in that case say to increase the electrode loading.

With conventional foil-coated cathodes, it was considered possible to fabricate prototype cathodes with loading up to about 90 mg/cm^2 ⁽²³⁾⁻⁽²⁷⁾. On the other hand, a 3D-structured collector, as shown in Fig. 3, is a porous metallic structure, and the possibility of loading it to 150 mg/cm^2 or more per electrode area by filling those voids with electrolyte composite slurry has been confirmed⁽²⁸⁾.

With the cell size held constant and with the proportion of active material and active material in the electrodes fixed, the cell energy density was calculated for cases of different loading on electrodes using ordinary collector foil and on electrodes using a 3D-structured collector (3D-structured cathode), respectively. The calculation conditions are shown in Table 1 and the calculation results in Fig. 4. As indicated in Fig. 4, when comparisons were made with loading of 150 mg/cm^2 under the specified calculation conditions, the cell using the foil-coated cathode had an energy density of 599 Wh/L , while the cell using the 3D-structured cathode had an energy density of 641 Wh/L . An increase of 7% can be anticipated. Since the limit on loading for foil-coated cathodes that allow for prototype fabrication is 90 mg/cm^2 , the limit on energy density for foil-coated cathodes is 581 Wh/L . This means that the application of 3D-structured cathodes can be anticipated to yield a 10% increase in energy density. That cell configuration is shown in Table 2. It is apparent that reducing the number of electrode layers from 40 to 24 layers cuts down on the number of other components used, and the energy density increases as a result.

It can also be seen from Fig. 4 that with cathode loading of 90 mg/cm^2 or more, the energy density of the 3D-structured cathode exceeds that of the foil-coated cathode.

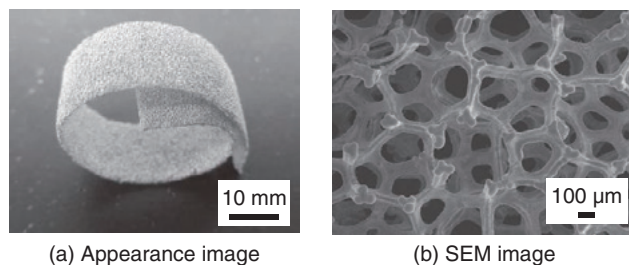


Fig. 3 Images of 3D-structured collector

Table 1 Calculation conditions of electrode

Cathode active material	$\text{LiNi}_{1/3}\text{Mn}_{1/3}\text{Co}_{1/3}\text{O}_2$
Cathode active material content	94 wt%
Cathode collector foil	Al 15 μm
Cathode 3D-structured collector porosity	97%
Anode active material	Graphite
Anode active material content	96.5 wt%
Anode 3D-structured collector porosity	97%
Element ratio	83 vol%
Anode collector foil	Cu 8 μm
Separator	15 μm
Negative/Positive ratio	1.05
Cell volume	360 mL

Table 2 List of cell components

	Cathode loading (mg/cm ²)	Cathode thickness (μm)	Number of electrodes (-)	Capacity (Ah)	Energy density (Wh/L)
Foil collector	90	250	40	57	581
3D-structured collector	150	469	24	61	641

Figure 5 shows the calculation results for the relationship between porosity and energy density in 3D-structured collectors with different porosities. The calculations were made in three patterns, with cathode loading of 90, 120, and 150 mg/cm². The porosity that exceeds the upper limit for energy density with the foil-coated cathode was 97% or higher at 90 mg/cm², 93% or

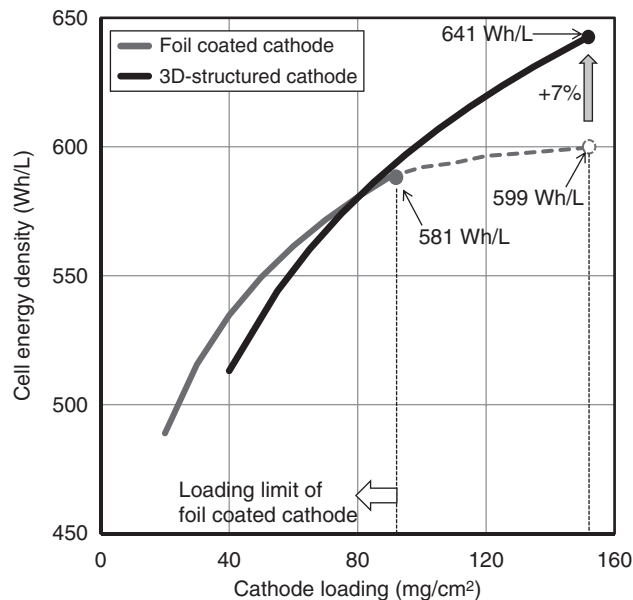


Fig. 4 Comparison between foil coated cathode and 3D-structured cathode

higher at 120 mg/cm², and 89% or higher at 150 mg/cm².

Based on the above results, the collector design guidelines call for increasing the porosity of the 3D structure collectors and increasing the active material filling amount in order to increase loading. Specifically, it was clearly shown that by fabricating electrodes with loading of 150 mg/cm² and with the collector porosity at 97%, the energy density of a cell using the foil-coated cathode would increase 10%.

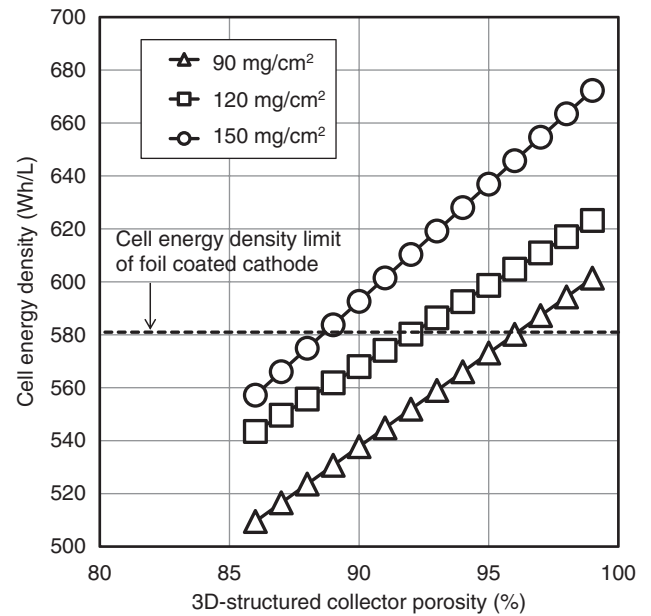


Fig. 5 Relationship between 3D-structured collector porosity and cell energy density

3. Testing Method

3.1. Cell Components

3.1.1. 3D-structured collector

For the cathode collector, Celmet manufactured from aluminum by Sumitomo Electric Industries, Ltd., was used^{(28), (29)}. Typical physical properties are listed in Table 3. As shown in Fig. 6, Celmet is made by applying a process to resin foam with continuous pores to make it electroconductive, after which aluminum is applied by a plating method and the resin foam is removed⁽³⁰⁾.

3.1.2. Cathode

The ternary layered oxide $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Mn}_{1/3}\text{O}_2$ (NCM) is used as the active material, acetylene black (AB) is used as the conductive agent, and polyvinylidene difluoride (PVDF) is used as the binder. These were combined with a composition ratio of NCM/AB/PVDF=94/4/2 wt%. The 3D-structured collector was filled with composite slurry

Table 3 Physical property values of Celmet

	Aluminum-Celmet
Porosity (%)	97
Average pore size (μm)	550
Specific surface area (m^2/m^3)	5500
Thickness (μm)	1000
Area density (g/m^3)	100

and the range of application for loading was confirmed. Next, it was filled to have a loading of $90 \text{ mg}/\text{cm}^2$ and then pressed in a roller press at 120°C so that the electrode density would be $3.2 \text{ g}/\text{cm}^3$, and fabrication of the electrode was completed. The reference electrode, on the other hand, was manufactured to have an electrode density of $3.2 \text{ g}/\text{cm}^3$ by placing a coating on $15\text{-}\mu\text{m}$ aluminum foil for loading of $90 \text{ mg}/\text{cm}^2$ on both sides. The active material was also manufactured in three types with d50 average particle diameters of $5 \mu\text{m}$, $7 \mu\text{m}$, and $10 \mu\text{m}$ for the purpose of confirming the influence of the size of the active material on the lattice structure of the 3D-structured collector.

3.1.3. Anode

For the active material, natural graphite (Gr) was used; for the conductive agent, AB; for the binder, styrene butadiene rubber (SBR); and for the thickening agent, carboxymethylcellulose (CMC). These were combined in a composition ratio of Gr/AB/SBR/CMC=96.5/1/1.5/1 wt%. The above composite was used to coat $10\text{-}\mu\text{m}$ copper foil so that the loading on both sides would be $45 \text{ mg}/\text{cm}^2$. The anode was then pressed in a roller press at room temperature so that the electrode density would be $1.5 \text{ g}/\text{cm}^3$, and fabrication of the electrode was completed.

3.1.4. Separator

A microporous polyethylene film $15 \mu\text{m}$ thick was used.

3.1.5. Electrolyte

A mixture of ethylene carbonate (EC), dimethyl carbonate (DMC), and ethyl methyl carbonate (EMC) was used for the solvent at EC/DMC/EMC=30/40/30 wt%. The supporting salt lithium hexafluorophosphate (LiPF_6) was dissolved in a 1.2 mol concentration in the solvent to make the electrolyte.

Table 4 Test cell components

Cathode active material	$\text{LiNi}_{1/3}\text{Mn}_{1/3}\text{Co}_{1/3}\text{O}_2$
Cathode active material content	94 wt%
Cathode loading	$90 \text{ mg}/\text{cm}^2$
Cathode density	$3.2 \text{ g}/\text{cm}^3$
Anode active material	Graphite
Anode active material content	96.5 wt%
Anode loading	$45 \text{ mg}/\text{cm}^2$
Anode density	$1.5 \text{ g}/\text{cm}^3$
Electrolyte	1.2mol LiPF_6 EC/DMC/EMC = 30/40/30 wt%
Separator	$15 \mu\text{m}$
Negative/Positive ratio	1.2

3.1.6. Exterior body

A laminate film with a thickness of $150 \mu\text{m}$ was used.

3.2. Cell Manufacturing Method

The cathode was punched out to be $30 \text{ mm} \times 40 \text{ mm}$ in size, and the anode, $34 \text{ mm} \times 44 \text{ mm}$. The separator was punched out to be $40 \text{ mm} \times 50 \text{ mm}$ in size. The cell elements were fabricated by placing the anode, separator, cathode, separator, and anode in layers. The laminate film was punched out to be $88 \text{ mm} \times 220 \text{ mm}$ in size, then folded in half. The elements were placed inside it and 1 mL of electrolyte injected, then defoamed and sealed to fabricate the laminate cells. Three of each type of cell were prepared and the average values they yielded were used as the evaluation results. The cell configuration is shown in Table 4.

3.3. Cell Evaluation Method

3.3.1. Rated discharge test

This test was conducted to confirm cell capacity. As an aging treatment, the cells were placed in a thermostatic chamber at 25°C and charged at 0.1 C under constant current (CC), with the upper voltage limit at 4.2 V. After charging under constant current-constant voltage (CCCV) for a constant voltage (CV) time of one hour, the cells were rested for one hour, then discharged at CC at 0.2 C, with the lower voltage limit at 2.5 V. This constituted one cycle, and a total of five cycles were carried out. Cell capacity

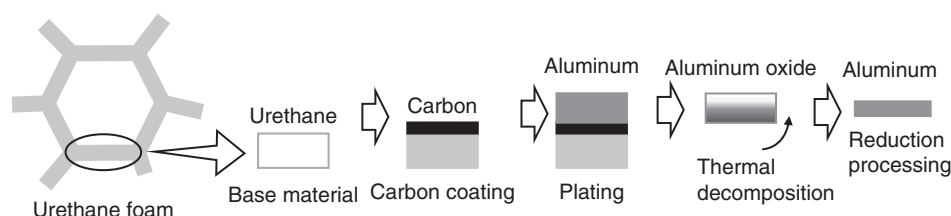


Fig. 6 Schematic processes of production method of Aluminum-Celmet

was defined as the capacity after CC charging at 0.3 C with the upper voltage limit at 4.2 V, charging for a CV time of one hour, then resting for one hour, after which the cell was discharged at CC at 0.3 C, with the lower voltage limit at 2.5 V. For the definition of the C-rate, the current value for full discharge in one hour is taken to be 1 C, where C is the cell capacity (Ah) divided by the full discharge time (h). In other words, for a cell with constant capacity, 0.5 C is the current value for full discharge in two hours, and 2 C is the current value for full discharge in 0.5 hour.

3.3.2. 10-second direct current resistance (10-sec DCR)

This test was conducted to evaluate the internal resistance of the cell. The state of charge (SOC) of the cell was adjusted to 50%. Next, the cell was discharged for 10 seconds at each set current value and the voltage was measured at 0.1 second, 1 second, and 10 seconds of discharge time. The set current values were 0.3 C, 0.5 C, 0.75 C, 1.0 C, 1.5 C, 2.0 C, and 2.5 C. The voltage at each time with respect to each current value was plotted, with the horizontal axis as the current value and the vertical axis as the voltage. The slope of that curve was taken as the resistance, and the resistance at 10 seconds was taken as the overall resistance. Resistance was viewed as having these primary components: the resistance at 0.1 seconds (0.1-sec DCR), which was taken to be electronic resistance; the resistance from 0.1 to 1 second, ((1-0.1)-sec DCR), which was taken to be reaction resistance; and the resistance from 1 to 10 seconds ((10-1)-sec DCR), which was taken to be ionic diffusion resistance⁽³⁰⁾.

3.3.3. C rate discharge characteristics

This test was conducted to evaluate cell capacity at each discharge current value. With the upper voltage limit at 4.2 V and the lower voltage limit at 2.5 V, capacity was measured at the respective discharge current values of 0.3 C, 0.5 C, 0.75 C, 1.0 C, 1.5 C, 2.0 C, and 2.5 C.

3.3.4. Cycle test

This test was conducted to evaluate cell durability. Measurements were made with the cells placed in a thermostatic chamber at 45°C, the upper voltage limit set at 4.2 V and the lower voltage limit at 2.5 V, and subjected to CC discharge at 0.5 C and CCCV charging at 0.5 C for CV time of one hour and rest time of one hour. Every 200 cycles, the thermostatic chamber was set to 25°C and discharge capacity at 0.3 C was confirmed. At the completion of 600 cycles, the 10-sec DCR was measured.

3.4. Analysis of Electrodes

3.4.1. Analysis of particle size distribution

The particle size distribution was measured using the LS13320 manufactured by Beckman Coulter, Inc. for the purpose of quantifying the particle diameter of active material particles.

3.4.2. Scanning electron microscope (SEM)

Cross sections were prepared using a cross-section polisher and observed using an ULTRA 55 SEM from Carl Zeiss AG to confirm the state of active material contact with the collector in the electrode.

3.4.3. Micropore distribution measurement

Measurements for the purpose of quantifying changes in micropore distribution in the electrodes before and after cycle tests were carried out by the mercury penetration method using the PoreMaster 60-GT, a fully automatic micropore distribution measurement device manufactured by Quantachrome Instruments.

4. Results and Discussion

4.1. Confirmation of Cathode Loading

Figure 7 shows the results for confirmation of the range of loading when the 3D-structured collector is filled with composite slurry using active material with $d_{50}=7\ \mu\text{m}$. It is apparent from Fig. 7 that the coating thickness and loading are in a linear relationship and that the filling is stable when the slurry is within the range of 40 to 165 mg/cm^2 . The possibility of manufacturing electrodes with loading of 150 mg/cm^2 is, therefore, confirmed. This shows that it is possible to achieve the energy density shown in Fig. 4.

In the testing that followed, the respective foil-coated cathodes that are possible to manufacture at the upper limit of 90 mg/cm^2 were fabricated and evaluated for the purpose of comparing the foil-coated cathode and 3D-structured cathode. The results of that comparison are shown.

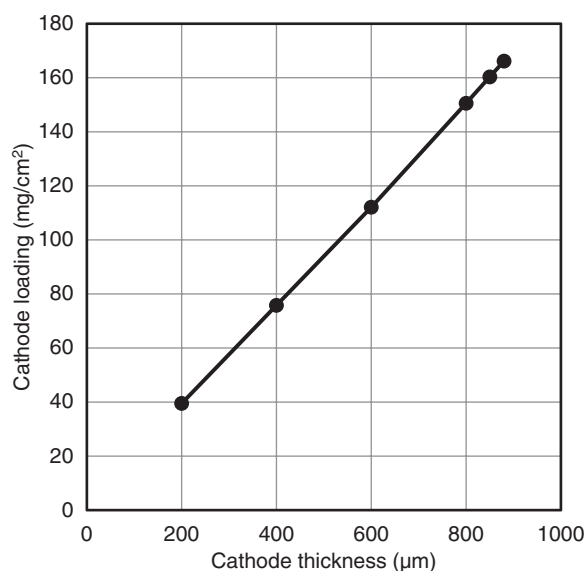


Fig. 7 3D-structured cathode loading

4.2. Particle Diameter and Electrode Characteristics

Figure 8 shows the discharge curves from the rated discharge tests. This confirms that the open circuit voltage (OCV) and discharge capacity for the reference electrode and the 3D-structured cathode are the same and that the active material is functioning fully in both electrodes.

