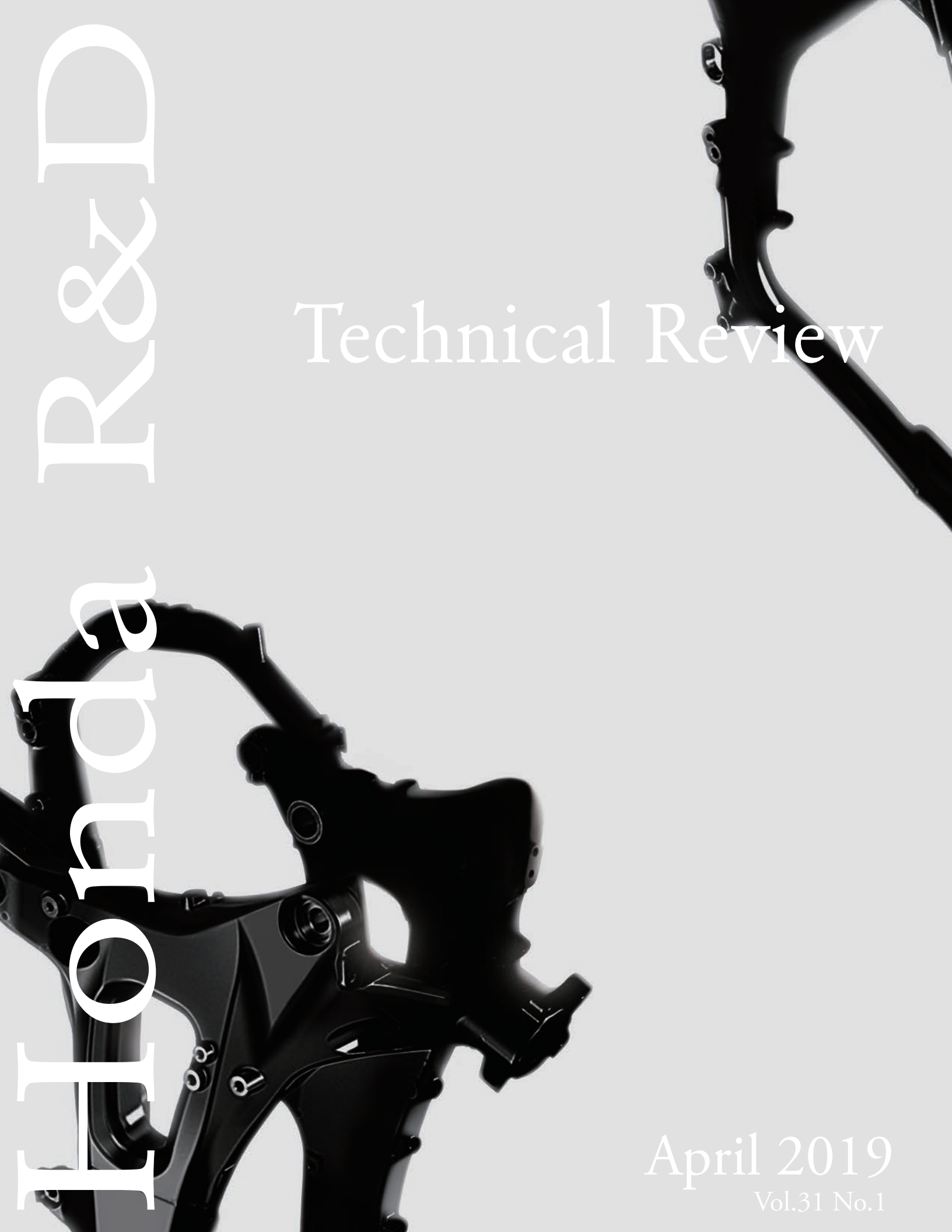
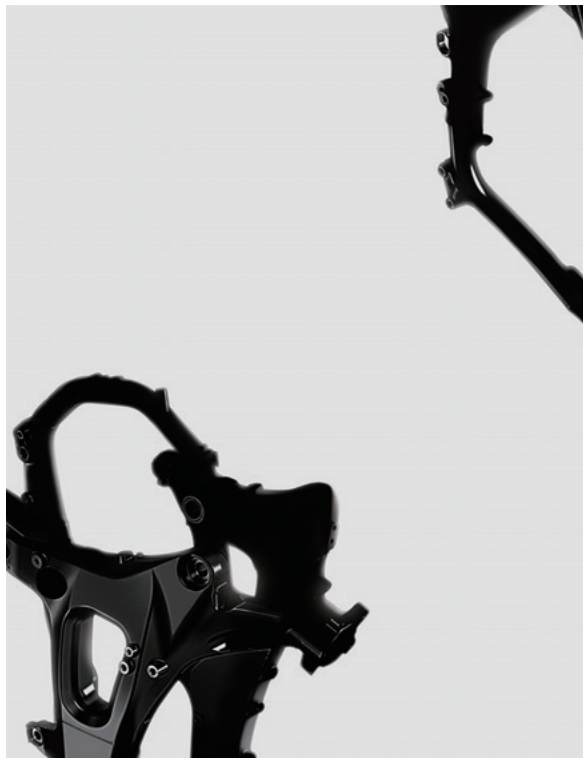




Honda R&D

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Comment on the Cover

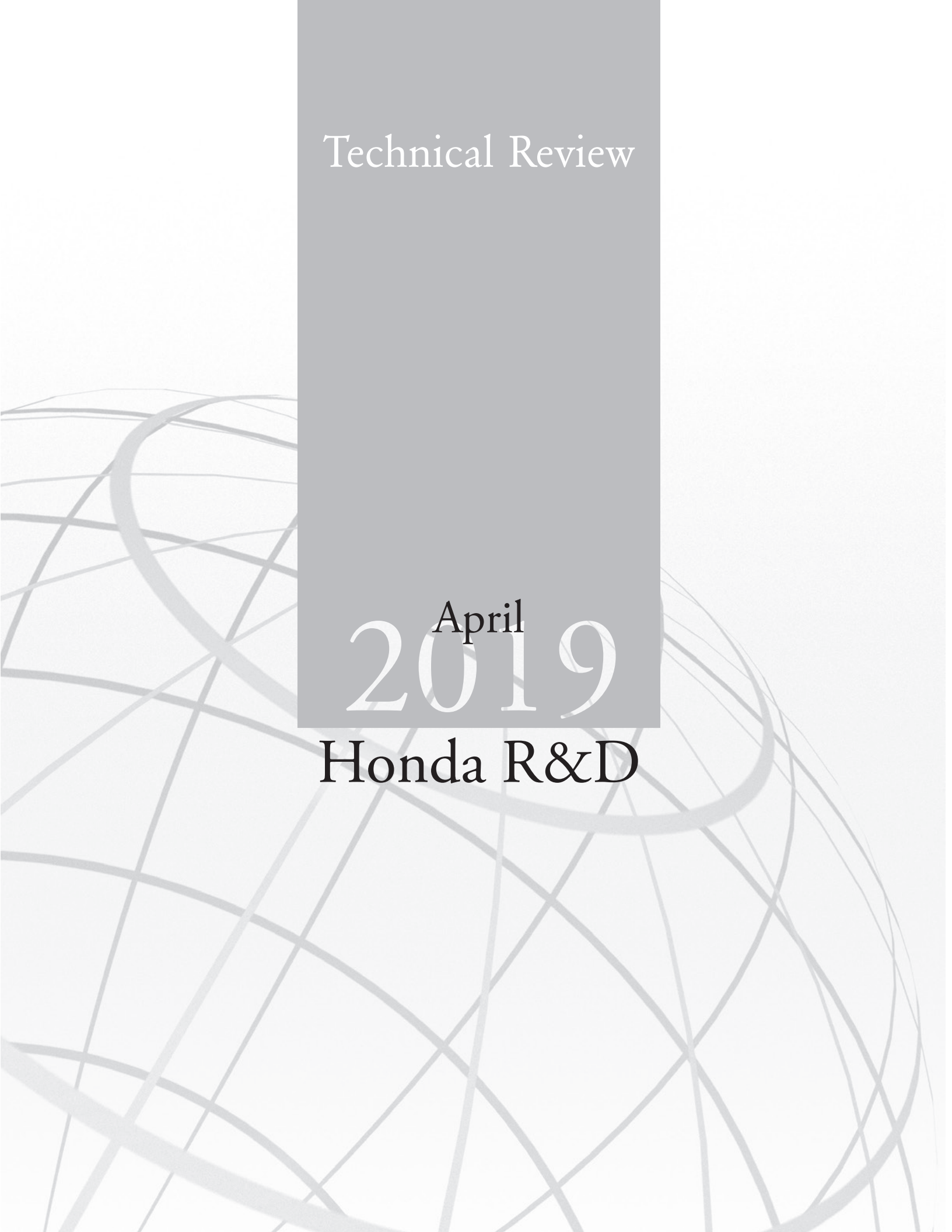
The theme adopted for the cover design of this volume of the Technical Review was the functional beauty of Honda products. We have chosen to express this functional beauty through a motif based on the frame design of the Honda Gold Wing.

Although this frame will ultimately be covered by the motorcycle's outer cowl, its shape is something born from repeated application and error on the part of our engineers, and it is expressed with careful attention to detail through a powerful sculptural form that includes both crisp lines and deep shadows.

Imagine the power of an object in which a harmony between function and beauty is formed from the inside out. I believe that the more one visually and palpably experiences such an object, the stronger the impact of its power will be.



Automobile R&D 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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Styling Design for 2018 Gold Wing

Yasuhiro SATO¹Nobutaka WAKITA²

ABSTRACT

In order to meet the values of our next generation of customers, Generation X, the design key words we used when designing the 2018 Gold Wing were lightweight and compact, essence of a motorcycle, advanced design, and high quality. These words were aimed at portraying a design that provided conciseness of form with the spaciousness required by an adult rider. The styling theme was “Styling with Refined Sharpness and Tension.” With this concept, we wanted to represent the vehicle body with qualities similar to those of a top athlete, refined and powerful to the utmost extent but free of excess weight and with the sense of internal physical capabilities invisible from the outside but hidden just beneath the surface. In addition, we focused on representing the grandeur, premium feel, and high quality appropriate for Gold Wing as the flagship motorcycle model produced by Honda. These ideas were incorporated into each of the design sketches and modeling activities, down to the finest details, in order to create a Gold Wing design that connected with the next generation.

1. Introduction

The Gold Wing has been the flagship model of Honda motorcycle ever since it went on sale in 1975. Mainly supported and shaped by North American customers of the baby boomer generation, each new model has brought with it advancements that have built the Gold Wing brand that exists today⁽¹⁾. With its luxurious equipment and dignified size, the Gold Wing has maintained its one-of-a-kind status among motorcycles, just as its concept of the “King of Motorcycles” implies. The Gold Wing’s singular and unmatched presence has made its name known to riders throughout the world.

2. Knowing the Customer

As previously noted, the customers who have long supported the Gold Wing are the baby boomer generation. As of 2018, however, baby boomers mainly consist of people aged 60 years and older (Fig. 1), and there are increasing requests for decreased vehicle weight and enhanced maneuverability. In addition, we had begun to question how the generation succeeding the baby boomers, Generation X, views the current Gold Wing. Against this background, our development team decided to conduct a customer survey in North America, the main market for the Gold Wing.

2.1. Survey of Traditions – Meeting the Customers Who Cherish the Gold Wing –

In June 2012, in order to determine the ideal form for a potential new Gold Wing, we attended Americade, one of the world’s largest touring motorcycle event, which is held annually in Lake George, New York (Fig. 2). Attendees of the event were generally older, appearing to be mainly 50 years of age or older.

Considering just the Honda products present, most were Gold Wings (Fig. 3). There were many successive generations of Gold Wings at the event, from the first

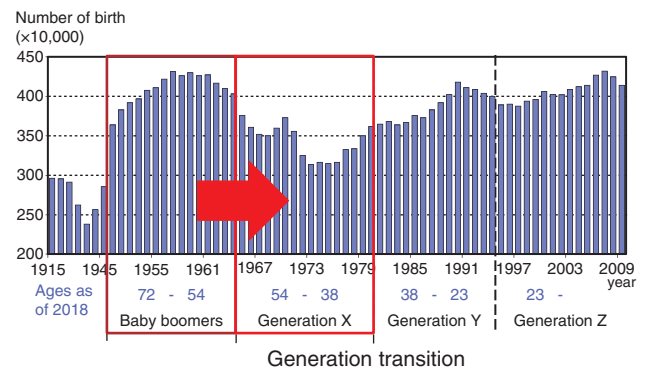


Fig. 1 Demographic distributions of Baby boomers and Generation X, and their ages as of 2018

¹ HONDA R&D AMERICAS, INC.

² Motorcycle R&D Center



Fig. 2 People gathered at Americade and their motorcycles



Fig. 3 The Gold Wings gathered at Americade site

generation to the present, and many loyal customers were present as well. Quite impressively, many Gold Wing customers were loving couples who were tandem riders.

One of the characteristics of the baby boomer generation is that they enjoy gathering with others at these types of events. Seeing the people gathered at this event made us realize how our customers have cherished their Gold Wings over the years and continue to enjoy riding these motorcycles.

2.2. Current Gold Wing Customers

Many of the Gold Wing customers gathered at Americade appeared to be over 60 years old. The scene

at the event seemed to indicate that Gold Wing has been supported by a greater proportion of customers from the baby boomer generation than we had imagined which elicited a sense of concern, since we saw only a few customers from subsequent generations. It was time to ask why the Gold Wing had fallen short of its goals over time.

We strongly felt that it was necessary to explore a new concept for the Gold Wing in order to develop model that meets the values of customers of the next generation, who love touring, and that we must appeal to those customers.