Figure 9 shows the 10-sec DCR results. This confirms that the overall resistance of the 3D-structured cathode is suppressed relative to the reference electrode by 17% and 22% at the diameters (a) d50=5 μm and (b) d50=7 μm ,

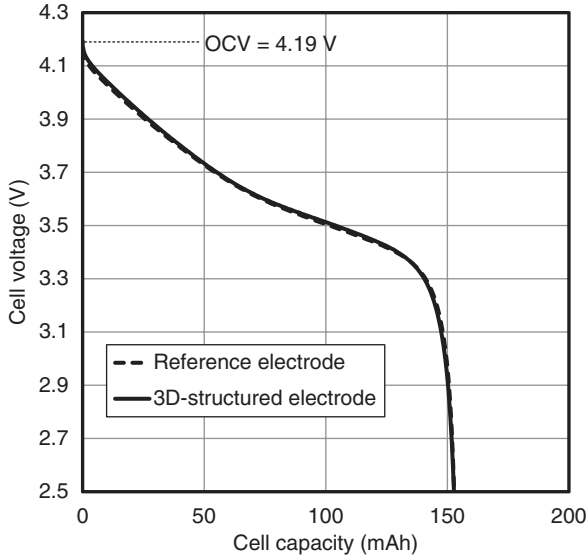


Fig. 8 Discharge curves at 0.3 C

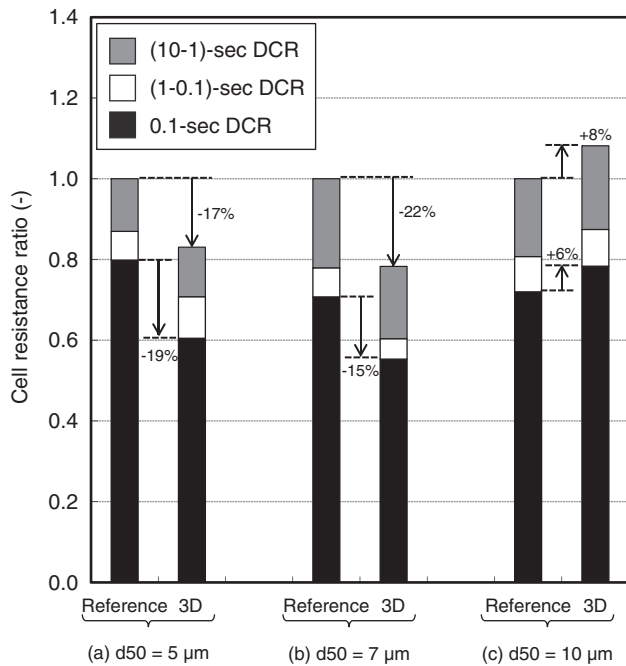


Fig. 9 Results of 10-sec DCR

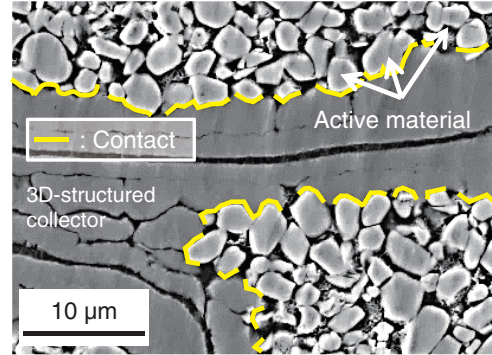
Table 5 List of particle sizes

	D ₁₀ (μm)	D ₅₀ (μm)	D ₉₀ (μm)
(a) d50 = 5 μm	2.5	5.0	7.5
(b) d50 = 7 μm	2.7	7.0	8.1
(c) d50 = 10 μm	6.1	10.1	16.9

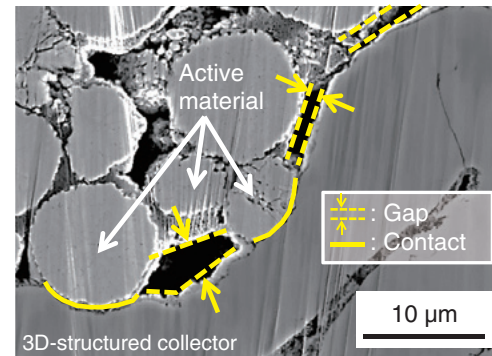
respectively. The portion of that contributed by the 0.1-sec DCR was 19% and 15%, respectively. This clearly established that application of the 3D-structured collector suppresses the electronic resistance. At the diameter (c) d50=10 μm , on the other hand, the total resistance value was found to have increased by 8% and the 0.1-sec DCR by 6%.

Table 5 shows the particle diameters for the particles of each active material at D₁₀ (the particle diameter at which the volume cumulative frequency will be 10%), D₅₀ (the particle diameter at which the volume cumulative frequency will be 50%), and D₉₀ (the particle diameter at which the volume cumulative frequency will be 90%). It was confirmed from Table 5 that the D₉₀ range for (a) and (b) is 8.1 μm or less. On the other hand, it was confirmed that the D₉₀ range for (c) was approximately 16.1 μm or less. This showed that there is a greater difference in particle sizes in (c) than there is in (a) and (b).

Figure 10 shows the results for an SEM observation



(a) d50 = 5 μm



(c) d50 = 10 μm

Fig. 10 Cross-section SEM images of 3D-structured cathode

of cross-sections of 3D-structured cathodes with diameters (a) $d_{50}=5\ \mu\text{m}$ and (c) $d_{50}=10\ \mu\text{m}$. It can be confirmed from the SEM images that at diameter (a) $d_{50}=5\ \mu\text{m}$, the active material has penetrated into the lattice structure of the 3D-structured collector. As indicated by the solid line in the figure, the active material can be confirmed to be uniformly in contact with the collector aluminum. Figure 10 confirmed, however, that a portion of the active material that is close to the collector aluminum had gaps where it was not in direct contact with the collector at diameter (c) $d_{50}=10\ \mu\text{m}$, as shown by the broken line in the figure. This is thought to happen because active material particles of $10\ \mu\text{m}$ or greater diameter can no longer readily penetrate in a uniform manner all the way inside the lattice structure to the region where the aluminum frame is curved when the 3D-structured collector is being filled with electrolyte composite. Electrons are supplied directly to the active material that is in contact with the aluminum, but the supply of electrons at locations that are not in contact will occur through the mediation of other active materials or auxiliary agents, so the resistance will increase. In other words, the fact that the active material has different particle diameters alters the status of contact between the active material and the collector, and the change in the state of electron transfer from the collector is thought to change the 0.1-sec DCR resistance value.

These results showed clearly that resistance is suppressed in the active material applied to the 3D-structured collector covered in this paper when the particle diameter at d_{50} is $7\ \mu\text{m}$ or less.

4.3. Electrode Characteristics

4.3.1. Rate discharge characteristics

Figure 11 shows capacity retention based on evaluation of the C-rate discharge characteristics at $d_{50}=5\ \mu\text{m}$. The effect of enhanced capacity retention from use of the 3D-structured collector could be confirmed in the region of 1 C and above. At 2.5 C, the retention increase was 3%.

The discharge curves for the reference electrode and the 3D-structured cathode are shown at 0.3 C and 2.5 C in Fig. 8 and Fig. 12, respectively. The discharge curves coincide at 0.3 C, confirming that there was no difference between the two types of electrode. The voltage drop at 0.1 second after discharge begins was also the same 20 mV or less for both electrodes. By contrast, a distinct difference was confirmed at 2.5 C. The voltage drop at 0.1 second after discharge begins was 301 mV in the reference electrode and 181 mV in the 3D-structured cathode electrode, for a confirmed difference of 120 mV. This voltage drop is IR loss, and it shows a tendency similar to the suppression of electronic resistance in Fig. 9. This difference is thought to occur because the 3D-structured collector has a specific surface area of $5500\ \text{m}^2/\text{m}^3$, and the increase in surface area by a factor of five or more relative to the reference electrode

means there is an increased area of contact between the collector and the active material, which results in heightened conductivity at the interface. It is also conceivable that the distribution of the aluminum frame throughout the entire electrode heightens conductivity in the electrode thickness direction. On the other hand, both discharge curves display similar profiles from 0.1 second on, which indicates that the electrodes have the same ion diffusion. The suppression of IR loss means there is a lag in reaching the discharge cut-off voltage, and this is known to contribute to the capacity increase in the higher rate region. It is clear from the above that with the 3D-structured cathode, the heightened conductivity produces suppression of the voltage drop immediately following discharge and increases capacity retention in the higher rate region.

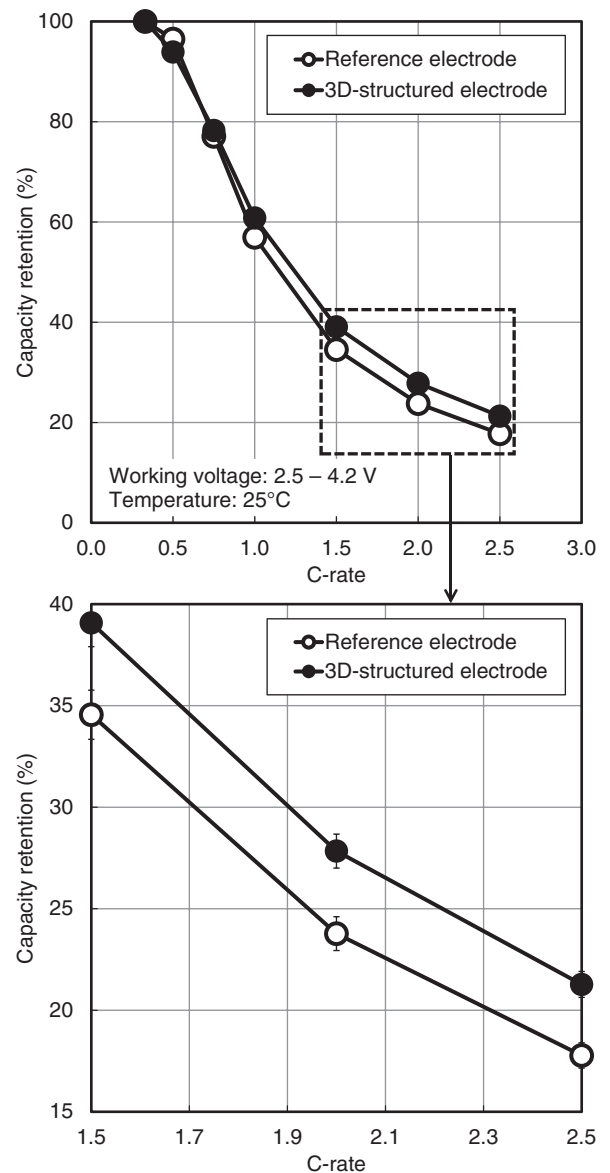


Fig. 11 Capacity retentions at different C-rate

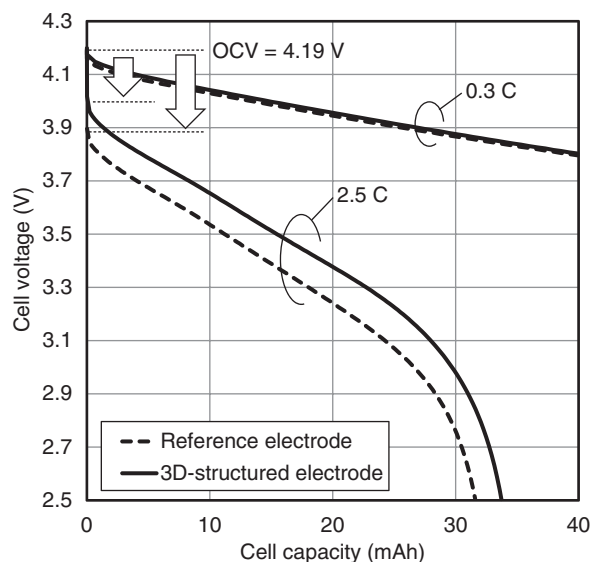


Fig. 12 Discharge curves at 2.5 C

4.3.2. Cycle test

Figure 13 shows the rate of change in capacity from the cycle test at 45°C.

In contrast to the reference electrode, which has 77.4% capacity retention at 600 cycles, the 3D-structured cathode has 87.9% capacity retention. This confirms that capacity retention is heightened in the 3D-structured cathode. This is thought to occur because the aluminum frame that forms the 3D structure maintains its structure during cycle testing, and maintaining the binding of the various constituent materials throughout the electrode keeps the active material from detaching.

Figure 14 shows that the overall resistance of the reference electrode and 3D-structured cathode increased by 149% and 29%, respectively, before and after the cycle test. Their respective 0.1-sec DCR increased by 141% and 14%. Based on the above results, the suppression of increases in electronic resistance in the 3D-structured cathode causes suppression of increases in all components of resistance. In the reference foil-coated cathode, on the other hand, active material detached from the collector and active material in the composite slipped off due to the influence of the formation of a thicker layer, and this is thought to interrupt the electron conductive path to the active material so that the increase in resistance is accelerated.

There was also an increase in the (10-1)-sec DCR before and after the cycle test that was 74% in the reference electrode and 18% in the 3D-structured cathode. The (10-1)-sec DCR is ionic diffusion resistance, so when an electrolyte is used in common, it is considered to be a component of resistance that depends on the electrode structure⁽³⁰⁾. In the present tests, the (10-1)-sec DCR accounts for 20% or less in

the 10-sec DCR as a whole. However, suppression of the increase in resistance was confirmed to occur during the cycle tests with 3D-structured cathodes. Figure 15 shows micropore distribution in the electrode before and after the cycle test. Where the average micropore diameter in the reference electrode shrank by 65 μm before and after the cycle test, the shrinkage was limited

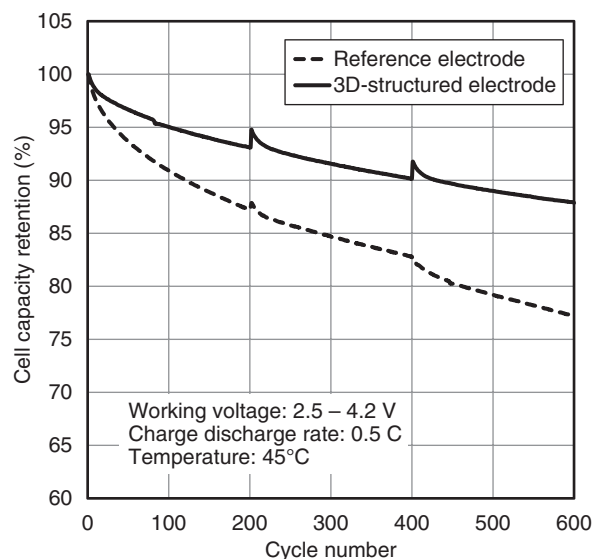


Fig. 13 Cell performances of capacity retention

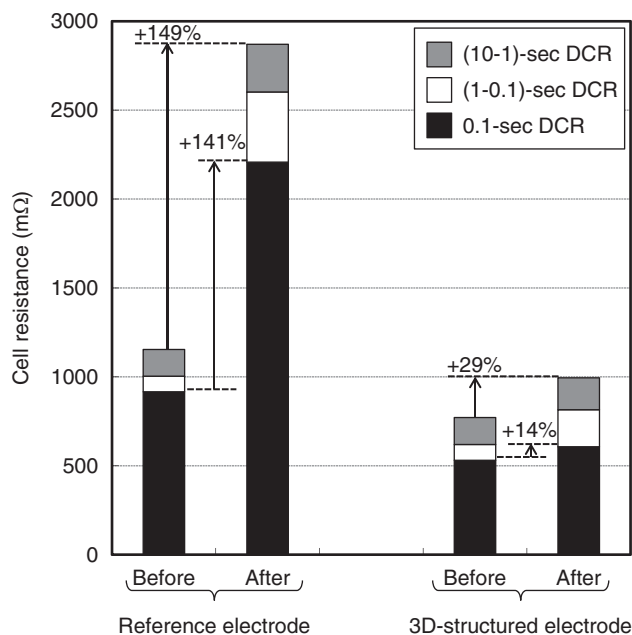


Fig. 14 Performance of cell resistance retention

to 15 μm in the 3D-structured cathode. A reduction in porosity also resulted, as calculated from Fig. 15, amounting to 15% in the reference electrode and 12% in the 3D-structured cathode. Based on these results, the suppression of structural changes in the micropores, voids, and gaps in the 3D-structured cathode that is due to its aluminum frame enables the retention of ion conductive paths before and after the cycle test, and this is thought to suppress the increase in resistance.

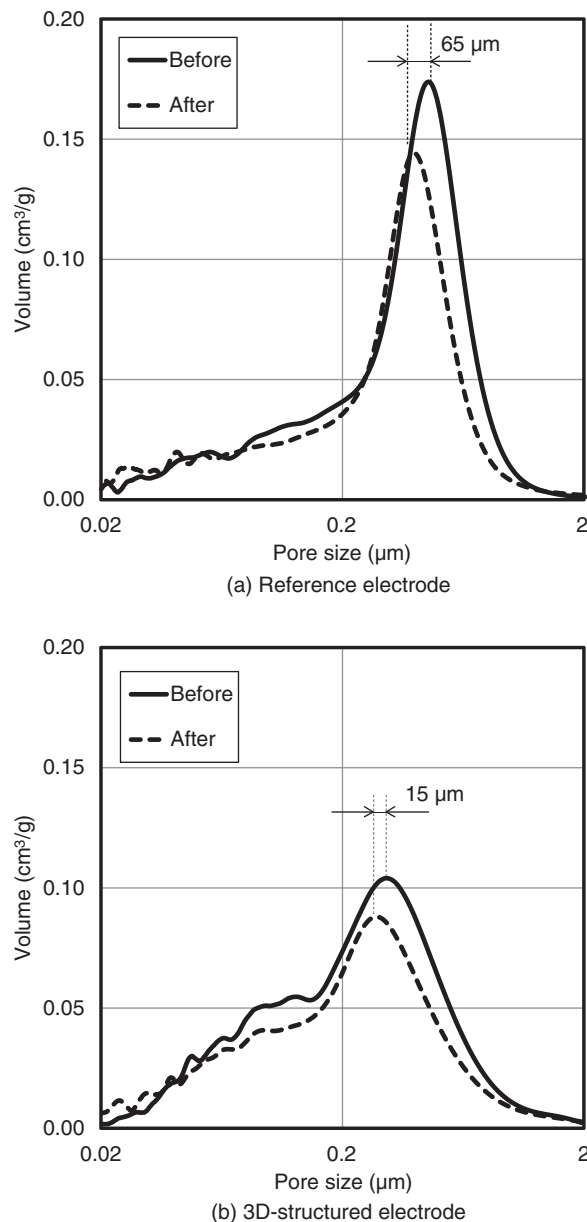


Fig. 15 Electrode pore distribution before and after cycle test

5. Conclusion

Cell evaluation was conducted for the purpose of confirming that the application of a 3D-structured collector made from aluminum as the cathode collector in a lithium-ion battery would increase the energy density while at the same time having the effect of suppressing the associated increase of internal resistance in the cell and the decrease in durability, which are issues. The following results were obtained as a result.