2.3. Two Issues for the Next Generation of the Gold Wing to Address

As a result of communicating with many customers, two major issues began to emerge with regard to redesigning the Gold Wing.

The first was a lack of “advancedness.” The successive generations of the Gold Wing were advanced and modern, employing the latest technology from each period. However, as of a survey conducted in 2012, the model sold in 2001 had not undergone a full model change in the past 11 years. Therefore, the style, specifications, and equipment were in need of an upgrade. The allure and advanced image which should be provided as a flagship model were reduced, and the Gold Wing was losing its competitive advantage.

The second issue was a lack of “versatility.” A “Customer Made Current Gold Wing” is handed down in our company, and this implies that it is the Gold Wing’s customers who increased the product’s value and had contributed to the success of Gold Wing. However, at the release of each generation, the Gold Wing was developed in a direction that

prioritized long-distance touring comfort and luxury, and as a result, the vehicle became larger and heavier, which began to limit its usage. This ultimately restricted the appeal of the Gold Wing to certain groups of customers and prevented the vehicle from meeting other customer demands for versatility of usage. In other words, this is one of the reasons why new generations of users, including Generation X, were not brought in.

If the Gold Wing does not address the two issues, the lack of advancedness and versatility, we believe it will not have a future in the market.

2.4. Design Directionality

We decided to clarify specific methods by which the styling designers could address the issues identified in the previous section.

First, with respect to the lack of advancedness, we decided to equip the Gold Wing with advanced equipment aligned with the values of the next generation of customers and to develop functional and attractive packaging. Thereby, we would present the Gold Wing as a modern vehicle, equipped with the latest technology in line with the age to come.

Next, with respect to the lack of versatility, we decided to depart from the large and heavy design and develop a lighter motorcycle with a compact body appropriate for the versatile usage required by the next generation of customers. This allows us to present the Gold Wing as a vehicle not limited to long-distance touring but capable of being enjoyed for other purposes as well.

The tradition of comfort and luxury that has been passed down through the Gold Wing models must also be updated to suit the current generation of customers.

3. Challenges to Achieving the Next-generation Gold Wing Design

3.1. Next-generation Representation and the Essence of the Gold Wing

An advanced Gold Wing design can be achieved by

selecting technologies and interfaces suited to the Gold Wing concept, from among the variety of those developed over the last decade.

However, our decision to develop a lightweight, compact body, as a means of addressing the issue of versatility, presented a design conflict. The Gold Wing proportions, themselves, have always provided customers with a sense of grandeur and magnificence of size, features passed down from generation to generation. These characteristics are the precise embodiment of the Gold Wing's another name, the "King of Motorcycles." Therefore, there is a concern that transitioning to a lightweight and compact design might result in a loss of the Gold Wing's essential, defining characteristics.

To address that concern, we decided to style the vehicle by emphasizing proportions that confidently reflected a sense of stateliness and grandeur, while at the same time rendering the body size more compact, in order to continue to express the essence of the Gold Wing.

3.2. Study of the Design Concept Model

In deciding the specific styling direction, we first created a design concept model (Advanced Design 1: AD1). We aimed to accurately reflect the design concept in the product design, which was an approach that had not been used in previous development efforts. Later, development proceeded through an issue verification model (Advanced Design 2: AD2), followed by a production model, in a three-stage process; the details of the model creation process are described in the paper "Styling Design for 2018 Gold Wing – Clay model –⁽²⁾."

Designers from R&D in both the U.S. and Japan collaborated to create the AD1 model, and many sketches were drawn. Proposal A and proposal B, shown in Fig. 4, were selected as the final candidates from those sketches.

Both proposals reflected a modern, lightweight, and compact package, styled to radiate a sense of presence and status, meeting the requirements of advancedness and versatility. Additionally, the functional beauty of the design was represented by emphasizing the horizontally opposed



Proposal A



Proposal B

Fig. 4 Two proposed styling concepts

six-cylinder engine and showing the functional parts around the engine as much as possible. These proposals eliminated the sense of excessive integration and highlighted each individual part or element to express the essence of a motorcycle.

Proposal A inherited the design of the previous generation (Fig. 5), featuring a backward-leaning character line that tilted downward in the rearward direction from the top of the middle cowl to the bottom of the pannier case, and the traditional horizontal motif, consisting of a line and the horizontally opposed engine of the successive generations of the Gold Wing. These lines created stately proportions resulting in a design that reflects a sense of stability (Fig. 6).

Although proposal B also had a backward-leaning character line similar to that of proposal A, it additionally featured a forward-leaning character line traveling from the bottom edge of the lower cowl to the bottom edge of the rear trunk box or bottom edge of the pannier case. These qualities resulted in a design that expresses a sense of sportiness (Fig. 7).



Fig. 5 Character lines of former Gold Wing



Fig. 7 Character lines of proposal B



Fig. 6 Character lines of proposal A



Fig. 8 Mockup model representing selected design concept

4. Creation of the Production Model

4.1. From King to Premium: Sharing Premium Concept

By completing AD1, a styling direction representing advancedness and versatility was decided. Also, the development concept of this model was changed from “King of Motorcycles,” which had previously been used for the Gold Wing for many years, to “The Honda Premium Tourer-More exciting and fulfilling riding experiences for rider and passenger⁽¹⁾.”

In light of this, all of the design team members handling the development of the production model went to work having formed a shared consciousness regarding the word “premium,” the core development concept.

Many discussions were held while keeping the levels of each following idea in mind as to whether “premium” referred to the premium qualities of the product in a general sense, the premium qualities of a motorcycle, or premium qualities specific to the Gold Wing. The answer to this question lays in the latter half of the development concept of “More exciting and fulfilling riding experiences for rider and passenger.” It was the idea that premium qualities were found in a lifestyle that incorporated a Gold Wing, rather than being qualities of the vehicle itself.

In line with this interpretation of premium, a single scenario was created in order to facilitate a shared image of this concept. This image was a scene in which a sophisticated adult couple, who rides a Gold Wing, rides up to a street corner in a high-class resort area lined by luxury brand shops. They change their jackets to walk through the city and enjoy a meal or tea at a restaurant. They can do a little shopping without concern, since the vehicle has a large trunk. This scenario symbolizes versatility, and it differs from the previous scenario for customers who are mainly long-range touring riders. This scenario is shown in Fig. 9.

The aim of the design was to inspire admiration in others for the freedom portrayed in the scene. The idea in this scenario was utilized as the cornerstone for a common image when designing each of the parts.

4.2. Design Keyword and Styling Theme for Realizing the Production Model

The following four terms were established as the design keywords required for the production model to realize the advancedness and versatility that were promoted when creating AD1 and to reflect the scenario interpreting premium as derived from the development concept.

- (1) Lightweight and compact design
- (2) Essence of a motorcycle
- (3) Advancedness
- (4) High quality

The design keyword we gave highest priority to was (1) lightweight and compact design. The theme was set as “Styling with Refined Sharpness and Tension.”

Re-clarifying the styling theme had the effect of consolidating the idea for the designers as a whole, while allowing them to apply their own individuality and talents. The style sketch of the production model that was based on this theme is shown in Fig. 10. The specific ideas and implemented details are explained below in accordance with the above-specified design keywords.

4.3. Realization of the Design Keywords

4.3.1. Achieving lightweight and compact design, and styling with refined sharpness and tension

The important feature for appealing to Generation X, who we focus on as users of next generation, is versatility with minimal restrictions on the way the vehicle can be used. The key to achieving this feature is a lightweight and compact design.

As depicted in the scenario in Fig. 9 of the previous Section 4.1., the new design allows customers to travel through city streets with agility, or sporty, winding roads with a fluttering heart (Fig. 11), while the touring potential that has long been a mainstay of the Gold Wing allows comfortable, tandem riding at a slower pace on the weekend (Fig. 12). This is the type of versatility with broad capabilities that is desired.

We wanted to create an image of the physique of a



Fig. 9 Conceptual photos of active pair with the Gold Wing

top athlete or boxer who was stoic, refined, and prepared to win, and to express that image through the appearance of the vehicle. The image is that of the beauty of a trim body, absent of any excess weight and refined to the utmost extent, with the sense of tension that occurs directly before participating in a competition (Fig. 13).

This image was realized during design, through a form, that provided a sense of internal strength and tension that

achieved the desired lightweight and compact nature, and not through a lightweight and compact style, with a simple and superficial representation of form.

4.3.2. Representation of the essence of a motorcycle

The initial Gold Wing was a bare motorcycle that was not equipped with a cowl or trunk box (Fig. 14). The minimal-vibration property of the engine and the low



Fig. 11 Driving on winding roads



Fig. 12 Touring in tandem riding



Fig. 10 Drawings for designing production type model



Fig. 13 Styling theme

center of gravity of the vehicle satisfied the characteristics required for a touring motorcycle, and therefore, the product was also supported by customers of long-distance touring motorcycles. Later, the Gold Wing continued to mature as a motorcycle suited to long tours such as a coast-to-coast journey across the U.S. Among these transitions, the large fairing design, which was one of the characteristics of the Gold Wing, was continually developed with each model change into an integrated design over the entire vehicle. As a result, the mechanical parts that were initially in plain sight were concealed beneath fairings and covers. In addition, as the design of each part was integrated, the alignment structure of parts and the processing of the panel and its periphery became increasingly similar to the interior furnishings of automobiles.

Therefore, the zone stretching horizontally from the frontal body to rear body, which has been inherited in the exterior designs of successive Gold Wing models, was defined as the “Mechanical Line.” A design that actively showed functional parts, such as the exhaust pipe, was employed to emphasize the mechanical parts, mainly of the horizontally opposed six-cylinder engine (Fig. 15).

Accordingly, the entire vehicle body design reflected a sense of integration, and while simply and clearly completed, the essence of the motorcycle reflected during the period when the mechanical parts were visible, was gradually lost. In the present development of the Gold Wing, for we wanted to strongly reflect the essence of a motorcycle allowing good agility, thus consideration was

given to prevent excessive design integration.

The surface was designed so that the area around the engine appeared static compared with the sense of movement suggested by the surface treatment around the upper body of the vehicle. Through these surfaces, we attempted to express the unique beauty of an elaborately designed machine⁽³⁾. Thus, the design intentionally shows a strong contrast between the area around the upper body of the vehicle, which is represented dynamically, and the area around the engine, which is represented statically.

In addition, a design representing the essence of a motorcycle was not only applied to the parts that were externally visible, but also to internal mechanical parts underneath covers and others. The designed parts were, for example, the compositional parts of the double wishbone type front suspension that was used for the first time in a Gold Wing (Fig. 16), the rear swing arm, and the transmission cover.

When designing the functional parts, such as those in the example above, we were conscious to make the meaning and role of each part could be sensed through its shape. Our aim was to represent the essence of a motorcycle through comprehensive functional beauty that blended function and design to a high degree.

4.3.3. Representation of advancedness

Each new model of the Gold Wing incorporated the latest technology of its period at the time of model change. In styling the current Gold Wing, we portrayed the sharp outer appearance as the “representation of advancedness” to make it appear more “cool.”

The area surrounding the upper body of the vehicle was shaped to produce a sense of youth and lightness by representing the surface with sharp lines and edges and strong tension connecting the lines. In particular, to further strengthen the image of the front fairing as being sharp and dynamic, we designed it with a slanting nose to give the impression of it slicing through the air.

Furthermore, in the headlamp, which is considered the face of a vehicle, we used the most recent vehicle lamp body with a multi-lens LED, in order to catch the attention of observers⁽⁴⁾ (Fig. 17).

For the cockpit, which is always within view of the rider, we aimed for a design that allowed instantaneous acquisition of large amounts of information, ease of



Fig. 14 1975 Gold Wing (first generation)



Fig. 15 Horizontally-opposed six-cylinder engine and its design composing “Mechanical Line”

operation, and creating an advanced atmosphere. In addition, by producing the first motorcycle in the world that is equipped with Apple CarPlay (Apple CarPlay is a trademark of Apple Inc.) (Fig. 18), we have demonstrated our commitment to technology and provide the most recent technology available to attract people living in the new era.

4.3.4. Representation of high quality – Portrayal of hospitality –

High quality was expressed in the complete vehicle by combining a suspension providing the highest comfort ride⁽⁵⁾, a silky, low-vibration horizontally opposed six-cylinder power unit⁽⁶⁾, and a smooth 3rd generation dual clutch transmission (DCT)⁽⁷⁾.



Fig. 16 Double wishbone type front suspension



Fig. 17 Multi LED configured headlight adopting latest lighting technology for vehicles

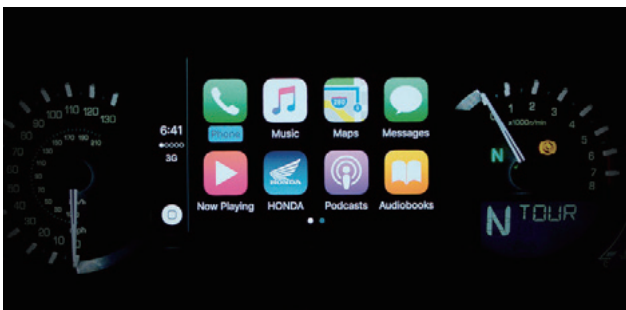


Fig. 18 Apple CarPlay

In order to represent high quality in the external design as well, we considered how to ensure a hospitable feel to each of the parts for our customers.

For example, for the coloring, we developed two new colors especially for the current Gold Wing; they were red and brown candy colors of high saturation and deep shadowing that instantly excites the heart when viewed and leaves a strong impression on the viewer⁽⁸⁾ (Fig. 19).