As regards energy density, it was confirmed that it is possible to manufacture electrodes with a loading of 150 mg/cm². Calculations yielded the result that reducing the number of electrode layers would have the effect of increasing energy density 10%.

As regards the internal resistance of the cell, a reduction in resistance relative to conventional foil-coated cathodes was confirmed. When the particle diameter of the active material is d₅₀=7 μm or less, the overall resistance is reduced by 17% relative to the foil-coated cathode and the 0.1-sec DCR is reduced by 24%, confirming that the reduction in electronic resistance makes a large contribution. It is thought that the enhanced contact between the active material and the collector is a major factor in this.

As regards durability, heightened capacity retention and suppression of the increase in resistance were confirmed during cycle testing. It was confirmed that after 600 cycles, capacity retention in the foil-coated cathode was reduced by 22.6%, while in the 3D-structured cathode, the decrease was held down to 12.1%. As to the increase in resistance, it was confirmed that the foil-coated cathode showed a 149% increase in the total resistance value, while the figure in the 3D-structured cathode was held to 29%. It is thought that the way the aluminum frame maintains its structure, thus maintaining the binding of the various constituent materials throughout the electrode and keeping the active material from detaching, is a major factor in this.

It was clearly shown by these results that application of the 3D-structured cathode in a lithium-ion battery makes it possible to achieve a balance between enhancement of energy density and suppression of the increase in resistance and decrease in durability, which are issues.

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Low Relative Permittivity of Magnet Wire Insulation Coating for HEV Motor

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ABSTRACT

An insulation coating that achieves a balance of heat resistance and insulating properties was developed for use in HEV motors. Technology was established that lowers the relative permittivity as low as 2.4, which is at the level of polyethylene and other such low-permittivity materials, while also having heat resistance with the high temperature index of 250°C by causing independent gas bubbles to be dispersed evenly in polyimide resin. This technology made it possible to maintain the insulating properties of conventional magnet wire while reducing the coating thickness by approximately 20% and increasing the cross-sectional area of the conductor by approximately 6%. As a result, losses in newly developed motors were successfully reduced by 5% relative to conventional motors.

1. Introduction

Due to the demand seen in recent years for reduced CO₂ emissions and higher fuel economy in vehicles when driving, the widespread adoption of electric-powered vehicles such as hybrid electric vehicles (HEV) and electric vehicles (EV) has progressed rapidly. Electrification is expected to accelerate further as fuel economy regulation becomes stricter in the future. The range of vehicle models to which this is applied has also broadened, from compact vehicles to large vehicles, minivans, SUVs, and other types of automobile. There is demand for drive motors to be made compact while maintaining both high torque and high power characteristics, particularly for installation in compact vehicles. However, the higher current needed for enhanced motor characteristics together with the more compact motor framework result in a lower heat capacity so that increased motor temperatures become an issue⁽¹⁾. In order to reduce the heat generated by the magnet wire, which is the heat source, it is effective to lower the resistance when current is applied by enlarging the cross-sectional area of the conductor.

In order to retain the motor framework as is while enlarging the cross-sectional area of the conductor, it is necessary to make the insulation coating thinner. However, this decreases the insulating properties of the coating, which are its main function. For the purpose of making the coating

thinner while also retaining its insulating properties, it is effective to reduce the relative permittivity of the insulation coating⁽²⁾.

The most effective known approach capable of reducing the relative permittivity is to increase the porosity of the resin. Causing the gas that is the component of the insulator with the lowest relative permittivity to be dispersed throughout the resin makes it possible to achieve a relative permittivity that cannot be obtained with the resin component alone. Increasing the porosity of the resin does not just heighten the insulating properties, it can also enhance a variety of other characteristics⁽³⁾⁻⁽⁵⁾, such as lightweight properties, sound-absorbing properties, heat insulating properties, shock-absorbing properties, and others. Although there have been numerous reports on research into the insulating applications of increased porosity⁽⁶⁾⁻⁽⁸⁾, there are no instances of practical application as insulation coating for magnet wire. In order to put it to this practical use, independent gas bubbles of several micrometers in size need to be dispersed evenly throughout the entire coating^{(9), (10)}.

Methods for increasing the porosity of resin can generally be classified into two kinds, physical approaches and chemical approaches. As a typical instance of the physical approach, the use of carbon dioxide or some other such supercritical fluid is a well-known method^{(9), (11), (12)}. Supercritical methods, however, require a high-pressure

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environment, which means that it will be a discontinuous product, making reduced productivity an issue⁽¹³⁾. On the other hand, chemical approaches generally use foaming agents that are thermally expandable, and the gas bubbles that are formed end up being large with adjoining gas bubbles forming continuous holes, so that the separateness of the gas bubbles cannot readily be maintained^{(9), (14)}. The physical approach using supercritical fluids and the chemical approach using foaming agents are, therefore, not suited for use in increasing the porosity of insulation coating.

Here, an insulation coating with increased porosity was put to practical use by applying a thermochemical method using a gas bubble forming material that has an outside shell. By applying this technology for use as insulation coating for magnet wire, the loss in a new model motor was reduced by 5% from previous motors. This paper describes the conceptual approach to insulation coating design for drive motors to be installed in vehicles, the design of gas bubble coating that is optimal for the developed motor, and the results from evaluation of the design as a motor characteristic.

2. Conceptual Approach to Insulation Coating Design

Drive motors to be installed in vehicles use inverters capable of highly precise control of the motor speed. However, the rapid switching in the inverter is accompanied by sharp spikes in the pulse voltage and mismatches between the inverter output impedance and motor input impedance. For these and other such reasons, high surge voltages from the inverter may be applied to the magnet wire. The peak value for the inverter surge voltage can at times be as much as about two times the usual inverter voltage⁽¹⁵⁾ (Fig. 1), so it is important to assure the magnet wire insulation.

The partial discharge inception voltage (PDIV) is

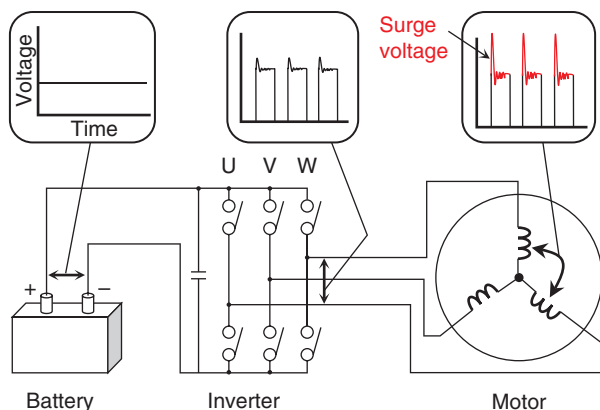


Fig. 1 Schematic diagram of inverter surge voltage

one of the characteristics that are important for assuring the insulation on the magnet wire. When the potential difference that occurs between wires exceeds PDIV, minute discharges called partial discharges take place in the space between insulation coatings. As shown in Fig. 2, when partial discharges continue to occur, the impact energy of the discharges causes erosion of the insulation coating, and there is a possibility that ultimately the vehicle may stop running when destruction of the insulation causes short circuits. The insulation coating, therefore, needs to be designed so that partial discharges do not occur even in environments that are challenging for the onboard motor, such as under high temperatures and at high elevations where the air pressure is lower.

Dakin's equation, shown in Eq. (1), is widely known as a guideline for such design. PDIV becomes a function of coating thickness and relative permittivity. In order to raise PDIV, it is effective to increase the coating thickness or to lower the relative permittivity, as shown in Eq. (1). Increasing the thickness of the coating will reduce the space factor of the conductor in the slot, which will lead to a reduction in the motor volume efficiency. For magnet wire used in the compact and highly efficient motors required to drive HEV, EV, or other such electric-powered vehicles, it is important to reduce the relative permittivity of the insulation coating.

$$PDIV = A \times (2 \times t / \epsilon_r)^{0.46} \quad (1)$$

A : Constant

ϵ_r : Relative permittivity

t : Thickness of coating

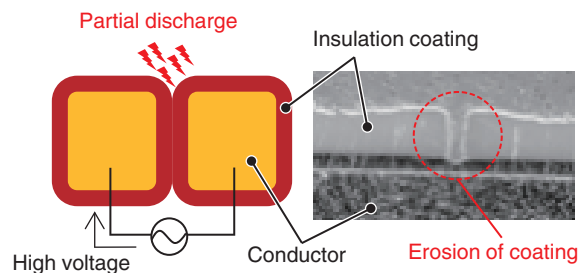


Fig. 2 Partial discharge of magnet wire and example of erosion of insulation coating

3. Low Relative Permittivity of Insulation Coating

3.1. Issues for Low Relative Permittivity

Figure 3 shows the relationship between the temperature index and the relative permittivity of the main

insulating resins. The temperature index is one indicator of the heat resistance of the magnet wire insulation coating⁽¹⁶⁾. Various characteristics are demanded for the organic parts in drive motors for HEV and other such vehicles, including heat resistance, oil resistance, and chemical resistance. Polyamide-imide (PAI), polyether ether ketone (PEEK), polyimide (PI), and other such insulating resins that are categorized as super engineering plastics are, therefore, commonly used as the insulation coating on magnet wire for drive motors. However, these have relative permittivity of 3.1 or higher, which is 30% or more higher than materials with low relative permittivity, such as polyethylene (PE) and polytetrafluoroethylene (PTFE), making their lower insulating properties an issue. PE and polypropylene (PP), on the other hand, are insulating resins that show low relative permittivity of 2.2 to 2.3. However, their heat resistance is low and they are not suited for use in vehicle drive motors, where they are exposed to high heat environments when driving up slopes, operating at high speeds, and so on. Furthermore, PTFE and other such fluorinated resins have lower adhesion and mechanical properties and so are not suitable for magnet wire, which requires adhesion to the conductor and processing resistance for bending.

An investigation was therefore made into the development of insulation coating that has low relative permittivity while also providing the heat resistance, adhesion, and other such characteristics needed for insulation coating on magnet wire. PI, which as shown in Fig. 3 has high heat resistance and comparatively low relative permittivity, was chosen as the resin to be used as a base for development of an insulation coating with low relative permittivity. A number of methods for lowering the relative permittivity of PI have been reported⁽¹⁷⁾, one of which is a chemical structural design according to the Clausius-Mossotti equation shown in Eq. (2) either to reduce the imide concentration or to give it a bulkier

structure. Although either method can lower the relative permittivity to around 2.7, however, it has been reported that this reduces the heat resistance that is one of the strengths of PI⁽¹⁷⁾. A lowering of relative permittivity by fluorine modification has also been reported⁽¹⁷⁾. As with the above, however, this conflicts with other characteristics, and the reduction in adhesion is a particular issue, so that this approach cannot readily be applied to the mass production of insulation coating for magnet wire.

$$\epsilon_r = \frac{1+2(P_m/V_m)}{1-(P_m/V_m)} \quad (2)$$

P_m : Molar polarizability

V_m : Molar space occupied volume

3.2. Dispersion of Gas Bubbles for Lower Relative Permittivity of Resin

The relative permittivity cannot readily be lowered in the resin component while providing the characteristics considered necessary in magnet wire. Attention was focused, therefore, on the gas that is the component of the insulator with the lowest relative permittivity. Although there have been numerous reports to date^{(6), (8), (17), (18)} of methods for lowering relative permittivity by causing gas bubbles to form within the PI resin, there are no cases of this method being put to practical use for insulation coating in a drive motor. Figure 4 shows the methods attempted here to lower the relative permittivity of resin by gas dispersion, and summarizes them in terms of application to insulation coating on magnet wire.

The supercritical method is a manufacturing method that requires a high-pressure environment. Manufacturing, therefore, needs to be done in a batch furnace, so it is not suited to mass production. There is also the formation of gas bubbles by the use of hollow particles, which can be applied to the conventional magnet wire process. However,

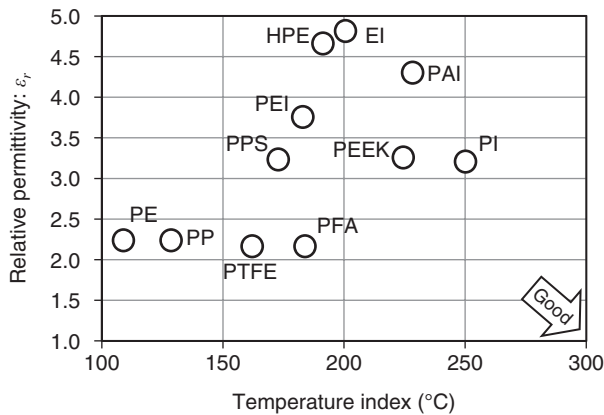


Fig. 3 Relationship between temperature index and relative permittivity of main insulating resins

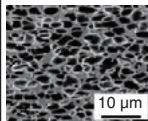
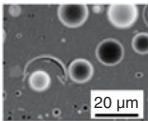
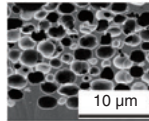
Item	Supercritical method	Hollow material method	Thermochemical method
SEM image			
Gas bubble size	1 - 5 μm (Large variation)	15 μm - (Large size)	3 μm (Controllable)
Gas bubble connection	Connected	Not connected	Connected
Varnish stability	Stable	Not stable	Stable
Continuous productivity	Not acceptable	Acceptable	Acceptable

Fig. 4 Methods and characteristics of gas bubble dispersion for insulation coating

polyamic acid, which is a basic ingredient of the varnish used for coating formation, is the precursor of PI and has a very different density from those gas bubbles so that the two tend to separate. This varnish, therefore, has issues with storage stability. There is also the common thermochemical method for forming gas bubbles. When the gas bubbles are formed, however, they make continuous holes that connect to adjoining gas bubbles. This means that there are questions as to whether the oil used to cool the motor will soak in and lower the breakdown voltage (BDV) of the insulation. An investigation was therefore made of resolving the continuous holes that are an issue with the common thermochemical method by using a gas bubble forming material with an outside shell so that the gas bubbles are made independent.

4. Optimal Design of Gas Bubble Coating

The following will discuss the porosity, the gas bubble diameter, and the uniform dispersibility of gas bubbles, which are key design elements for the purpose of application to mass production of the insulation coating for magnet wire to be used in on-board drive motors.

4.1. Porosity

The A. S. Windeler formula in Eq. (3) is commonly used as a theoretical formula for relative permittivity and porosity in the insulation coating as a whole.

$$\frac{\varepsilon_i - \varepsilon_r}{\varepsilon_i - \varepsilon_a} = \frac{F}{100} \cdot \frac{3\varepsilon_r}{2\varepsilon_r + \varepsilon_a} \quad (3)$$

ε_i : Relative permittivity of resin

ε_r : Relative permittivity of entire insulation coating

ε_a : Relative permittivity of gas (=1.0)

F : Porosity (%)

Figure 5 shows the relationship between the gas bubble ratio (porosity) of the gas bubble coating and the relative permittivity. It was confirmed that when the gas bubble

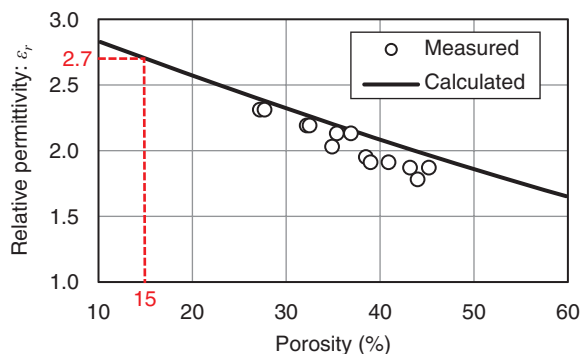


Fig. 5 Relationship between relative permittivity and porosity of PI

ratio increases, the relative permittivity decreases, just as aimed for, largely matching the theoretical formula. The loss reduction target value for the developed motor was used to determine target values for the cross-sectional area of the conductor and the coating thickness. The necessary insulating properties were also taken into account and the relative permittivity target value was set at 2.7 or lower. According to the theoretical formula, the porosity that achieves a relative permittivity of 2.7 or lower is 15% or higher.

Raising the gas bubble ratio is beneficial for the insulating properties, but the reduced processing resistance for bending becomes an issue. Figure 6 shows an example of simulation results for distribution of stress occurring in PI when tensile stress is applied to a PI gas bubble coating model with a porosity of 30% and gas bubble diameter of 3 μm. A concentration of stress is observed in the PI in the vicinity of the gas bubbles, and it is apparent that the stress is unevenly distributed. This concentration of stress becomes more conspicuous as the porosity increases, becoming a cause of reduced coating elongation.

Figure 7 shows the formed shape of the magnet wire

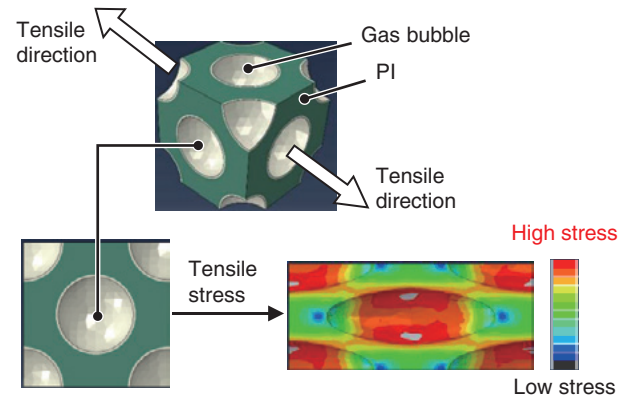


Fig. 6 Simulation results of elongation and stress distribution of bubble film

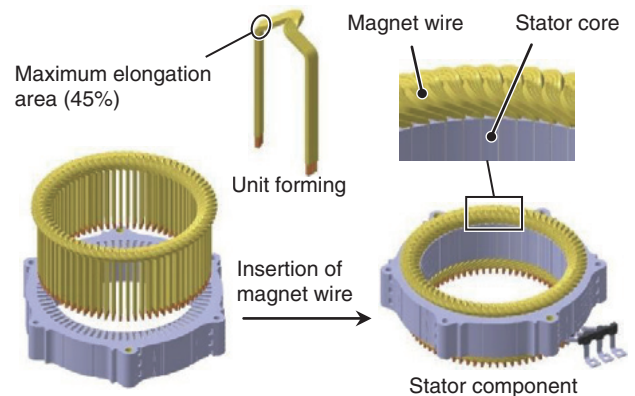


Fig. 7 Shape of magnet wire in stator component

in the stator component of the developed motor for which application of the gas bubble coating was investigated. In order to make the developed motor compact and highly efficient, a method of assembly⁽¹⁹⁾ was adopted that connects the conductors by making unit coils from four rectangular magnet wires formed into a U-shape, placing them together side by side, inserting them all together into the stator core, and joining them. As a result of this method, a large tensile deformation occurs in the gas bubble coating when forming into the U-shape. The maximum tensile elongation comes to as much as about 45%.