A digital speedometer and tachometer were not used; we intentionally employed the analog type. The needles and dials were designed in fine detail (Fig. 20), offering a sense



CANDY ARDENT RED



PEARL STALLION BROWN

Fig. 19 Newly designed two colors specifically for developed Gold Wing



Fig. 20 Analog type tachometer

of high quality reminiscent of a luxury watch. The nighttime illumination of the meters was devised to allow the rider to appreciate the luxury of the design, for example, by the use of light cast from the needle tip onto the metallic dial ring.

The design and testing departments collaborated on devices with which the operator would have direct contact, such as switches, dials, and directional buttons, imparting the most appropriate level of damping in order to achieve a gentle contact sensation. This allowed high quality to be experienced through the sense of touch in the fingertips during operation (Fig. 21).

In addition, we were particular about the sense of quality and the tactile sensation of the seat that the rider would use for an extended period of time, and we developed a surface skin with a dedicated embossed pattern (Fig. 22). In this way, we did not stop at the mere outer design, but rather aimed to achieve an even higher sense of high quality⁽⁸⁾.

Further, the emblem was designed using the motif of an imaginary lion with wings, which has been passed down from previous generations of the Gold Wing, so that the finished design was fine and elegant (Fig. 23). We designed

this emblem with hope that it will symbolize the pride of the Gold Wing as a flagship model and customers will feel the joy of owning a Gold Wing.

4.4. Completion of the Production Model

Figure 24 shows the produced vehicle. When developing the 2018 Gold Wing, we used the AD1 styling direction to set a new styling theme for production.

The premium quality presented in the development concept was shared by illustration, and it was used as a basis of our imagination.

By setting the design keywords lightweight and compact design, essence of a motorcycle, advancedness, and high quality, we aimed to realize the theme “Styling with Refined Sharpness and Tension.”

The styling design that represents youthfulness was established keeping customers in Generation X in mind, while maintaining the flavor that Gold Wing has inherited.

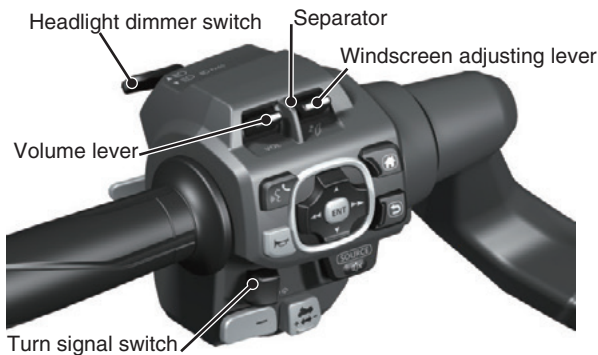


Fig. 21 Handle switch design that makes fine quality feelings through operations



Fig. 23 Vehicle emblem



Fig. 22 Texture of seat devised with high ingenuity



The Gold Wing Tour DCT Airbag (2018)

Fig. 24 Production model of 2018 Gold Wing Tour

5. Conclusion

In order to achieve advancedness and versatility, the Gold Wing was represented with confident proportions that maintained the heritage of the horizontal line while still allowing the vehicle body to be compact. While possessing presence, stateliness, and high quality, the new model lived up to reputation of successive Gold Wing models and greatly restored youth.

This allowed a styling design embodying the development concept “The Honda Premium Tourer” to be achieved.

The designers involved in this development effort contributed to more than 200 parts both large and small. The new Gold Wing design represents a compilation of the best ideas and techniques of the designers who handled each design process.

We designers sincerely hope that the Gold Wing brand, which was built over many years, will continue to connect with subsequent generations and that the design reinforces the love that customers around the world have for the Gold Wing.

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■ Author ■



Yasuhiro SATO



Nobutaka WAKITA

Styling Design for 2018 Gold Wing – Clay model –

Hidekazu IWATA¹

ABSTRACT

Seventeen years post its debut, the 2018 Gold Wing was developed in the pursuit of transforming its brand. In this study, we aimed to realize advanced design, functionality, and performance that reflect various changes in the markets, including environmental concerns and transitions in people's values, experienced during those 17 years. A high-quality design that meets every aspect of the requirements was envisioned. To achieve this, design models were fabricated for three individual stages of the design process. The styling theme was determined as "styling with refined sharpness and tension." Based on this theme, we selected the Japanese sword, katana, that symbolizes the culmination of functional beauty, and a track and field athlete, who represents power and muscularity; we set them as the symbolic images for the design. By implementing these image motifs on to the design models, the exterior design aimed for was harmoniously fulfilled with functional requirements, design evolution was achieved, and a design appropriate to representing the developed Gold Wing was established.

1. Introduction

The currently developed Gold Wing represents a full model change, over 17 years, from the previous model. Over the past 17 years, society as well as people's lifestyles and tastes have changed considerably. Therefore, significant changes are needed in design styling to adapt to the pace of society's changing needs and tastes.

This model's development concept was established as, "The Honda Premium Tourer-More exciting and fulfilling riding experiences for rider and passenger⁽¹⁾." In that message, these desires are put in as follows:

- Capture the hearts of new customers in younger generation, in addition to former customers.
- Represent being advanced befitting for the pioneering motorcycle in the era.
- Expand wider the occasions of using this motorcycle to a variety of enjoyable ways, while the opportunities of the use used to be mainly limited for long touring.

In addition to the previous Gold Wing's powerful and majestic styling, the following points were set as the direction for creating this design model.

- (a) Expressing the styling design and the components, to show the appearances that evoke the status of being on cutting edge.
- (b) The co-existence of functionality and beauty

conventionally required of motorcycles, and the expression of the engine in the principal functional role.

- (c) The expression of a versatile range of use from travelling on city roads to long touring.

To realize these elements for next-generation Gold Wing as Honda's flagship model, the targeted development concept required to be expressed as an exhaustive three-dimensional entity. Hence, in this study, we decided to move ahead with the creation of a three-stage model as follows:

- (1) Design concept model (Advanced Design 1: AD1): design study model.
- (2) Issue verification model (Advanced Design 2: AD2): shape compatibility confirmation model for layout of parts and test conditions.
- (3) Production-type model: factory production master model.

The following sections of this paper briefly describe the AD1 model, followed by the detailed descriptions of the AD2 and production-type models.

2. Creation of Prior Study Models, AD1 and AD2

2.1. AD1 (Design Concept Model)

In pursuit of an ideal design, AD1 clay modeling was

¹ Motorcycle R&D Center

performed on the base of a pre-prototype frame and engine layout.

From the three design directions previously mentioned, as for the item of:

- (a) “Expressing the styling design and the components, to show the appearances that evoke the status of being on cutting edge,” it was realized by the followings:
 - Producing of the likeness of motorcycle by emphasizing of the elements of individual parts.
 - Efficient packaging utilizing the chassis and the vehicle components incorporating the latest technologies.
- (b) To achieve co-existence of functionality and beauty conventionally required of motorcycles in addition to the expression of functional parts centered on the engine, effective exposure of each functional part peripheral to mainly the horizontally opposed six-cylinder engine was obtained.
- (c) To express a versatile range of use, from travelling on city roads to long touring, the realization of a lightweight, compact body, while proportionately maintaining the presence of a flagship model, was achieved (Fig. 1).

2.2. AD2 (Issue Verification Model)

In AD1, which embodied an ideal design-like form, layout feasibility was verified through the frame design division, and steering stability and power performance were verified by each testing division. Based on these results, modifications were made to the clay model to satisfy the required conditions. In order to compare and verify the detailed layout of each component, data from the AD1 and post-change model were overlaid and compared, which produced a large disparity in the context of styling between the models’ mounted components such as the frame and the engine owing to a capacity shortfall. For the shape data of AD1 shown in gray, the portions shown in red have gained a larger volume compared to the original shape of the lump (Fig. 2).

To correct and change the data for the areas of insufficiency and required technological conditions, numerically controlled machine tools were used to create another clay model known as AD2.

2.3. Loss of Design Balance with AD2

One can easily predict that developing a beautiful, design-like form cannot be realized with the data correction described in the section above. However, to ascertain a specific directivity for correction, this issue verification model known as AD2 was inevitably a necessary step.

As predicted, the impression created by the sculpted clay model differed considerably from AD1, with an overall loss of balance. The difference in impression was due to a collapse of the basic skeleton seen in the deviation of the mass balance and main character line between AD1 and AD2. As a result, the powerful and majestic styling expressed in AD1 completely failed to be reproduced.

In terms of motorcycle design, the mass balance disposition of solid elements and exquisite balance of each part configured around the main character line are vital elements in realizing the basis of styling. However, this balance, being established by an extraordinarily fine



Fig. 1 AD1 (Design concept model)

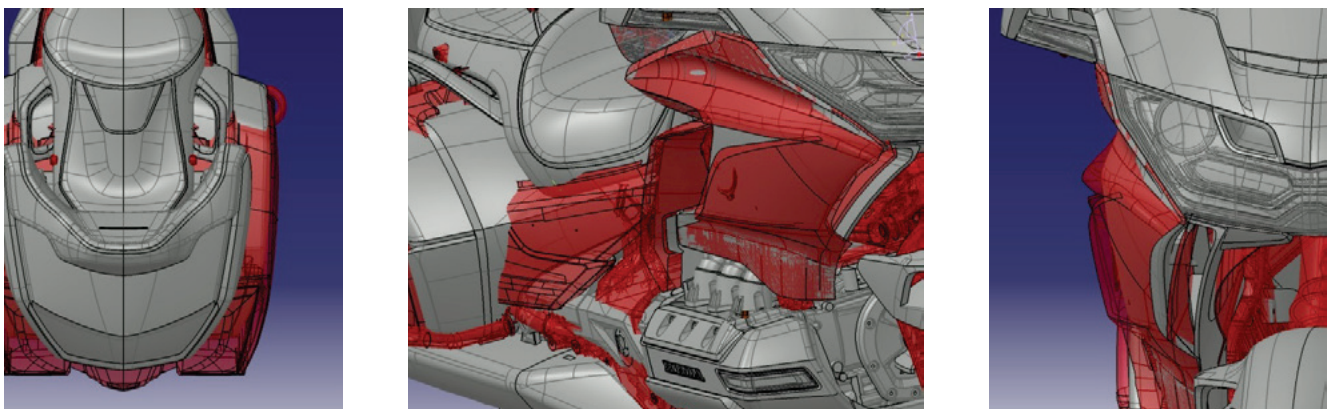


Fig. 2 Differences in styling between concept models of AD1 and AD2



Fig. 3 Beauty in form of Japanese sword

equilibrium is easily destroyed by a variation of a few millimeters. The loss of design balance in AD2 was the result of a method that introduced changes to the completed AD1 through the accumulation of data-based component parts.

3. Reconfiguring Beauty – Creating the Production-type Model

3.1. Rebirth of Styling (Reborn)

A decision was made to create a production-type model reflecting the various issues, divergences, and inadequacies confirmed by AD2. Although considerations were naturally accorded to returning to AD1, it was considered essential to aim for a design surpassing that of AD1 to create a higher-level model.

Work began by reconfirming the charm of AD1 made noticeable by the creation of AD2. By reinterpreting various elements such as the balance, formal energy, and surface tension of AD1, we built our own sensibility into the new model.

This was not the case of creating “something similar” by using data, but of recreating elements absorbed by us through visual and manual effort (Reborn). Through this process, for the first time, it was possible to breathe life into a new form.

3.2. Styling Theme Settings and Considerations

To realize the above characteristics, the key element of a styling theme, “Styling with Refined Sharpness and Tension⁽²⁾,” was set and shared among the design team members. As modelers, we further analyzed our own thinking to determine what the expression should be.

3.2.1. Styling theme studies – ridge line and Japanese sword

The expression “Styling with Refined Sharpness and Tension” initially evoked the traditional Japanese sword in our minds. The Japanese sword (katana) is a symbol of esthetic form, combining sharpness, beauty, and strength within its functions. The ridge line of the blade (character line) with these elements as its background is breathtaking

in its beauty (Fig. 3).

Beauty along with a unique strained tension is felt through the functional esthetic, born of the literal sharpness of the blade. The beauty of the ridge line and hardness of the blade, born of the rationale for a clean cut at one stroke, and its inherent flexibility, are the inevitable results of the process of forging, “sunobe” stretching, shaping, quenching, and sharpening of the blade. Superimposing the beauty displayed by the katana ridge line on the character line of the clay model, we gave a concrete expression to the theme, “Styling with Refined Sharpness and Tension.”

3.2.2. Styling theme considerations – surface expression and muscularity

A surface expression motif that came to mind as a counterpart to the katana’s ridge line motif was the muscularity of a top athlete. These were the muscles tempered to the limit and including the powerful instantaneous quality and stamina of a track and field athlete (Fig. 4).

Muscles specially adapted for the act of running express that function in their very form. We considered a surface expression that resembles the muscles of a track and field athlete to be the most appropriate means of expressing the 2018 Gold Wing, which aims for a lightweight compact



Fig. 4 Muscles appearing on body of top athlete

design through the reduction of each component.

Essential to a muscular motif is the relationship produced with the internal skeletal structure. In the examples of drawing or sculpture of a human body, what they do is not just copying the visible appearance from outside. Through imaging of the skeleton embedded in the muscles and interpreting the balance and muscular tension as controlled by the laws of gravity, an accurate depiction first becomes possible. Shaping that lacks this awareness will result in a breakdown at the visual level.

Therefore, we considered that without the reasoned shaping and surface expression based on the skeleton of a new production-type model, formation of a clay model surpassing AD1 would not be feasible.

Hence, we proceeded to express the styling theme “Styling with Refined Sharpness and Tension,” considering the powerful muscles of a track and field athlete as a motif.