Taking this into consideration, tensile testing was carried out using samples with varying gas bubble ratios and the correlation between porosity and coating elongation was verified. Figure 8 shows the relationship between the porosity and elongation at break of the coating obtained through the present experimentation. As in the simulation, the two were found to be in an inverse relationship, with the elongation at break decreasing as the porosity increases. It was determined from these results that with a porosity of 33% or less, the magnet wire can undergo a maximum elongation of 45% during forming without breaking.

4.2. Gas Bubble Diameter

An investigation was made of the optimum gas bubble diameter with respect to the variation in the coating thickness and discharge in the gas bubbles. Equation (4) shows the relationship between discharge and spatial gap, for which the Paschen formula is widely used⁽²⁰⁾. Figure 9 shows the relationship between the electrode distance and the spark discharge voltage obtained using Eq. (4) at barometric pressure (1013 hPa). As can be seen from the graph, the spark discharge voltage has its lowest value when the electrode distance is 22 μm , since the spark discharge voltage starts to go high at smaller distances and spikes at around 8 μm . This means that at an electrode distance of 8 μm or less, discharge does not occur even under voltages as high as several thousands of volts.

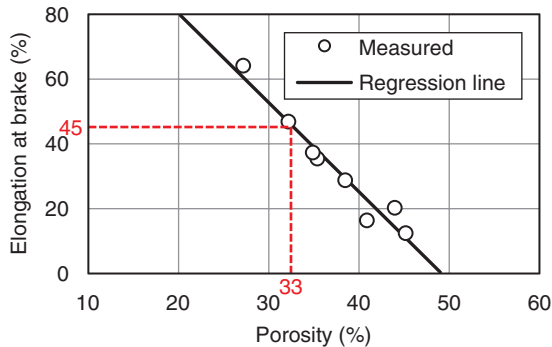


Fig. 8 Relationship between elongation of insulation coating and porosity of PI

$$V_s = \frac{B(Pd)}{\log(Pd) + C} \quad (4)$$

V_s : Spark discharge voltage (V)

P : Barometric pressure (hPa)

D : Electrode distance (μm)

B, C : Constant (Air: $B=94.5, C=0.095$)

Figure 10 shows schematic diagrams of the discharge generation mechanism in the discharge generation area (a) and at an electrode distance of 8 μm or less (b). As shown in Fig. 10 (a), an electric field is generated by the potential difference between electrodes, and discharge occurs when the initial electrons in that space are accelerated by the field so that they collide with oxygen or other such molecules in the air and electrons are ejected. The continuous occurrence of this phenomenon causes the discharge to grow. As shown in Fig. 10 (b), however, sufficient distance to allow the initial electrons to accelerate is not provided when the electrode distance is small, so the level of energy to cause ejection of electrons due to collision with molecules is not reached, and discharge does not occur. Yanaze et al. verified the relationship between gas bubble diameter and partial

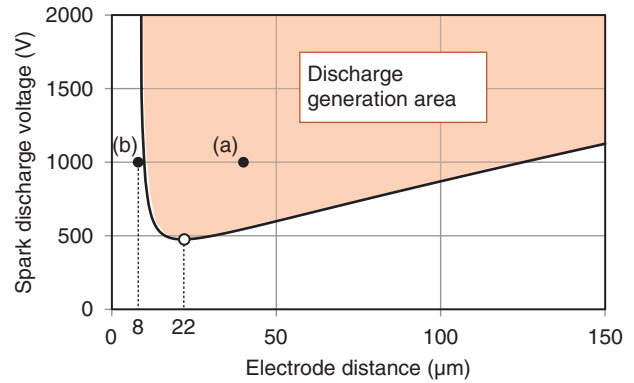


Fig. 9 Relationship between spark discharge voltage and electrode distance

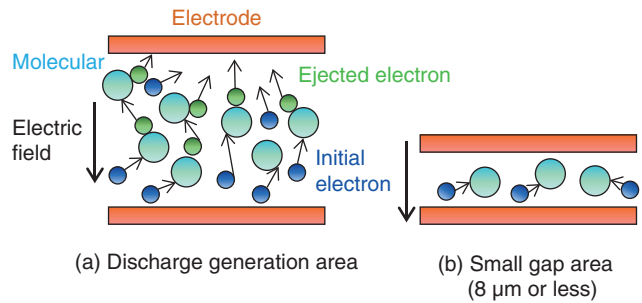


Fig. 10 Schematic diagram of discharge generation mechanism

discharge inside the gas bubbles and reported⁽²¹⁾ establishing that partial discharge does occur with a gas bubble diameter of 34 μm , but does not occur in gas bubbles at bubble diameters of 5 μm and 11 μm . These results support the conceptual approach of Eq. (4). In light of the above, it was reasoned that when the gas bubbles in the insulation coating have a diameter of about 8 μm or less, discharge does not occur inside the gas bubbles, and the relative permittivity can be reduced.

There is also the matter of applying the insulation coating, which in the interest of productivity is normally coated on the conductor in a thickness on the order of several micrometers. That process is repeated for the specified number of passes to obtain the required coating thickness. For that reason, when the gas bubble forming material has a diameter that is large in relation to the thickness of coating applied in a single pass, then the surface of the coating becomes rough and the variation in coating thickness becomes greater. In order to make the coating thickness more uniform, therefore, the gas bubble forming material, which determines the gas bubble diameter, is made so that it will have a diameter on the order of several micrometers.

4.3. Uniform Dispersibility of Gas Bubbles

The magnet wire used in a single developed motor amounts to several hundred meters in total length. If the gas bubbles in the coating become packed closely together, then it is possible that cracking will occur in the coating during forming, and under some conditions, partial discharge will occur in areas where there are, conversely, fewer gas bubbles. For that reason, it is desirable to have the gas bubbles dispersed uniformly in the coating. Figure 11 shows the processes of baking on the coating and forming the gas bubble coating. First, PI varnish that contains an

admixture of the gas bubble forming material that provides a base for the gas bubbles is coated onto the conductor. Next, the conductor is placed in a baking furnace where the PI varnish is hardened and progressive vaporization takes place due to the heat of the internal constituents of the gas bubble forming material. Ultimately, the PI that has completed hardening and the outside shell of the gas bubble forming material remain, forming the gas bubble coating. For this reason, the dispersibility of the gas bubble forming material in the PI varnish governs the uniform dispersibility of gas bubbles in the coating.

Figure 12 shows a schematic diagram of three different types of PI varnish with different degrees of dispersion of the gas bubble forming material, together with the particle size distributions, photographs of the surface appearance of gas bubble coating made as prototypes using those dispersions and distributions, and cross-sectional SEM images. The degree of dispersion increases from A to B and C, in that order. In C, the gas bubble forming material is in a uniformly dispersed state. With the varnish in A, aggregation of the gas bubble forming material is observed due to the particle size distribution, and the surface of the completed gas bubble coating is rough for that reason. Aggregation of the gas bubbles was also confirmed from the cross-section. With the varnish in B, peaks were observed that originated in secondary and tertiary aggregations due to the particle size distribution. Although this was an advance over A, the coating formed in B was observed to have partial aggregations based on surface appearance and cross-section SEM. With the varnish in C, a peak was observed that matched with the diameter of the gas bubble forming material due to the particle size distribution, and it was confirmed to be a monodispersion. The surface of the completed coating is smooth in appearance, as well, and uniform dispersion of the gas bubbles was also confirmed

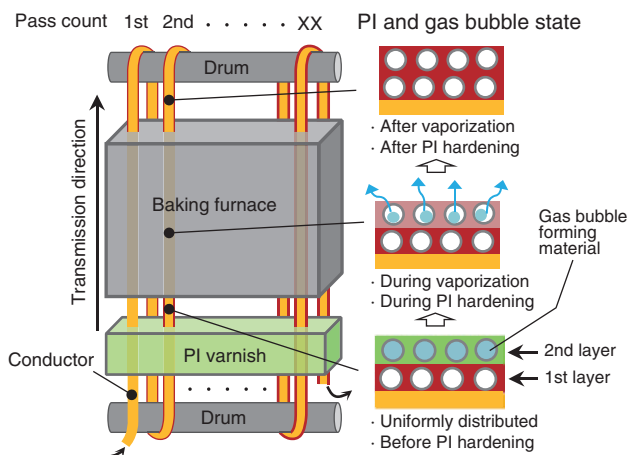


Fig. 11 Schematic diagram of developed magnet wire coating process and gas bubble formation

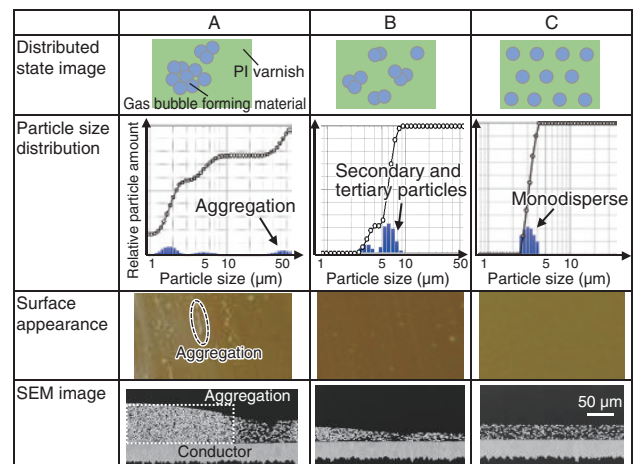


Fig. 12 Comparison of three types of PI varnishes with different degrees of dispersion

from the cross-sectional SEM image. In this way it was found that insulation coating with uniform dispersion of the gas bubbles could be obtained by controlling the dispersibility of the gas bubble forming material in the PI varnish.

Figure 13 shows a schematic diagram and cross-sectional SEM image of the developed coating as obtained from the results of optimal design. It is apparent that, due to the existence of an outside shell, there is uniform dispersion of gas bubbles that are several micrometers in size and independent, without links forming to nearby pores. Taking into account the elongation that occurs during processing of the magnet wire, material of a composition that allows for elongation was used for the outside shell.

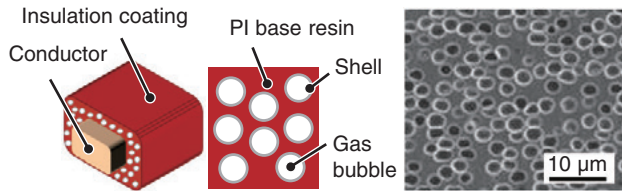


Fig. 13 Schematic diagram and cross section SEM image of newly developed insulation coating

5. Characteristics of the Developed Coating and Its Motor Loss Reduction Effect

5.1. Insulating Properties and Heat Resistance of the Gas Bubble Coating

Figure 14 shows the positioning of the relative permittivity and temperature index of the previous coating⁽¹⁹⁾ and the developed coating. Through uniform dispersion of independent gas bubbles in the PI, the relative permittivity of the PI was successfully lowered to 2.4 while retaining its higher heat resistance. This made it possible to develop an insulation coating that achieves a balance between heat resistance and insulating properties to an unprecedented extent.

5.2. Motor Loss Reduction Effect

Figure 15 shows the loss reduction effect of the developed motor. Relative to the motor using conventional technology⁽¹⁹⁾, the thickness of the magnet wire coating has been reduced by approximately 20%, the cross-sectional area of the conductor has successfully been increased by approximately 6%, and a loss reduction effect of 5% has been confirmed. With the additional adoption of technology for low loss control and other such techniques together with current reduction by the amount of the torque increase from optimization of the magnetic circuits, losses in the motor as a whole were successfully reduced by a total of 14%.

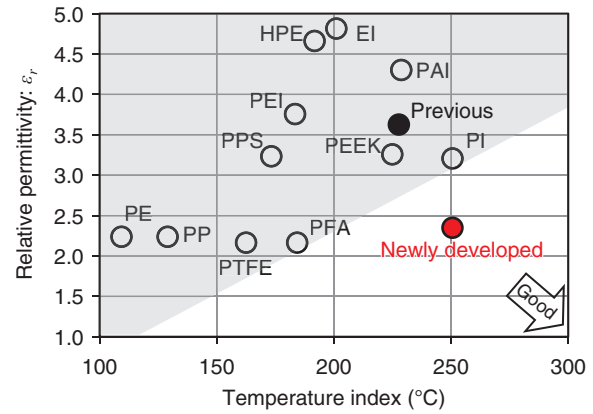


Fig. 14 Positioning of relative permittivity and temperature index of developed insulation coating

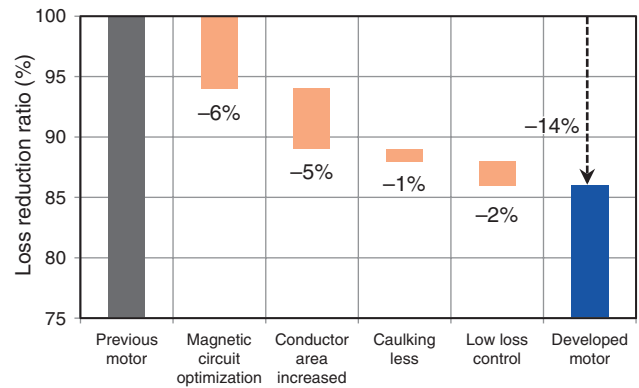


Fig. 15 Loss reduction effect of developed motor

6. Conclusion

- (1) When applying gas bubble coating to insulation coating for magnet wire, the use of a thermochemical method that utilizes gas bubble forming material that has an outside shell successfully yielded a gas bubble coating with independent gas bubbles that are several micrometers in size and dispersed evenly throughout.
- (2) By applying this gas bubble coating to the magnet wire in a new model motor, the motor loss was reduced by 5% from previous motors.

This is the first known successful application of this technology for practical use as insulation coating for magnet wire. The motor in which this technology was adopted is installed in the FIT e:HEV that went on sale in February 2020.

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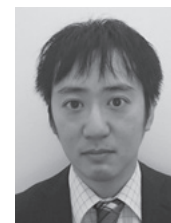
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Analysis of Subjective Values of Car Users in Japan and U.S. Using Free Description Keyword Method

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ABSTRACT

In order to investigate “Customers’ Joy,” one of Honda’s philosophies, a survey was conducted in Japan and the United States to collect keywords concerning the attractiveness and value of automobiles. The collected data was visualized as clusters of keywords by using the singular value decomposition method on discrete data, which is a quantification type III of statistical analysis. Then, through semantic interpretation of the keywords belonging to these clusters, the concept structure of the attractiveness and value of automobiles perceived by automobile users was clarified. As a result, it was noticed that both Japanese and U.S. users share common values on economy and fuel efficiency, while Japan users value handling and safety and U.S. users value reliability, asset values, loading capacity, and comfort. In addition, the differences of value by age and value preferences by gender were also visualized by analyzing user attribute data collected in the survey. The differences in brand recognition between Honda and Acura were also explained by the differences in value concepts of reliability, asset values, and premium values.

1. Introduction

The founder of Honda once said, “Our research center is about our customer’s mind, not about technology.” This means that pursuing our customers’ values takes priority when creating our products. The enthusiasm of our founder has been inherited as our corporate philosophy of pursuing our “Customers’ Joy”^{(1), (2)}.

In order to investigate automotive user’s value concepts, the most commonly used method is user questionnaires. However, in subjective surveys such as user questionnaires, it often happens that the bias of the questioner contaminates the questions and can have unignorable effects on the objectivity of the research results^{(3), (4)}. So a new objective research method, different from ordinary questionnaires, has been needed to investigate the attractiveness and value of automobiles. Furthermore, the attractiveness and value that automotive users expect in their automobiles might vary depending on the country, its culture, and its development level. So a suitable analytical method that can express and clarify these diverse values using objective data is also needed.

In recent years, AI technology has evolved remarkably, and the techniques used to extract fundamental factors from large amounts of non-quantitative data by combining natural language analysis techniques and quantification type III method^{(5), (6)} have advanced greatly. In this technique, discrete data such as keywords and/or figures are quantified using frequency of appearance and other items, and fundamental factors of the data are identified by a singular value decomposition to understand the essence of the target data.

Therefore in this research, first, we collected linguistic data regarding the attractiveness and value of automobiles using a free-keyword description method so that the bias of the questioners was not mixed in. At the same time, the strength of connection between the keywords was also quantified by accompanying questions.

By applying quantification method III on the collected keyword and relevance data, the keywords that represent the attractiveness and the value of automobiles were clustered. Then the semantic interpretation of the keywords in the clusters was used to examine the structure of the subjective values of automotive users.

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² Life Creation Center

2. Method

2.1. Survey Method

A web questionnaire survey was conducted in 2017, and responses from 5,000 automobile users in Japan and the United States, which are Honda's major markets, were collected. The survey participants answered the questions through a questionnaire site on the Internet. The survey sampling was adjusted so that the users' demographics and male/female ratio were close to those of Japan and the United States.

First, the participants answered the name of the car that they currently use most, and what car they would choose if they were to buy another car. For another car, both the car name and car category name were accepted as answers. Next, the participants listed four words about why they chose that car or the points they preferred, and then listed six words about what points they would value when choosing their next car. Then the 12 keywords they listed in the previous steps were displayed in a paired comparison and the relevance between the keywords was shown for four levels: strong, slightly related, weakly related, and almost irrelevant. In addition to the above questions, attributes of participants such as age, gender, annual income, and so on were collected, with privacy protection taken into consideration. The number of electric vehicle (EV) users is increasing, so these were also included in our survey as proportionally as possible to market share in order to investigate the attractiveness and values of EV.

2.2. Analysis Method

The collected data was analyzed in Japan and the United States, respectively.

As shown in Fig. 1, the matrices that represent the relevance between collected keywords were integrated from

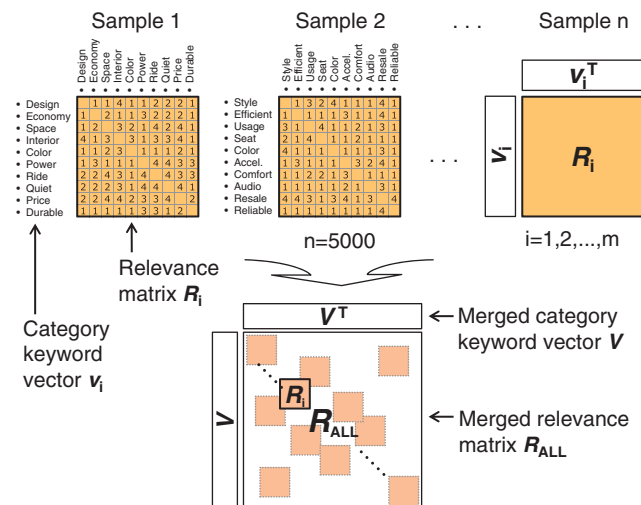


Fig. 1 Schematic image of creation of keywords and their relevance matrix from 5,000 samples

5,000 samples into a single comprehensive matrix and then analyzed. In the integration, we extracted frequent keywords using a certain threshold in which enough keywords for investigation could be included. Minor keywords only used by certain participants or keywords considered uncommon were removed as outliers. As a result, 410 words in the Japanese version and 475 words in the U.S. version were extracted for the analysis.

The top ten keywords in the Japanese version were fuel economy, design, color, price, safety, ease of driving, K-class cars, ride comfort, interior quality, and safe. In the U.S. version, they were price, color, safety, comfort, style, reliability, size, gas mileage, quality, and design.

In multivariate analysis, some methods use objective variables such as regression analysis, and some do not. The quantification method III belongs to the latter and can deal with category data, such as keyword data we are to deal with, as explanatory variables.

This method, also called correspondence analysis, extends the method of principal component analysis to category data, extracts latent variables from a vast number of explanatory variables, and can rearrange keywords into an x-y plot using the latent variables⁽⁷⁾. To find the latent variables, the correlation between the row and column components of the matrix were maximized. By repeating this mathematical operation, it becomes possible to plot each keyword with two independent essential factors as axes (Fig. 2).

The resulting keyword plot is the polar plot shown in Fig. 3, which can be interpreted using the following three indices.

- (1) Smallness of the polar angle: high relevance between keywords
- (2) Distance from the pole: high independence of keywords
- (3) Plot size: keyword appearance frequency

By plotting keywords on two axes, it became possible to interpret keywords without the clutter of complicated lines such as dendrograms, which are used in cluster analysis.

In order to interpret the mapped keywords, we presumed several keyword clusters along each polar coordinate angles.

Analysts interpreted the keywords contained in the

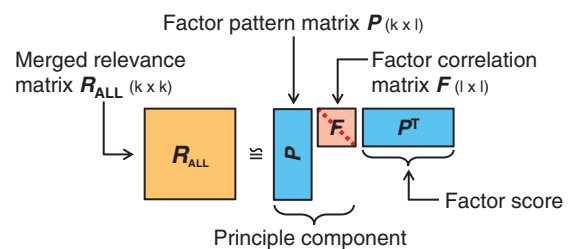


Fig. 2 Schematic image of quantification type III method and singular value decomposition on relevance matrix

clusters, and clarified the structure of the value that automobile users feel in their cars. Comparison of the analysis results from Japan and the United States and discussion regarding a few user attributes were conducted based on cluster interpretations.

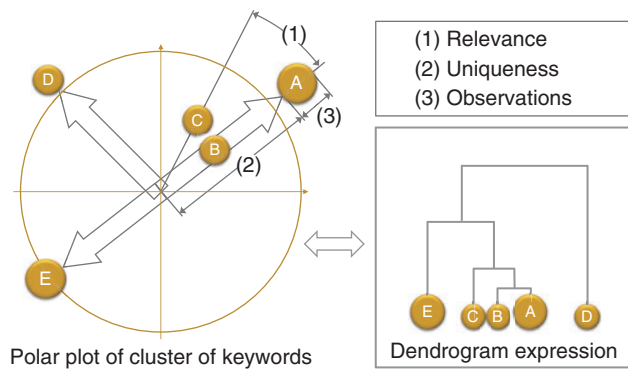


Fig. 3 Polar plot of cluster of keywords

3. Cluster Analysis

3.1. Japan

The plot of keywords regarding the attractiveness and value of automobiles answered by Japanese car users is shown in Fig. 4.

In the figure, the keyword “autonomous driving” is plotted in the upper left of the plot, “low maintenance cost” in the lower left and “color” in the lower right in each direction from the pole and at a distance. This means that these keywords are less related to each other and are being acknowledged by users as independent attractiveness or values.

The keywords aligned in the same direction of the above-mentioned keywords are those with related attractiveness or value, and so form each distinctive cluster. The keywords plotted outside at a distance from the pole represent unique attractiveness or value, and the keywords inside nearer the pole represent more general ones, as they are relevant to other keywords.

In addition, keywords with large plots such as “fuel economy”, “design”, “price”, “color”, and “safety” are the keywords frequently quoted by many users and are regarded

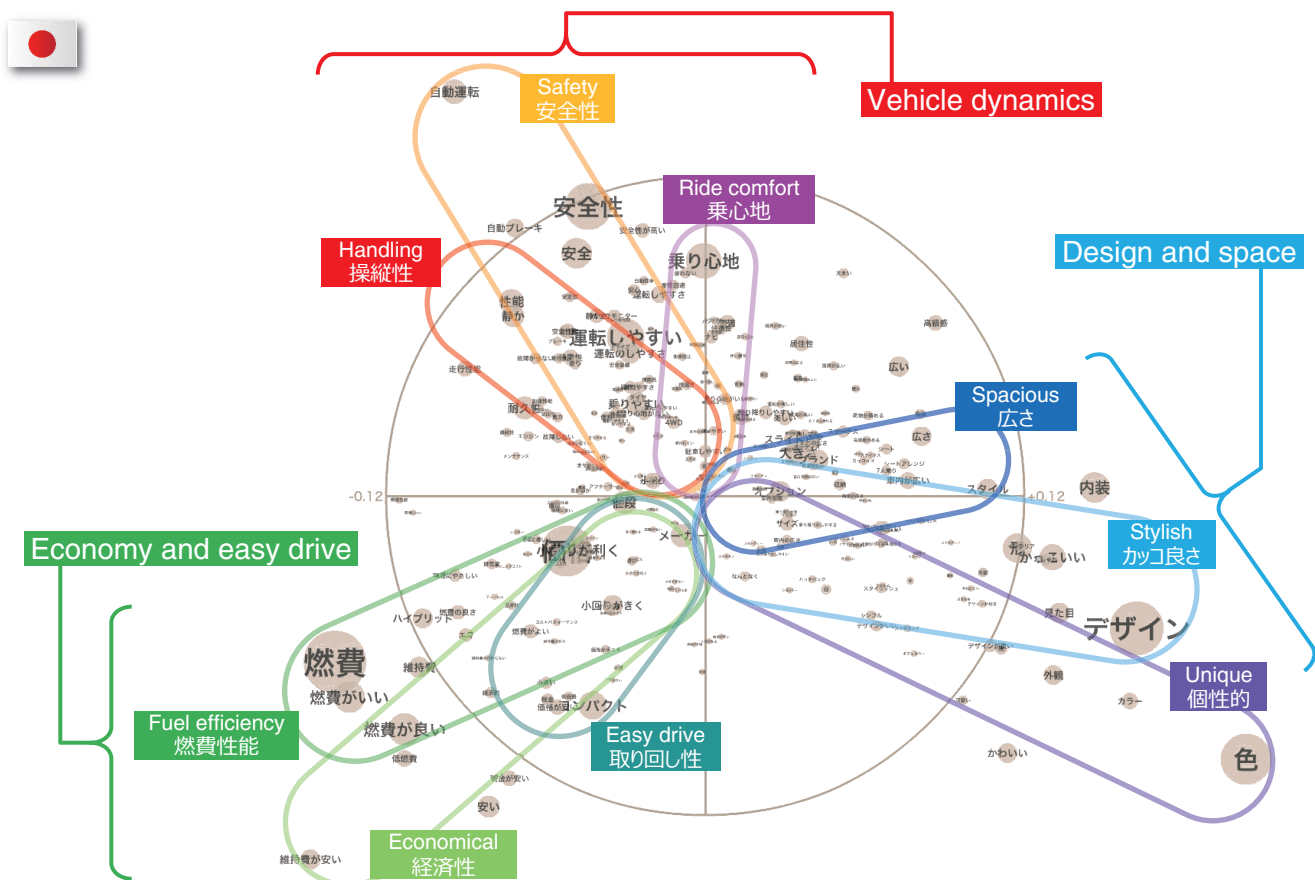


Fig. 4 Comprehensive polar plot of keywords of car values from Japanese car users

as widely supported values.

By interpreting the keywords in the clusters plotted in the polar plot in this way, it will be possible to look into the concept of the attractiveness or value of automobiles.

Now let's focus on the large cluster of keywords in the upper left direction in Fig. 4 to start the analysis.

First, in the upper left and most outside of the figure, the keyword "autonomous driving" is plotted. It is the keyword representing attractiveness or value of the cluster to which it belongs. Since keywords such as "autonomous braking", "safety", "safe", and "back monitor" are aligned in the same polar angle of the plot, this keyword cluster could be semantically interpreted as a concept of "safety" that users perceive from automobiles.

In the left of the "safety" cluster, keywords such as "performance", "quiet", "driving performance", "easy to drive", "easy to ride" are aligned at a slightly different angle. These keywords are thought to be attractiveness or value users feel when driving their cars, so we regarded it is appropriate to name the cluster as a "handling" cluster.

On the right side of the "safety" cluster, there are keywords such as "ride comfort", "do not get tired", "comfortable", "comfort", and "navigation". So this cluster could be named a "ride comfort" cluster.

To summarize the above interpretations, the large keyword cluster in the upper left consists of "safety", "handling", and "ride comfort" value concepts, and it can be said to form a conceptual structure that can be called "Vehicle dynamics".

By the way, if you look closely at this "Vehicle dynamics" cluster, keywords with almost the same meaning are plotted in close relation, such as "easy driving", "easy to drive", and "easy drive" or "safety", "safe", and "high safety". This indicates that the proposed method can classify keywords with the same meaning into almost the same position on the plot. Vice versa, the range where those keywords with similar meaning plotted into roughly represents the resolution of this method. Keywords related to "easy drive" were plotted near the center of the plot. These keywords are thought to be related more to other keywords than to safety-related ones.

Next, let's focus on keywords in the lower left part of the figure. Keywords such as "fuel economy", "good fuel economy", and "fuel efficiency" are prominent, and "hybrid" and "environmentally friendly" are also in the same cluster. Therefore it can be said that this keyword cluster is generally regarded by ordinary users as "fuel efficiency" performance.

Below the cluster of "fuel efficiency" performance, we find the keywords "low maintenance cost", "low cost", "low tax", and "maintenance cost". Near the center of the plot, "price" and "cost" are also plotted in a large circle. This cluster with these keywords, therefore, can be regarded as the concept of "economical", excluding fuel efficiency.

Keywords such as "compact", "small turning circle", and "zippy" exist in the same lower left area near the

"economical" cluster, so this cluster can be interpreted as "easy drive" performance, as we usually call it.

In summary, the large keyword cluster in the lower left is a group of concepts such as "fuel efficiency", "economical", and "easy drive", and it can be analyzed as a cluster that represents the value concept of "Economy and easy drive".

Third, we would like to focus on the right side of Fig. 4. The keyword "color" is plotted on the outmost side, and in the same direction, there are the keywords "color", "appearance", and "cute". This cluster can be interpreted as the "unique" value concept. Above the "unique" cluster are keywords such as "design", "appearance", "coolness", and "shape", and they represent the attractiveness felt by users about a good shape. So, this cluster was interpreted as the concept of "stylish".

Keywords that are distributed slightly inside such as "size", "wide interior", "wide cabin space", and "seat arrangement" seem to represent the value of the interior space that is relevant to the external shape. So we named this concept "spacious". This "spacious" cluster can be explained as being distributed more inside the plot due to its relevance to other attractiveness or values.

We summarize that the large keyword cluster existing on the right side of the plot forms a cluster representing "unique", "stylish", and "spacious", and that the whole concept can be called "Design and space".

The analysis result of the survey in Japan is summarized as follows. Japanese automobile users have three major concepts regarding attractiveness or value for automobiles. Each concept has its own conceptual structure, consisting of more detailed value concepts loosely combined with each other.

- (1) "Vehicle dynamics" is a value concept composed of individual values of "safety", "handling", and "ride comfort"
- (2) "Economy and easy drive" is a value concept composed of "fuel efficiency", "economical", and "easy drive"
- (3) "Design and space" is a value concept composed of "unique", "stylish", and "spacious"

3.2. U.S.

The plot of keywords provided by U.S. automobile users was analyzed in the same way as in Japan. The resultant plot is shown in Fig. 5.

The prominent keywords plotted at a distance from the polar were "color" in the upper right, "gas mileage" on the left side, and "roomy" in the lower right.

First, in the same direction as the keyword "color" in the upper right of Fig. 5, there are the actual names of colors, such as "red", "blue", and "white" as well as "attractive", "stylish", "sporty", "pretty", "sexy", "luxury", "beautiful", and "cool". These are the keywords the users provided when they were impressed and/or amazed. So this keyword cluster could be semantically interpreted as the concept of the exclusiveness of automobiles, and we called it the

“premium” cluster.

The keyword cluster under this “premium” cluster, including “looks”, “look”, “appearance”, and “exterior” could be interpreted as a cluster expressing beauty of form, so we named it “beauty”.

Further below the “premium” and the “beauty” clusters, keywords like “style”, “styling”, “design”, and “sleek”, as well as “sunroof”, “leather”, “leather seats”, and “heated seats” are aligned. This cluster includes keywords for a variety of optional equipment. The semantic interpretation of this cluster was concluded to be “customizability”.

To summarize, the clusters in the upper right of the plot consist of the three major concepts of “premium”, “beauty”, and “customizability”, so the whole value concept can be regarded as a “Style and design” cluster.

Second, we will look at the left side of Fig. 5. The most prominent keyword, “gas mileage”, is found on the farthest left side of the plot, and keywords such as “good gas mileage”, “fuel efficiency”, “fuel economy”, and so on are listed in the same direction as “gas mileage”. This cluster is the same concept of “fuel efficiency” performance that we have already seen in the Japanese version.

Under the cluster of fuel efficiency, keywords such as “economical”, “gas”, “fuel”, “hybrid”, “affordable”, “cost”,

and “good price” are observed, and they form the same cluster representing the concept of “economical” as in the Japan version. The keyword “environmental” is also found to the lower right of “hybrid” and is regarded as belonging to this “economical” cluster.

If we look into under the “economical” cluster, keywords such as “practical”, “towing”, and “ease of use” are found. The concept implied by these keywords can be interpreted as the application value of automobiles, so we analyzed this cluster as the concept “practical”.

Above the cluster of fuel efficiency, we find such keywords as “reliability”, “dependable”, “durability”, and “maintenance”. These keywords are thought to represent the “reliability” of hardware, and were rarely observed in the Japan survey. Furthermore, there is a cluster that includes the keywords “reliable”, “warranty”, and “resale value”, and these keywords are understood to be the concept of maintaining the “asset value” of automobiles. These concepts, “reliability” and “asset value”, are clusters of value concept that are characteristic to the U.S., as the frequency of these keywords is very high.