3.3. Design of the Basic Skeleton

The “Styling with Refined Sharpness and Tension” styling theme is not limited to the design of just the outer packaging. The basic skeletons of the frame and engine are also important styling elements. Hence, a styling theme must also be embodied for these features.

Specifically, when it comes to the main frame, from pivot plate to header pipe, a thorough rigidity was expressed through formal constriction. Moreover, the minimization of the frontal edge curvature creates powerful shading, with the beautifully tense ridge line implemented in just the way the ridges of a sword consistently travel the length of a blade (Fig. 5).

For the design of the engine’s external appearance, the cylinder head cover was shaped as the same as the frame to resemble sword ridges. Furthermore, a sharply constricted shape for the lower cowl generated a form with the powerful tension and modulation of an athlete’s muscles (Fig. 6).

3.4. Character Lines

To transmit the styling heritage handed down from the



Fig. 5 Representation of styling concept on basic body skeleton

previous-generation models to the currently developed Gold Wing, we took up the precedent of the two following character lines. Figure 7 is an image of the previous-generation model and its character lines.

(1) Horizontal line: line displaying a stately stability in its horizontal keynote.

(2) Backward-leaning character line: line running from the upper portion of the deflector to the pannier case.

We decided to express a styling with a total of three character lines by adding, to the above-mentioned character lines, a new main character line displaying the inherent personality of the currently developed Gold Wing. The three character lines are as follows:

(1) Horizontal line (mechanical line).

(2) Backward-leaning character line.

(3) Main character line.

With regard to the current development, we named the horizontal line the “mechanical line,” making it the keynote line for expressing the model’s motorcycle-like quality through functional parts, including the engine (Fig. 8).

The main character line we newly set this time is a vital



Fig. 6 Appearance of engine design



Fig. 7 Character lines applied to previous model of Gold Wing

character line for the creation of the beauty of modeling, through which sharpness, magnificence and the forces like a katana are exhibited. We made this the essential line to express a sense of leaping forward and advancement into the next-generation motorcycle. Furthermore, this line did not depend on data, but became the formal foundation of the rebirth of the clear-cut image possessed by the AD1.

Through the respective shaping of these three lines, we expressed the sense of power generated by the muscles, trained to the highest pitch, of a track and field athlete in the surface expression (quality) of each part.

In forming an integrated whole comprising the functional beauty of individual parts for the overall body, we provided an overall mass balance as well.

3.5. Principal Parts Configuring the Main Character Line

3.5.1. Front fairing

Front fairing is morphologically the tip of the main character line, while simultaneously being an important part for influencing the quality of wind protection. While clearly maintaining the main character line, a wind protection performance suited to the Gold Wing with potential speeds exceeding 200 km/h is required.

To realize this, in maintaining protection performance, we slanted the front mask (frontal area of the front fairing), except for the major character lines, and we reduced its presence as much as possible. Then, we arrayed the solid elements in a forward direction, emphasizing the “mass forward” shape. In doing so, while guaranteeing comfort for the long touring, we also suited the fairing for short touring and achieved a “sporty” design windshield shape.

For front fairing peripheral parts for which compatibility with functional conditions is required, our design was based on the posture of a track and field athlete at the instant he drives into the wind and breaks into a sprint.

By using obtuse angles, the curvature of the cross-section of the ridge line (blue line in the center of Fig. 9), running from the headlights through the front fairing to the

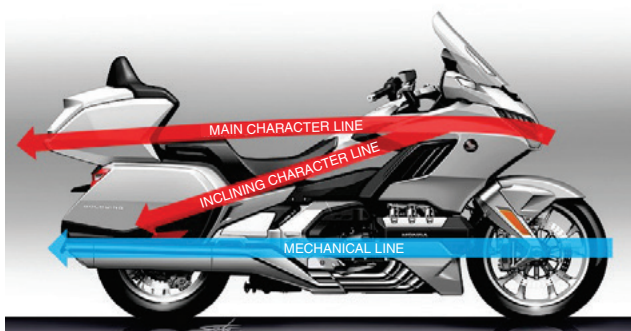


Fig. 8 Three lines that constitute styling of developed Gold Wing

indicators, was minimized as much as possible. This is the start of the main character line equivalent to the tip of the katana (Fig. 10).

The expression of surface change enabled by the limited curvature fulfills an effective role in modulating the impression when facing the Gold Wing from the front (Fig. 9).

3.5.2. Middle cowl, seat, and trunk

The middle cowl generally occupies the largest area of all the exterior parts. Owing of this, the middle cowl design has a major influence on the impression conveyed by the overall vehicle design.

To clearly express the main character line, we



Fig. 9 Front design fulfilling characterized design expression and performance



Fig. 10 Slanted front mask, with obtuse-angled surfaces and small radius corner, representing forward mass concentrated looks

maintained a constant tension in the line running from the side of the headlights, byway of the top face of the passenger seat, to the side panel of the top box. We implemented a tense and sharp ridge line just like the blade of the katana, where it runs from the tip to the end of the blade (Fig. 11).

Considering the external line of the middle cowl as part of this ridge line, we fused it with the flow of the main character line shaping the overall structure. Boldly compressing the top surfaces of the side radiators inward, we applied deep shading to the design (Fig. 12), and in addition, we narrowed down the lower side portion of the middle cowl so as to link it with the intake manifold. Through these changes, we implemented a solid sculpted look. By endowing the whole structure with a liquid sense of power exuded by the connotation of the inward muscular potential, we expressed an athlete's physique.

By implementing this expression, we preserved a constant tension throughout the entire vehicle design and were able to effectively express the main character line traversing the vehicle body in a three-dimensional context (Fig. 11).



Fig. 11 Main character line of developed Gold Wing



Fig. 12 Middle cowl with mass boldly removed inward

4. Verification of Co-existence of Performance and Design Using a Test Vehicle

Customers' enjoyment of a comfortable touring experience is, as it was previously, an important factor for the currently developed Gold Wing. For that purpose, it is a prerequisite to be able to provide a high-quality ride and light and comfortable running. However, the aforementioned tension-displaying cowl surface configuration and character lines do not necessarily contribute to wind resistance and, depending on circumstances, may even serve as a hindrance. Therefore, to establish the forms required by the design and shape needed for high wind resistance, shape changes in 0.1 mm units and evaluations were repeatedly conducted.