Summarizing the above analysis, the group of concepts on the left side of Fig. 5 consists of value concepts such as “fuel efficiency”, “economical”, “practical”, “reliability”,

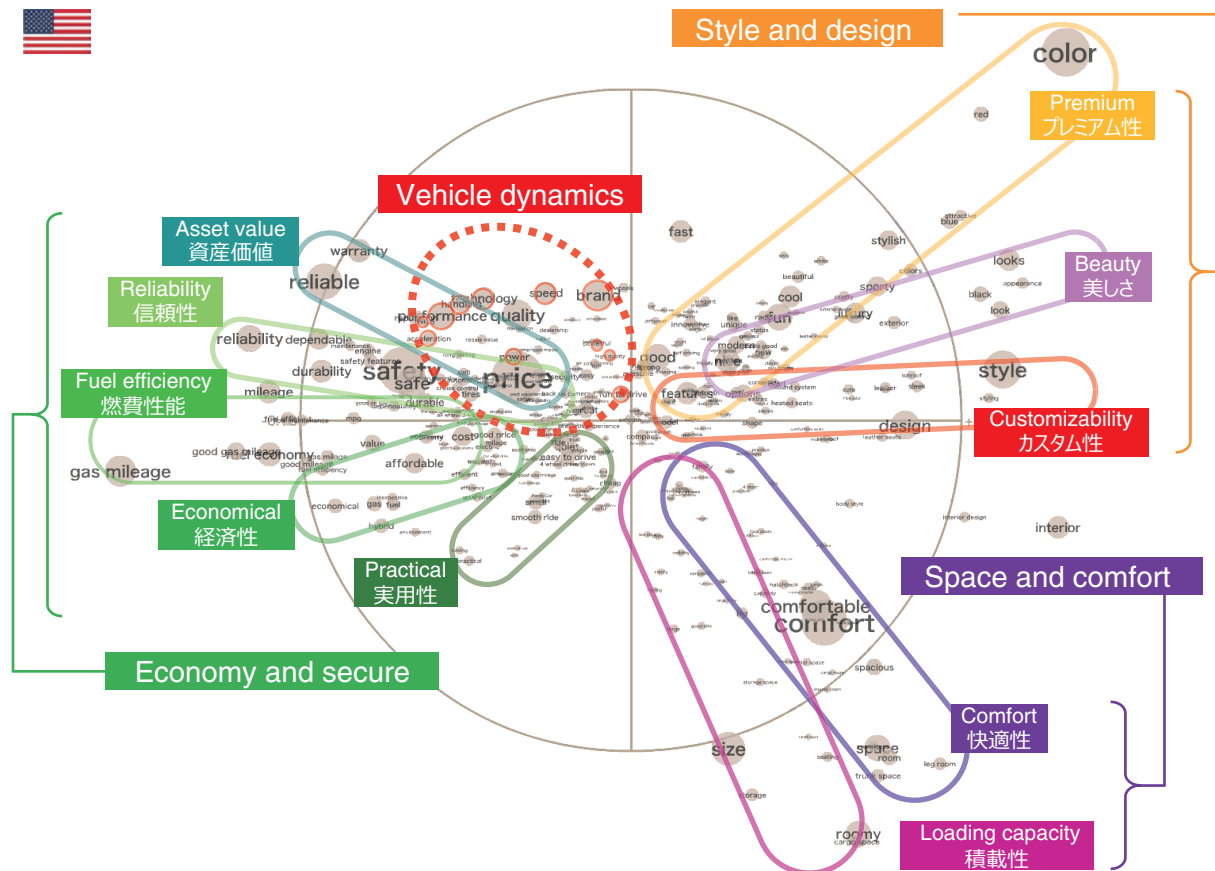


Fig. 5 Comprehensive polar plot of keywords of car values from U.S. car users

and “asset value”. It can be analyzed as a large cluster representing the value concept of “Economy and secure” that is characteristic to the U.S.

In addition, keywords we see in the Japanese version’s “Vehicle dynamics” cluster are observed to be distributed in the inner part of the upper left, rather ambiguously. In the U.S. version, these keywords, which seem to represent mechanical performance, appear not to be very remarkable in the plot. However, these keywords could be presumed to be distributed in the third axis perpendicular to this polar plot. Therefore, we defined a cluster of value concepts as “Vehicle dynamics”, also in the U.S.

Third, we see the most characteristic cluster of value concepts in the U.S. case in the lower right part of Fig. 5. In this cluster, we find many characteristic keywords with a high frequency of appearance.

In the direction of the prominent keyword “roomy”, at a distance from the center of the polar plot, there is a cluster of keywords such as “cargo space”, “storage”, “size”, and “luggage space”, and we find that the clusters are relevant to the value concept of “loading capacity”.

Slightly to the upper right of “loading capacity”, there is a cluster with “leg room”, “room”, “space”, “comfort”, and “comfortable”. This keyword cluster is regarded as the spatial value for passengers and we define this cluster as “comfort”.

These clusters of value concept, “loading capacity” and “comfort”, have many keywords and the frequency of appearance is also high, and they are not observed in the Japanese version. So “loading capacity” and “comfort” are distinctive value clusters as well as “reliability” and “asset value”. The large cluster on the lower right on the whole can be interpreted as the value concept “Space and comfort”.

We can summarize the analysis result of the survey in the U.S. as follows. U.S. automobile users have four major value concepts regarding attractiveness or value for automobiles: “Style and design”, “Economy and secure”, “Space and comfort”, and “Vehicle dynamics”. Each value concept has its own detailed value structure loosely combined each other.

- (1) “Style and design” is a value concept consisting of the individual values of “premium”, “beauty”, and “customizability”
- (2) “Economy and secure” is a value concept consisting of “reliability” and “asset value”, which are unique to the U.S., followed by “fuel efficiency”, “economical”, and “practical”, similar to those of Japan
- (3) “Space and comfort” is a value concept consisting of “loading capacity” and “comfort”, and is also unique to the U.S.
- (4) “Vehicle dynamics” is a value concept consisting of the individual values of “safety”, “handling”, and “ride comfort”, as in Japan

4. Discussion

By using the proposed method, well-cited user attributes such as age, gender, automobile brand recognition, and so on can be analyzed objectively, as can the value of EVs which are expected to be popular in the future.

4.1. Age and Gender

In Fig. 6, the age groups and genders of automobile users in Japan and the U.S. were plotted using an overlay in Figs. 4 and 5, respectively.

In both Japan and the U.S., plots of each age group were plotted in line and older age groups were placed toward

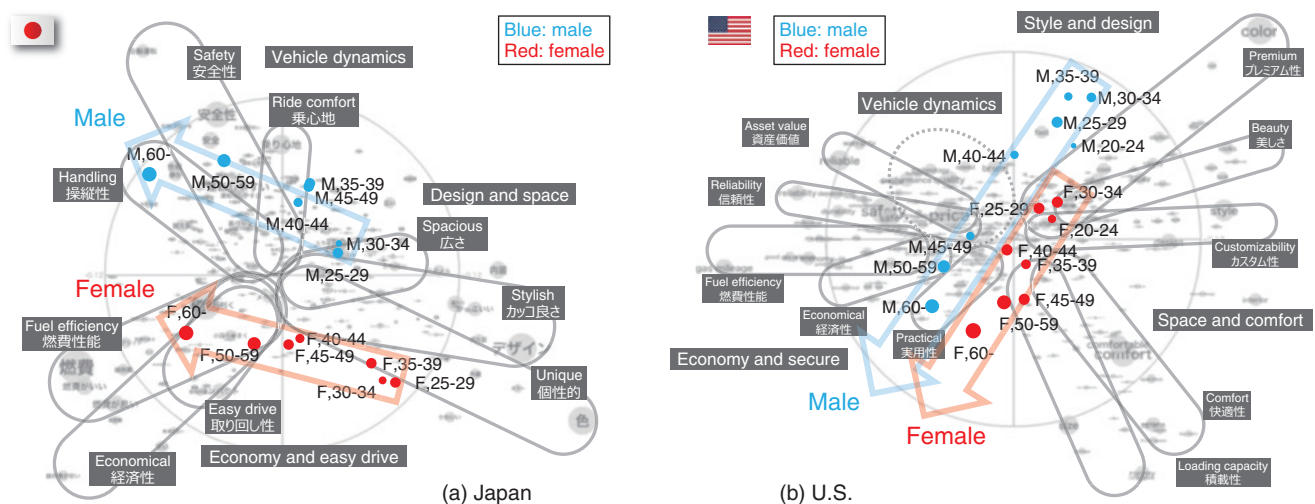


Fig. 6 Transition of values by age and gender in Japan and the U.S.

the direction of the arrows in the plot. Even though the direction of the arrows appears to be different in Japan and the U.S., the general trend seems to be common for both genders. Judging from the meanings of value clusters in the plot, the younger the user was, the closer the plot plotted near the design-related clusters that belong to a kind of sensual attractiveness. On the other hand, the older the user was, the closer the plot plotted near functional clusters, which belong to practical attractiveness.

In Japan, plots of older males are located closer to the functional values in the “Vehicle dynamics” value cluster, and plots for older female are closer to the utility values in the “Economy and easy drive” value cluster. There is a distance between the male and female plots, which means that automobiles that appeal to male users for their functionality might not be attractive to female users who value utility more than male users. This overlay plot can provide a basis for this type of discussion.

Since the relatively young female age class of 25 to 39 in Japan plotted close to design-related clusters, it is important to pursue rich color variations and good design as well as ordinary application values in order to enhance joy for these customers. On the other hand, the position of plots of females over 50 suggests that fuel efficiency, economical, and easy drive are extremely important for them. Realizing these value concepts would be effective in gaining joy for these customers.

Next, let’s look at the U.S. Similar to Japan, the younger the user, the closer the plot is plotted near design values, and the older the user, closer the plot is plotted near practical values clusters, such as “Economy and secure”. However, in the U.S., younger males aged 20 to 39 have plots far from the center of the polar plot, in the direction of the design cluster, which is not like Japan. Therefore, enhancing design values of automobiles might be more appealing to younger male users in the U.S. The gap between male and female plot points in the U.S. is smaller than in Japan, so the difference of values concepts of both genders is likely to be smaller than that of Japan.

These differences in value concept among age groups can be applied to analysis when planning and developing our products and technologies. Such analyses could help us by visualizing whether a single product can satisfy the value required by several user segments, such as younger users and older users. Such analyses could also tell us at what point the users would be satisfied. In the development of global vehicle products using common chassis platforms, compatibility with the demands of each country or region of the world would be required. In the new development process, the proposed method could provide measures to understand the values of various car users.

However, this single-year survey alone cannot distinguish whether the identified value concept changes with age or whether the value concept is just unique to each generation. It is important to note that clarification requires continuous surveys and fixed-point observations.

The same sort of analysis can be applied to a wide range of attributes, such as the users’ residence areas, the way users spend holidays, occupations, and annual income, and the proposed method is, therefore, versatile enough for future demand.

4.2. Brand

In Fig. 7, automobile brand names of the cars owned by survey participants in the U.S. were overlay plotted on Fig. 5.

The plot of the Honda brand, which is defined by the positions of keywords Honda users cited, was located in a slightly higher section on the left side, on the outermost side of the plot. Compared with other brands, Honda’s location is the most distant from the center of the plot and is near “reliability” and “asset value” in the “Economy and secure” cluster. Therefore, the Honda brand is thought to have better recognition for these values than other brands.

The plot of the Acura brand was located in the upper right, relatively to the outside, in the direction of the “Style and design” cluster. So-called premium brands, such as BMW, Mercedes-Benz, Audi, and Lexus are located here, and in the outermost area, BMW can be said to be the most clearly recognized brand by users. The position of Acura is the second outermost, next to BMW, and this can be interpreted as Acura being recognized for its attractiveness and values, which are close to those premium brands.

4.3. EV

In Fig. 8, the plots of EV users, EV potential users, and EV reluctant users in the U.S. were overlay plotted.

EV users and EV potential users were located near the upper section of the plot, near the premium cluster “Style and design”, which is close to the area of the

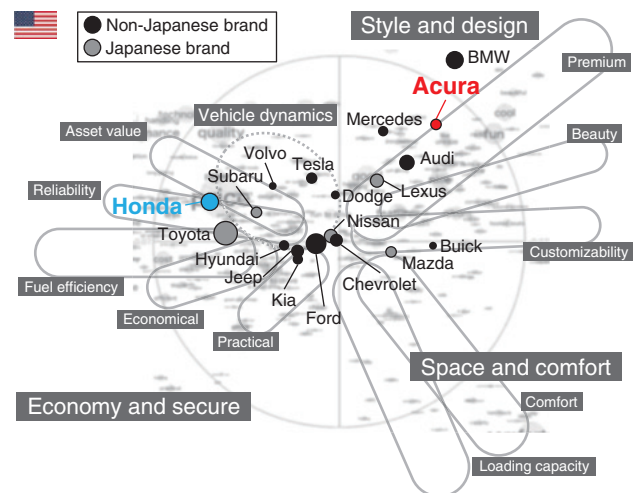


Fig. 7 Center positions of users' value keywords by each automobile brand (magnified plot)

premium brands. This suggests that EVs are recognized by automobile users as a kind of premium brand car in regard to attractiveness and value concepts. The top ten cited keywords both by EV users and by EV reluctant users were compared in Table 1. The six keywords were common to both users, and no special keywords relevant to environmental values were cited by EV users. This fact suggests that the previous assumption, that EVs are recognized as a kind of premium car, is appropriate.

When we look into the plot of EV reluctant users, it is located near the “practical” and “loading capacity” value clusters. If we plan to sell more EVs on the market in the near future, we need to take these user values into account in our products.

4.4. Commonality and Uniqueness of Japan and the United States

The common value concepts of the attractiveness and value of automobiles, both in Japan and in the U.S., were the value concepts of color, design, economy, and fuel efficiency.

In Japan, there is the value concept “spacious” in the large concept cluster “Design and space”, and Japanese users place importance on mechanical performance, or “Vehicle dynamics”, which is characteristic compared to the U.S. If size, space, and mechanical performance could be incorporated with our products in Japan, it could have a positive effect on users’ value.

On the other hand, it was characteristic in the U.S. for the large value concept cluster “Style and design” to include the concept “customizability”, and for the value concept cluster “Economy and secure” to incorporate both the “reliability” and “asset value” concepts. In the U.S., enhancing the customizability and/or providing various

Table 1 Comparison of keywords cited by EV users and EV reluctant users

EV users [%]	Keyword	EV reluctant users [%]	Keyword
14.15	Color	25.63	Price
13.21	Price	22.50	Color
12.26	Safety	20.43	Safety
11.32	Design	19.99	Comfort
11.32	Good	13.90	Style
10.38	Comfort	12.52	Reliable
9.43	Gas mileage	10.99	Size
9.43	Quality	10.17	Comfortable
9.43	Brand	9.26	Gas mileage
8.49	Comfortable	8.78	Safe

optional equipment could enhance the user perceived value concept “Style and design”, and enhancing reliability and durability in order to reduce users’ anxiety about malfunction could be of value to users. As “loading capacity” and “comfort” also form a large value cluster in the U.S., functionality oriented pickup trucks could be very attractive if equipped with large cabins with enhanced ride comfort, for example.

Meanwhile, the value concept cluster “Vehicle dynamics”, including the keyword “autonomous driving”, which was a stand-out keyword in Japan, was not prominent in the United States. It can be seen that U.S. users are choosing their cars not only based on mechanical performance-related values, but also on various values that are more diverse than those in Japan. In order to develop products targeting U.S. users, it should be a priority to study the psychology of customers in the United States, which has been shown to be very different than in Japan.

5. Summary

In this research, in order to analyze the value concept of attractiveness or value of automobiles, we used a free-keyword description method to conduct cluster analyses using the quantification method III of statistical analysis, based on the following:

- (1) Analysis of value concepts regarding attractiveness and value of automobiles through the semantic interpretation of keyword clusters
- (2) Difference analysis between Japan and the U.S., user attribute analysis, and brand recognition analysis to show the extensibility of proposed method

It is known that the keyword “autonomous driving”, prominent in the Japanese version, was not extracted in a similar survey two years prior to this. As collision damage mitigation brake systems and ADAS (Advanced Driving Assistant Systems) have become well recognized, users’ interest in autonomous driving has increased. This survey can be said to grasp such users’ psychology successfully. Similarly, it can be said that other keywords collected in

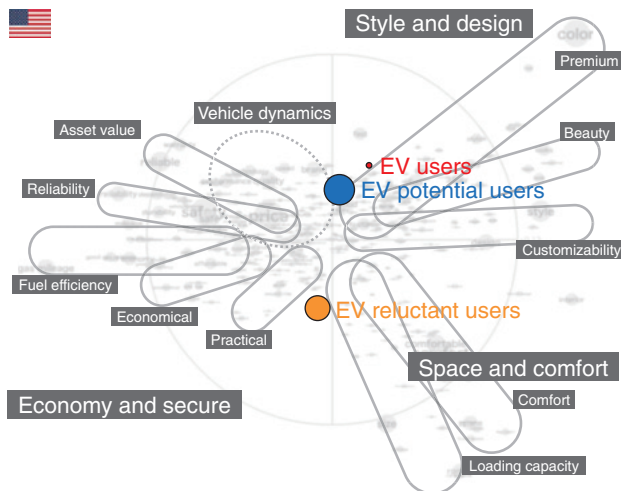


Fig. 8 Center positions of value keywords from users, potential users, and reluctant users of EV

this survey are also likely to capture the value concepts of automobile users accurately.

We hope that the proposed method will be developed further in order to help realize the Honda philosophy “Customers’ Joy” in the future.

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Traversability Analysis for Mobile Robot Navigation in Rough Terrain

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ABSTRACT

For the research described here, the road surface necessary to enable autonomous navigation by a robot in rough terrain was modeled and a method of traversability analysis of that road surface was created. As in much preceding research, this method consists of three steps, which are (1) dividing the road surfaces around the robot into grids, (2) generating a road surface model of each grid, and then (3) performing traversability analysis of those road surfaces by evaluating those models. The new contribution made by this method is that, by optimizing the grid size of the road surface to be modeled, it can assure the validity of modeling a road surface on rough terrain by means of planes. In addition, this method is robust with regard to outliers and noise near maximum and minimum values in a measurement point cloud, and the small number of setting parameters is another distinguishing characteristic. Application of this method to an environment of rough terrain, including slopes, uneven surfaces, and obstacles, made it possible for robots to correctly perform traversability analysis of road surfaces and to navigate autonomously in that environment.

1. Introduction

In the societal context of labor shortages and other such issues due to the influence of the declining birthrate and growing population of elderly people in recent years, there has been growing demand for robots to transport supplies, agricultural robots to work on farms, and other such robots that can autonomously navigate rough terrain⁽¹⁾. In order for robots to navigate autonomously in a rough terrain environment, they need to use data obtained from cameras, light detection and ranging (LIDAR) systems, and other such sensors to recognize height differences and slopes in surrounding road surfaces, and they need to perform traversability analysis of those road surfaces.

Previous research on methods of road surface traversability analysis with the objective of autonomous navigation by a robot over rough terrain can be categorized relative to the two axes: the type of information used to model a road surface and the method used to model that road surface. Road surface models are mainly built using either visual information obtained from image data, or geometric information obtained from point cloud data, or other information obtained from acceleration data and so on, or a combination of multiple types of information. Almost all the methods for building those models use either

a model-based approach founded on certain rules, or a machine learning-based approach.

Machine learning-based methods have been actively researched in recent years. These include methods of obtaining models for performing traversability analysis of road surfaces by supplying the course followed when driven by humans as training data, applied with respect to input consisting of point cloud geometric information and light reflection intensity⁽²⁾; methods of obtaining models for performing patch-by-patch traversability analysis when a height map obtained from point cloud data is converted into a grayscale image, which is divided into multiple patches, and the travel results for a robot operated in simulation are used as training data with respect to those patches^{(3), (4)}; methods of enabling traversability analysis by supplying training data consisting of the results of image-by-image traversability analysis by humans with respect to input consisting of multiple feature quantities obtained from RGB images⁽⁵⁾; a method combining this method with predicted future images⁽⁶⁾; and so on. Research has also focused on numerous methods that combine a multiplicity of information, such as a method that adds robot vibration information obtained from an inertial measurement unit (IMU) to the results of uneven surface estimation and texture estimation obtained from image data⁽⁷⁾, a method

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that uses segmentation images in combination with the geometric features of those images to judge whether an obstacle on the road surface can be traversed⁽⁸⁾, and so on.

These methods are capable of expressing traversability analysis functions that cannot readily be expressed in model-based approaches, and are therefore very useful. However, learning-based methods in general have issues with regard to applicability to unfamiliar environments of types that are not included in the learning data. For robots that navigate rough terrain, many are expected to operate in unfamiliar environments, and therefore there is concern that this method's traversability analysis results may degrade performance. It is also the case that robots have different navigation performance and, depending on requirements, differing labels on their learning data. When a method is used with a different robot, therefore, and when the requirements change, it is necessary to rebuild the learning data, which presents convenience issues for the method.

When higher priority is assigned to applicability in unfamiliar environments and to convenience, model-based methods are effective. Many model-based methods first divide the road surface around the robot into grids, and their geometric features identified from point cloud data obtained using LIDAR and depth camera are used for grid-by-grid modeling of the road surface. Then, based on those models, traversability analysis is performed. Prior research includes methods for performing traversability analysis, such as a method for modeling the slope of the road surface and its surface roughness from specific vectors and eigenvalues of the point cloud distribution covariance matrix, and performing traversability analysis by threshold values set according to those quantities^{(9), (10)}; a method for grid-by-grid modeling of the road surface by a plane equation using random sample consensus (RANSAC)⁽¹¹⁾ and then performing traversability analysis from the magnitude of the slope and the continuity of the grid⁽¹²⁾; and so on. There are also many methods that define their own, unique evaluation indices for performing traversability analysis, such as a method for analyzing traversability by defining evaluation functions such as the weighted sum from the slope, variance, or other such parameters in the road surface model^{(13), (14)}; fuzzy-based methods for judging traversability using fuzzy membership functions that define the extent of those parameters⁽¹⁵⁾; and so on. Most of these methods, however, have the three issues shown below.

(1) Appropriate modeling of road surfaces to include obstacles

As explained above, many model-based methods use planes as constituent elements of road surface models. When they are measuring road surfaces, with obstacles included, the planes are influenced by both the ground surface point cloud and the obstacle point cloud. With regard to the inclination of the plane, in particular, the

values can differ greatly because of differences in the proportion of the road surface taken up by the obstacle region. Unless these influences are taken into account, therefore, planes may be estimated that are not in line with the intention of the method, and the criteria for performing traversability analysis will not be met. Consequently, appropriate modeling of road surfaces when obstacles have been measured is an issue.

(2) Road surface modeling that is robust with regard to point cloud measurement noise

On rough terrain, the influence of the sunlight environment and reflection characteristics of the road surface may result in large amounts of noise being included in measured point cloud information. Of such noise, that from outliers and noise near maximum and minimum values in a measurement point cloud in particular can yield incorrect traversability analysis results. Consequently, those noise elements need to be taken into consideration as a practical matter when modeling road surfaces.

(3) Simplification of setting parameters

When parameters and indices for which explaining the physical meaning is troublesome are used for weighting with respect to road surface modeling and traversability analysis indices, tuning the parameters can be troublesome and not only does this contribute to degradation of traversability analysis performance, but it also diminishes the method's general purpose properties. Consequently, it is desirable for the setting parameters in this method to be simple and intuitive.

This paper therefore proposes a traversability analysis method that resolves these issues; that is, the aim here is to create a method that assures the validity of modeling a road surface by means of planes, that is also robust with regard to noise from outliers and noise near maximum and minimum values in a measurement point cloud, and that the parameters expressing the criteria for traversability analysis used in this method are not dependent on the robot's system integrator, but rather are judged solely by the hill-climbing performance and traversal performance of the robot.

2. Method of Traversability Analysis Appropriate for Uneven Surfaces

Like the various methods described in part 1, the proposed method is made up of three parts: (1) The part that divides the road surfaces surrounding the robot into grids; (2) the part that generates a road surface model for each grid; and (3) the part that performs traversability analysis of the road surface by evaluating the model.

In this part, Section 2.1. will first assume a road surface of natural terrain without any obstacles and describe a method for traversability analysis of that road surface. This method is like much preceding research in using planes to model road surfaces. It also includes several statistical methods, and a

feature of this method is its ability to remove the noise from outliers and noise near maximum and minimum values in a point cloud of road surface measurements.

Section 2.2. will describe a method for traversability analysis in terrain that includes obstacles. The road surface that includes obstacles has different geometric features than a road surface that does not include obstacles. Therefore, as described in the previous chapter with regard to issues faced by modeling methods, when a road surface that includes obstacles is modeled using planes, there are instances when the inappropriateness of that approach means that those planes can cause traversability analysis to produce incorrect judgments. In the proposed method, however, the division into grids in part (1) is performed with the grid divisions defined in an appropriate size. This makes it possible to perform traversability analysis without loss of the model's validity even if the method for modeling a road surface of natural terrain that does not include obstacles is applied, just as it is to a road surface that does include obstacles.

2.1. Method for Traversability Analysis in Natural Terrain

- (1) Division into grids of road surface surrounding the robot
Division into square grids of appropriate size is performed. In this section, as in much of the preceding research, the division into grids is done without any need to impose constraint conditions.

- (2) Generation of road surface model

The road surface is first modeled using three procedures: (a) estimating representative planes, (b) modeling the surface shape of the representative planes, and (c) separating outliers. A general view of this is shown in Fig. 1.

- (a) Estimating representative planes

For each grid that has been divided, RANSAC⁽¹¹⁾ is used to estimate the representative planes. With RANSAC, the number of outliers is smaller and planes that are compatible with point clouds other than those of outliers can be obtained, so planes that are less susceptible to influence by measurement

noise outliers are estimated.

- (b) Modeling the surface shape of the representative planes

Plains, ridge-top paths, slopes, and other such outdoor natural terrain have continuously changing elevations. It is assumed that the variations in elevation within each grid are based on the Gaussian distribution $N(\mu, \sigma^2)$. Here, μ is the representative plane estimated in procedure (a) while σ is approximated by the root mean square (RMS) value for the whole point cloud with respect to that μ .

- (c) Separating outliers

Areas where the distance from the representative plane is $\pm 2\sigma$ (hereinafter referred to as an effective model area) are defined and point clouds outside those areas are removed. If the road surface model is to strictly follow Gaussian distribution, about 2.5% each of the point cloud on the largest and smallest sides of the signed distance from the representative plane will be removed. The purpose of this process is to reduce noise from outliers and noise near maximum and minimum values in a measurement point cloud. In some cases, a portion of the point cloud of the road surface model itself can also be removed, but if the terrain features are continuous and dense, then the value of the point cloud that was removed can be approximated by the point cloud within the boundary of the effective model area and close to that boundary.

- (3) Analysis of traversability

Traversability is judged for the road surface model generated for each grid on the basis of the following two criteria.

$$T_1 = \begin{cases} 1 : \theta \leq \theta_{lim} \\ 0 : \text{otherwise} \end{cases} \quad (1)$$

$$T_2 = \begin{cases} 1 : d_{max} - d_{min} \leq h_{lim} \\ 0 : \text{otherwise} \end{cases} \quad (2)$$

Here, θ is the absolute value of the slope of the representative plane, θ_{lim} is the absolute value of the slope

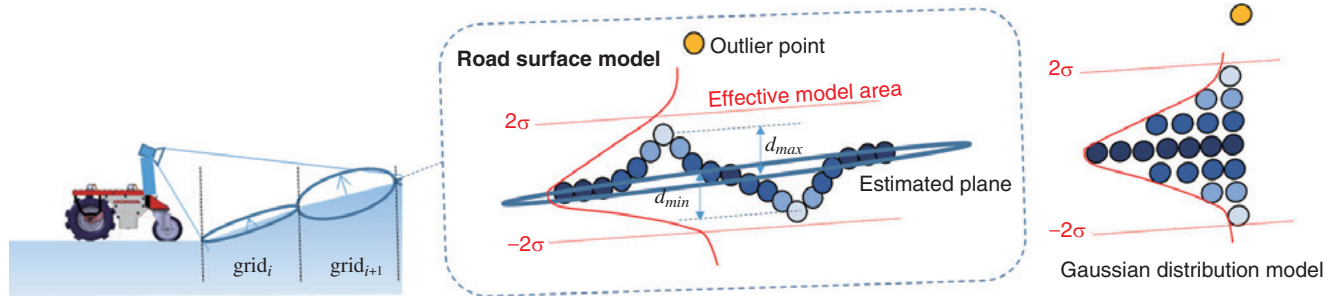


Fig. 1 Road surface model based on Gaussian distribution

angle that the robot is able to ascend and descend, d_{max} is the greatest value for the signed distance between the points included in the effective model area and the representative plane, d_{min} is the corresponding smallest value, and h_{lim} is the greatest height value for an obstacle that can be traversed by a robot. For this paper, the absolute value of the largest slope angle that can be ascended and the absolute value of the smallest slope angle that can be descended are considered to be equal, and θ_{lim} is used for these values. If the two values differ, however, then when θ is between the smallest and the largest slope angles, it will suffice to set Eq. (1) so that $T_1=1$. Equation (1) expresses the traversability analysis index for a slope, and Eq. (2) expresses the traversability analysis index for uneven ground. Preceding research used variance and standard deviation as traversability analysis indices for uneven ground instead of Eq. (2), and many such approaches assigned some kind of threshold value to those indices. The threshold value in that kind of method can carry the same implications as Eq. (2), depending on how the threshold value is assigned, in cases where the road surface model completely follows Gaussian distribution as assumed in (2)(b). When the road surface model diverges to some extent from Gaussian distribution, however, and in an environment where the extent of concavities with respect to the estimated plane are not equal to the extent of convexities, degradation of performance can be expected. With the present method, therefore, the peak-to-peak value for the point cloud within the effective model area, as in Eq. (2), is taken as the traversability analysis index for uneven ground. This enhances the method's robustness when the road surface diverges from Gaussian distribution.

The traversability analysis index is defined using T_1 , T_2 as follows:

$$traversability = T_1 \cdot T_2 \quad (3)$$

When $traversability=1$, the terrain is traversable. When it is 0, the terrain is untraversable.

2.2. Traversability Analysis in Terrain that Includes Obstacles

Obstacles on the road surface being traversed are modeled as shown in Fig. 2 (a). An actual robot would use a three-dimensional plane model. Here, however, the

explanation will use a simplified two-dimensional, straight-line model. In this model, the obstacle is represented with respect to a traversed road surface segmented into grids that have one side of length l , where a convex portion with height h exists with occupancy rate α as a proportion of the grid. In other words, a difference in level or other such obstacle can be expressed by changing the values of h and α . In this section, it will be shown that the traversability analysis method described in previous sections can be applied as it is to a road surface that includes this obstacle model if the size of the grids dividing the road surface is set appropriately.

For that purpose, the size of the grid divisions first needs to be optimized, and the reason for this will be shown using concrete examples. With respect to a road surface that includes the obstacle model shown in Fig. 2 (a), the ideal representative plane with least variance, estimated by the procedure in (2)(a) of Section 2.1., will be as shown in Fig. 2 (b). Consider a robot with navigation performance of $\theta_{lim}=25$ deg and $h_{lim}=0.05$ m (a robot with this navigation performance will be referred to hereafter as Robot A) that performs traversability analysis with respect to a road surface model that includes obstacles. Figure 3 is a judgment diagram showing recognition of an obstacle of height $h=0.03$ m and occupying a proportion $\alpha=0.25$ of a grid that has one side of length $l=0.05$ m. In Eq. (1), $\theta=33.1$ deg > 25 deg yields $T_1=0$, while in Eq. (2), $d_{max}-d_{min}=0.0251 < 0.05$ yields $T_2=1$ so that according to Eq. (3), $traversability=0$. It is apparent that the obstacle is judged to be untraversable even though this is an obstacle that by its nature should be fully traversable. This is a phenomenon that can occur in all methods that express a road surface model using representative planes. The reason for it is that when the grid size is small, the slope of the representative plane on a road surface that includes obstacles becomes steep. Due to this phenomenon, a divergence occurs between the obstacle height that can be traversed based on the robot's navigation performance and the result of the traversability analysis, and the robot's traversable region is reduced. On the other hand, when the grid size becomes larger, the resolution of the road surface is correspondingly reduced so that the robot's movement becomes constrained. In performing traversability analysis of a road surface that includes obstacles, therefore, a

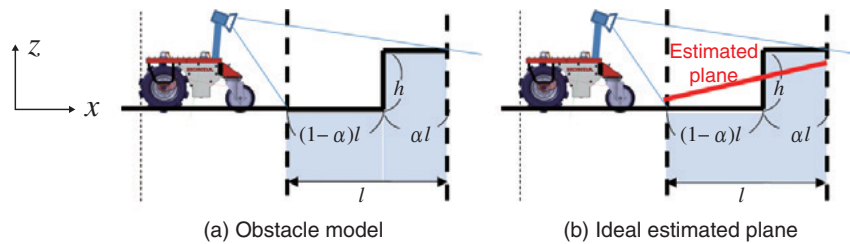


Fig. 2 Definition of obstacle model and traversability estimation of obstacle

grid division method is needed that provides for the least divergence in traversability analysis so as not to cause these issues to occur.

The proposed method has established such a grid division method. The incorrect judgment in traversability analysis described above occurs because the obstacle height, on which traversability hinges in accordance with grid size, changes so that it diverges from the actual threshold value h_{lim} . When a robot that has θ_{lim} , h_{lim} navigation performance recognizes surrounding road surfaces with grids that are of length l on one side, and performs traversability analysis by the method shown in Section 2.1., then in the case of an obstacle with the occupancy rate α , the robot will define the height that it judges internally is untraversable as $h_{internal}(\alpha, l)$. The method of derivation will be described later. In the case of the example shown in Fig. 3, for instance, the threshold value at which this robot judges internally that a road surface is untraversable is $h_{internal}(0.25, 0.05) \approx 0.015$ m, which diverges from the set threshold value $h_{lim} = 0.05$ m. The result, as discussed above, is that the traversability analysis with respect to an obstacle with height $h = 0.03$ m that is within the range of $h_{internal}(0.25, 0.05) < h < h_{lim}$ will yield an incorrect judgment.

The method for deriving $h_{internal}(\alpha, l)$ can be described by Algorithm 1 shown below.

Algorithm 1: $h_{internal}(\alpha, l)$

```

1  $h \leftarrow \text{null}$ ; traversability  $\leftarrow \text{True}$ 
2 while traversability do
3    $h \leftarrow h + \Delta h$ ;
4   traversability  $\leftarrow \text{Judge}(\theta_{lim}, h_{lim}, l, \alpha, h)$ ;
5 return  $h$ ;

```

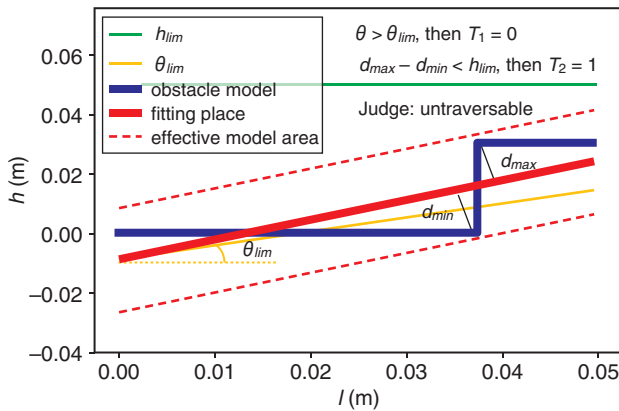


Fig. 3 Example of incorrect estimation result
($l = 0.05$ m, $\theta_{lim} = 25$ deg, $h_{lim} = 0.05$ m)

Here, $\text{judge}(\theta_{lim}, h_{lim}, l, \alpha, h)$ is a function that returns traversability analysis results when the traversability analysis method shown in Section 2.1. is applied to a robot with threshold values θ_{lim} , h_{lim} with respect to an obstacle model expressed by l, α, h as defined in this section.

When l takes a certain value, an obstacle of height h will definitely be traversable if $h < \min_{\alpha} h_{internal}(\alpha, l)$ and will definitely be untraversable if $\max_{\alpha} h_{internal}(\alpha, l) < h$. If $\min_{\alpha} h_{internal}(\alpha, l) < h < \max_{\alpha} h_{internal}(\alpha, l)$, then traversability will change according to the value of α .

Here, consider the case when l takes a certain value and $\min_{\alpha} h_{internal}(\alpha, l) \approx h_{lim}$. In this case, the traversability analysis can be performed correctly to judge that an obstacle with $h < h_{lim}$ is traversable while an obstacle with $\max_{\alpha} h_{internal}(\alpha, l) < h$ is untraversable. On the other hand, even though an obstacle with $h_{lim} < h \leq \max_{\alpha} h_{internal}(\alpha, l)$ is untraversable, there are cases when it is incorrectly judged to be traversable depending on the value of α . If the traversability analysis update cycle is adequate, however, then even if a certain road surface has once been judged to be traversable, when the robot navigates it, the judgment can be changed to untraversable in the course of changing the value of α . Consequently, when a grid that satisfies the condition $\min_{\alpha} h_{internal}(\alpha, l) \approx h_{lim}$ has sides set to length l , then the robot will be able to perform traversability analysis of the road surface while satisfying the value h_{lim} set on the basis of the robot's navigation performance.

An objective function such as $J(l)$ in Eq. (4) is, therefore, defined and a value for l that yields the smallest $J(l)$ as in Eq. (5) is assigned as the length of one grid side.

$$J(l) = h_{lim} - \min_{\alpha} h_{internal}(\alpha, l) \quad (4)$$

$$l = \arg \min J(l) \quad (5)$$

However, Eq. (5) is considered to yield a solution under the following constraint condition.

$$h_{lim} - \min_{\alpha} h_{internal}(\alpha, l) > 0 \quad (6)$$

According to Eqs. (4) and (5), $\min_{\alpha} h_{internal}(\alpha, l) \approx h_{lim}$ is valid, so as stated above, the robot is able to perform the traversability analysis while maintaining the threshold value of h_{lim} that was set on the basis of the robot's navigation performance. Equation (6) has the role of providing for the highest road surface resolution within the range of threshold values h_{lim} that the robot is able to maintain.

For example, when the same procedure is applied to Robot A (however, with $\Delta h = 0.001$ m), then the objective function will be as shown in Fig. 4, and $l = 0.21$ m will be derived according to Eqs. (5) and (6).

Based on the above, when an obstacle model defined as in Fig. 2 (a) is assigned the constraint condition of grid size l shown in this section, then it can be judged whether an obstacle can be traversed using the same method of

traversability analysis for natural terrain shown in Section 2.1. The above method can be summarized as shown in Fig. 5.

Under the constraint condition of Eq. (6), $\min_{\alpha} h_{internal}(\alpha, l)$ will be the threshold value for the robot to judge internally that a road surface is untraversable. In practical terms, therefore, if this value is within the range of allowable values, then l will not necessarily need to be decided by Eq. (5). It will be sufficient to use a convenient figure that is close to the solution of Eq. (5).

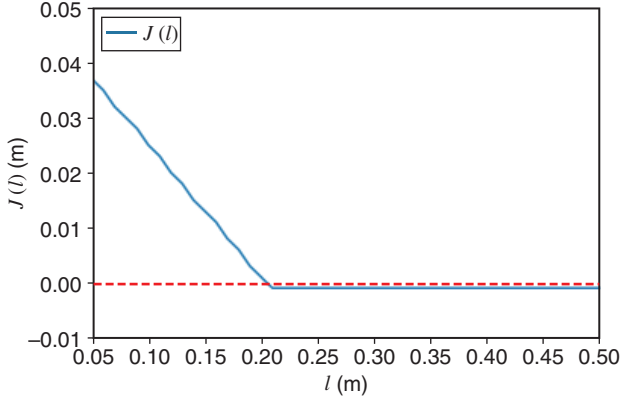


Fig. 4 Objective function of grid size optimization ($\theta_{lim} = 25$ deg, $h_{lim} = 0.05$ m)

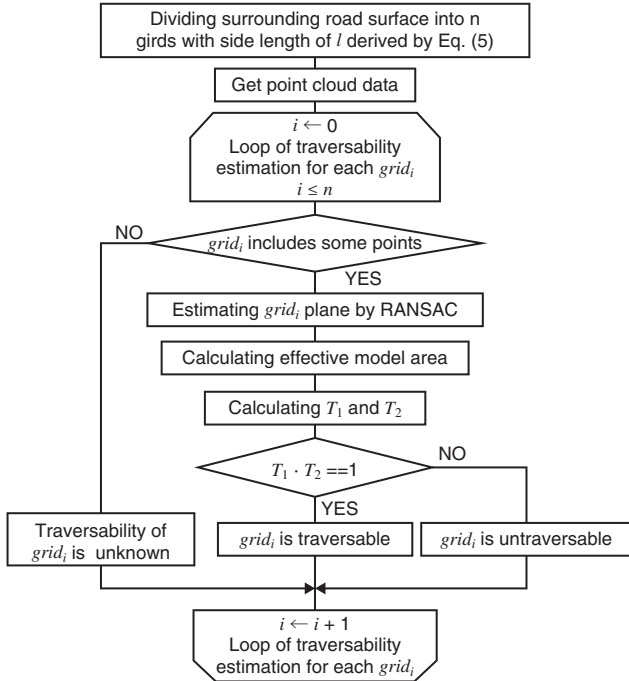


Fig. 5 Flowchart of proposed method

3. Test Conditions

Figure 6 shows the robot used in verifying the effectiveness of the proposed method shown in Chapter 2. This robot is equipped with a stereo camera, and the forward camera can be used to acquire the road surface point cloud. Fixed values $\theta_{lim}=25$ deg, $h_{lim}=0.05$ m were assigned as the threshold values for the robot's navigation performance. The threshold values were calculated on the assumption that the wheels would have sufficient grip force on the road surface and taking into consideration the radius of the wheels under the same conditions.

A square bar placed on a flat road surface was used in verifying the effectiveness of the grid size optimization method. With width 0.31 m, length 0.04 m, and height 0.04 m, this square bar was made slightly lower than the threshold value for an obstacle height that is untraversable by the robot.

In verifying the effectiveness of the robot's traversability analysis method in a rough terrain environment, a rough terrain environment like that shown in Fig. 7 was used, with gravel road, lawn, trees and tree trunks, protruding obstacles, slopes, and so on. The central illustration in Fig. 7 is a schematic view, and the proportion of the actual environment taken up by each of the road surface attributes such as lawn, surfaced road, and so on, largely matches the area ratios in the schematic view. The slopes are all uneven road surfaces. The slope angles differ, varying across a range from about 5 to 40 degrees. There was a mixture of regions with traversable slope angles and regions with untraversable slope angles. The lawn was less than 0.05 m in height, and was a traversable region. However, the obstacles on the lawn and the trees were all more than 0.05 m in height and were untraversable regions. The gravel road was surfaced with stones about 0.04 m or less in height, and much of it was traversable. However, portions of it had the stones packed closely together and overlapping so that the height exceeded 0.05 m, and those were untraversable regions. The environment in Fig. 7 does not include road surfaces that would reduce the grip force of the wheels, such as wet road surfaces, sand pits, and so on. It was an environment in which every road surface would provide the



Fig. 6 Test robot with stereo camera

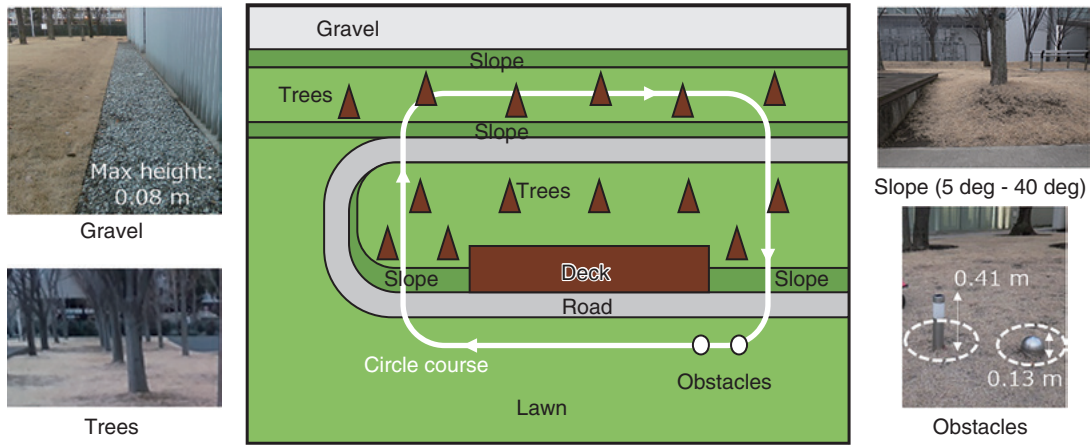


Fig. 7 Test environment

wheels with adequate grip force. The environment in Fig. 7 was configured as above to serve as the test environment. Although it did not provide a completely exhaustive rough terrain environment, it did constitute an environment of road surfaces with diverse attributes, some regions being traversable for a robot and other regions being untraversable.

4. Results and Discussion

4.1. Verification of Effectiveness of the Grid Size Optimization Method

The effectiveness of the grid size optimization method shown in Section 2.2. was verified. The method for optimizing the navigation performance of the robot shown in part 3 was first applied and the grid side was given a length of $l=0.20$ m. As described in Chapter 3, fixed values were used for θ_{lim} , h_{lim} , so the grid side length of $l=0.20$ m was also a fixed value. At this point, the threshold by which the robot would judge internally that a road surface was untraversable was $\min_{\alpha} h_{internal}(\alpha, 0.20)=0.047$ m. The case with a length of $l=0.10$ m was set up for comparison and the results of traversability analysis by the method shown in Section 2.1. were compared. Traversability analysis was performed for two patterns with square bars placed on the road surface, one with $l=0.10$ m and the other with $l=0.20$ m. The results are shown in Fig. 8. The directions of the arrows indicate the directions of the normal vectors of each grid's representative planes. The colors of the arrows are according to the definitions in Table 1.

Since the height of the square bars is lower than h_{lim} , a road surface that includes those square bars would by its nature be traversable. In the case of $l=0.10$ m, however, then, as shown in Fig. 8 (a), the slopes of the representative planes in grids that include square bars exceeded the threshold value for a slope that the robot can climb, so that $T_1=0$ and the result was that those road surfaces were judged

Table 1 Definition of arrow color

	$T_2 = 0$	$T_2 = 1$
$T_1 = 0$	Clear Red	Red
$T_1 = 1$	Clear Black	Green (traversable)

to be untraversable. This showed that when performing traversability analysis of a road surface by a method that involves dividing that road surface into grids and using the slopes of the estimated planes in each grid as factors in the traversability analysis, then an incorrect judgment could occur in the traversability analysis unless an appropriate grid size has been specified. In the case of $l=0.20$ m, on the other hand, a similar phenomenon did not occur. As shown in Fig. 8 (b), a plane including the same square bar was correctly judged to be a traversable road surface. Moreover, the judgment results did not change even when the square bars were moved to lower the occupancy rate of the square bars in a grid, or when multiple square bars were placed side by side to raise that same occupancy rate. The road surface that included square bars was correctly judged to be traversable. The above indicated the effectiveness of the method for optimizing grid size shown in Section 2.2.

4.2. Verification of the Effectiveness of the Proposed Method in a Rough Terrain Environment

The effectiveness of the proposed method was verified in the environment shown in Fig. 7. Following the previous sections, the length of one side of a grid was made a fixed value at $l=0.20$ m.

An example of traversability analysis results in natural terrain is shown in Fig. 9 (a) and (b). In this figure, (a) illustrates the recognition of the slopes in Fig. 7 and (b) illustrates the recognition of the gravel road. Figure 9 (a) has a region with green arrows that is judged to be traversable and a region with red arrows that is judged to be

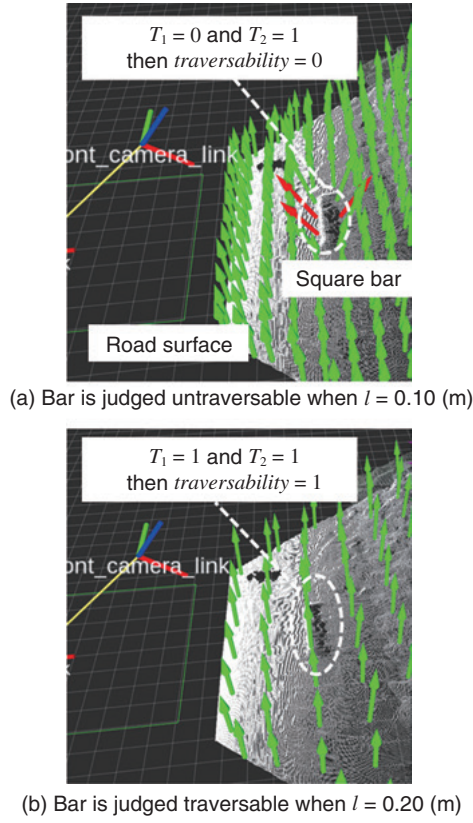


Fig. 8 Grid size optimization

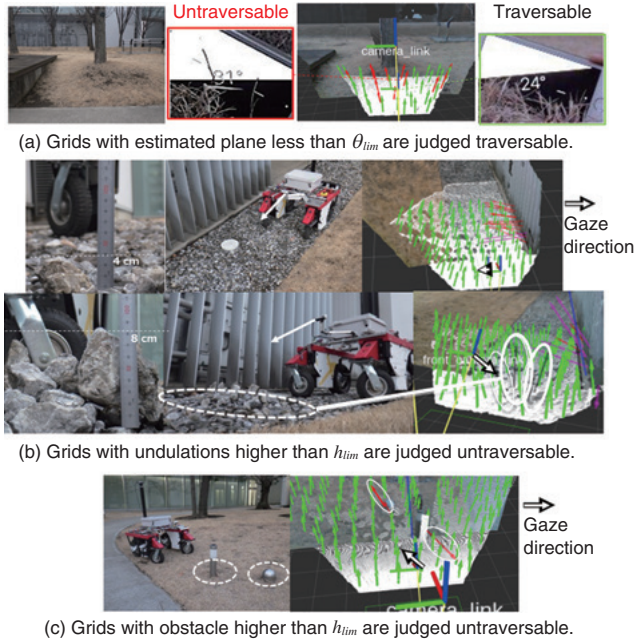


Fig. 9 Result of traversability estimation

untraversable according to the Eq. (1) index. In the green region, the slope is 24 degrees. In the red region, the slope is 31 degrees. The judgment of the slope's traversability can be considered to occur with $\theta_{lim}=25$ deg as the approximate boundary.

Figure 9 (b) has green arrows indicating the judgment of traversable with respect to a road surface on uneven ground with height differences of approximately 0.04 m. On the other hand, a road surface on uneven ground with height differences of approximately 0.08 m has clear black arrows, indicating that it was judged untraversable by Eq. (2).

Autonomous navigation by a robot was tested on the circular course shown in Fig. 7. In addition to performing traversability analysis of slopes, lawns, and other such natural terrain, the robot performed traversability analysis of road surfaces including trees, tree trunks, and other obstacles shown in Fig. 7 [Fig. 9 (c)] while successfully traveling around the circular course at a rate of 0.85 m/s.

For the future, measures will continue to be taken to verify the usefulness of this method by various means. These would include (1) testing in environments that include obstacles of a variety of shapes and sizes in order to verify the comprehensiveness of the environments for application of the method; (2) testing in environments that are more likely to produce measurement noise from sensors in order to verify the robustness of the method; and (3) testing of traversability analysis using a variety of robots in order to verify the convenience of the method; and so on.

5. Findings

This paper has proposed a method whereby a robot models surrounding road surfaces and performs traversability analysis of that model. Most existing methods that use estimated planes as elements of a road surface model face issues of inadequacy in the road surface model when measuring obstacles, and the proposed method indicates a way of resolving these issues by placing constraints on how surrounding road surfaces are divided into grids. This approach successfully assures the validity of modeling road surfaces using planes, and the proposed method is unique in this respect.

It is also the case that this method is theoretically robust with regard to noise from outliers and noise near maximum and minimum values in measurement point clouds. In addition, the parameters required by the method are determined solely on the basis of the obstacle height h_{lim} that can be traversed by the robot and the largest slope angle θ_{lim} that the robot can ascend and descend, so this can be considered a highly convenient method that is not dependent on the specific robot.

For the future, continuing measures will be taken to verify the usefulness of the method by verifying its comprehensiveness in terms of the environments and robots to which the method is applied, verifying the robustness of the method, and so on.

6. Conclusion

This paper will conclude with remarks on the prospects for this research. The proposed method determines the size of grids created when dividing the road surface surrounding the robot based on the values θ_{lim} , h_{lim} that express the robot's navigation performance. Traversability analysis is then performed of that road surface. It is to be anticipated, therefore, that if θ_{lim} , h_{lim} could be estimated from the material properties and state of the road surface, which were outside the bounds of this research, then robots will become capable of performing traversability analysis while dynamically changing θ_{lim} , h_{lim} using information about the road surface and changing the size of the grids accordingly. Expanding the method in such ways will further enhance the comprehensiveness of the environments to which the proposed method is applied and realize traversability analysis methods with a wider range of universal applicability.

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Editorial Afterword

First, I want to express my thanks to everyone who submitted a paper to this issue of the Honda R&D Technical Review and to all who provided their cooperation. There is considerable work involved in writing a paper while finding moments for it in the midst of a busy everyday schedule. This time, however, a number of unforeseen circumstances have arisen in the world, so that in addition to the impact of the coronavirus crisis from around February, there have also been the cyber attack on Honda, the heavy rainstorms in July, and so on. The organization of Honda R&D Co., Ltd. underwent major changes starting in April 2020, and even such matters as coordinating among those involved on a work project or rechecking some items of data, which previously would have needed little effort, under the current circumstances have come to require great amounts of time and trouble.

The Editorial Committee has been no exception, with everything being done through online meetings. We reviewed all the manuscripts, and worked with the authors to make corrections, without ever being able to see each other's faces. It was very different from what we had been accustomed to. Nevertheless, if asked whether we should go back to the pattern of participants gathering together in a single location for meetings again if matters take a turn for the better, since the way things are now is so challenging, I would not necessarily think so. Around June, I had the opportunity to talk with a university student who had no choice but to attend their lectures and meetings online. I thought I would ask about how values had been changed by the coronavirus crisis, and the answer was, "Having fewer chances to get together with friends is a lonely feeling, but I've learned very well that lectures and meetings can be held more efficiently online." This may be unexpected, but we may be in a time when we can reassess what seems obviously self-evident to see where it is actually inefficient.

On a personal note, this was my first time back on the Editorial Committee in four years. When I compare the content of this issue with that of issues from four years ago, it strikes me that more manuscripts on information-based technology and robotics are being submitted, and that changes have taken place in the R&D Centers. I feel very keenly that as a reviewer, I need to constantly upgrade my own knowledge, and I can sense that this work demands an eye that does not lose track of the key elements in engineering and technology. In closing, I would like to say that this Technical Review is a publication unlike any other in the way that it mixes together such a wide range of content between its covers and yet is edited so that it all fits together without feeling incompatible. I will be very pleased if, for our readers, the Technical Review provides an opportunity to catch glimpses into technical fields other than your own.

Gaku NAOE

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