In Fig. 13, the yellow-colored portions are the areas to which changes of shapes have been applied by even to the precision of 0.1 mm. The trials and errors for finding the shape fulfilling both requirements were done in cooperation between the designers and the engineers. This was realized through repeated changes using wind tunnels, and steering stability and power performance tests. Figure 14 shows

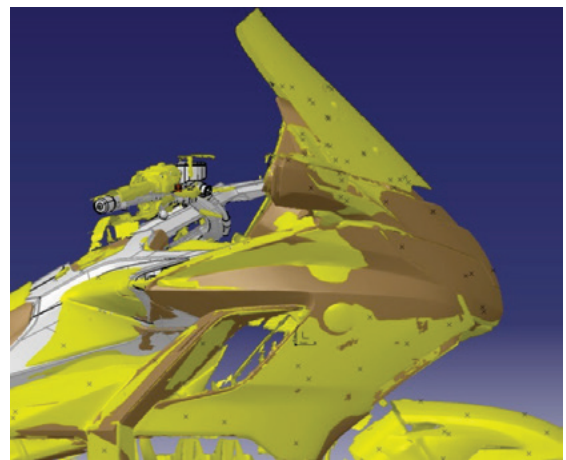


Fig. 13 Changes to satisfy design and performance requirements

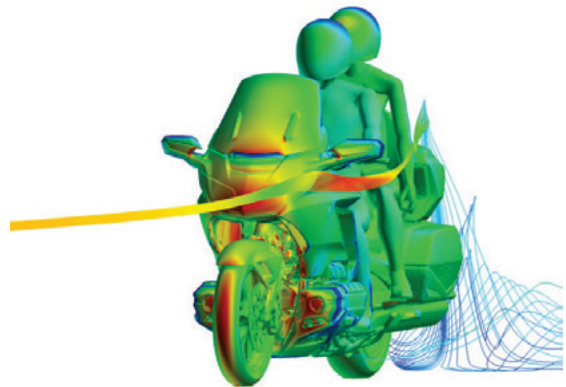


Fig. 14 Realizing compatibility between design and performance through repeated tests (example of CFD analysis)

confirmatory examples from shape data acquired by Computational Fluid Dynamics (CFD).

5. Completion of the Model

As modelers, the mission we were tasked with was to create an appealing solid entity by bringing together functionality, performance, and design on an elevated level. To achieve this, a high degree of creativity was required to establish a solid form from images sketched on a flat surface. The currently developed Gold Wing, born through a conviction that permitted no compromise, down to the finest parts, and a persistent pursuit, is a model fastidious in every circumstance required by design. Figures 15 and 16 show the completed clay and mockup models, respectively.



Fig. 15 Completed clay model of developed Gold Wing



Fig. 16 Completed mockup model of developed Gold Wing

6. Summary

To develop a production-type model, we needed to bring together the AD1 design concept model and requirements from the component side. To achieve this, reinterpreting these elements at the clay modeling stage and adding the new styling theme, “Styling with Refined Sharpness and Tension,” proved effective.

We used our visual and manual skills to recreate these reinterpreted elements (Reborn) for modeling. At that time, setting as images “the traditional Japanese sword, symbolizing the acme of functional beauty” and “a track and field athlete possessing powerful muscles,” and in proceeding to form these, we completed styling for a production-type model.

It is our earnest wish that the modeling created for the currently developed Gold Wing and styling born of it will lead to a high level of customer satisfaction and long-lived presence in our customers’ hearts.

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■ Author ■



Hidekazu IWATA

Styling Design for 2018 Gold Wing – Coloring –

Midori KATSURAGAWA¹

ABSTRACT

For the 2018 Gold Wing exterior design, the coloring design was carried out involving materials and surface treatment as well as the colors themselves, pursuing to create a “presence like no other” in its design. In the creation of the new red color, deep color saturation yet having clearness, and shadow falling to intense darkness were employed to represent a dramatic hue. In the expression of metallic feel of lower area on the vehicle body, the method, in which metallic expression is explicitly enhanced by exposed metal parts partially arranged within the whole area mainly outfitted in black color, was applied. By using those methods, the coloring design that represents the “presence like no other” deserving for the flagship model was successfully materialized.

1. Introduction

This is the first full-model change version in 17 years for the Gold Wing, the flagship model in Honda’s motorcycle lineup (Fig. 1). The theme for the development was set as “The Honda Premium Tourer-More exciting and fulfilling riding experiences for rider and passenger” with the aim to continue its legacy as an attractive long-range



The Gold Wing Tour DCT Airbag (2018)

Fig. 1 Appearance of 2018 Gold Wing Tour

tourer while gaining ownership from new age groups such as Generation X. Also things set forth at the time were weight reduction, size reduction, and having advanced features that would place the model at the forefront of motorcycles, among others⁽¹⁾.

Product appeal is mostly and generally recognized first through visual information, and thus the appearance design, including the colors, is an influential factor. The coloring in particular speaks directly to one’s soul and has the effect of immediately conveying the model’s concept to customers.

To manage the entire Color, Material, and Finish (CMF) scheme for the Gold Wing, a study was done on non-visual aspects of design such as presence and stance. The coloring expressions that move one’s soul on first glance, and creating a new feel for metal, were among what was covered by its theme.

The details of the individual efforts are illustrated hereafter with examples.

2. Color Lineup of the Gold Wing Series

The entire color lineup for all the Gold Wing 2018 models will be first introduced. The colors to be made available in the various regions in the world will be selected from this lineup.

The 2018 model has two versions: the Gold Wing Tour

¹ Motorcycle R&D Center

equipped with a standard rear trunk, and the Gold Wing without the trunk.

The Gold Wing Tour, with the rear trunk, has three color variations (Fig. 2). Its top trim version with an airbag system offers two color options, one of them with an exclusive graphic design (Fig. 3).

The standard Gold Wing without the rear trunk has three color options (Fig. 4).

3. Setting the Coloring Theme

3.1. The Gold Wing's Message in the Past

Many product groups these days are often referred to as being in a “mature market.” In such market situation, it is important not only to simply enhance product functions and performances but the philosophy and intention of those making the products. The product can be established as



Fig. 2 Color lineup of the Gold Wing Tour



Fig. 3 Color lineup of the Gold Wing Tour (airbag-equipped model)



Fig. 4 Color lineup of the Gold Wing

brand only after striking chord with customers.

In order to determine the coloring design for the full model change, the intention and message that we wish to communicate to the users had to be set. For this purpose, the messages communicated in the past were revisited. The messages from the respective periods are shown in Table 1.

As shown here, the Gold Wing's message has gone through changes with time. Through realizing what the messages communicate, the Gold Wing has gained popularity and established itself as a motorcycle model like no other (Fig. 5).

The coloring design is an important factor in making the next generation of the Gold Wing customers' time with the motorcycle a special one. As such, the coloring theme was to have a message from a coloring design perspective.

3.2. "Presence Like No Other" and Coloring Theme

The presence of the Gold Wings is one of the reasons why the series has been the "one and only." With this iteration, the Gold Wing is going further to become a "Presence like no other" through a new coloring method. The aim was to have the Gold Wing a stance that can exude the model's dignity.

It is said that only when the visual and superficial (such as color and shape) as well as the sensory aspects are present and affecting each other can one recognize the presence and stance of something. As such, it was imperative to have an integrated approach to manage not only the paint colors, but also the part materials, textures, and the finishes, and the feel that the product gives. Expanding the definition of the role that the coloring design has, the team chose "Amazes,

Table 1 List of messages appeared in past catalogs

	Period	Message of catalog copy writing
1	1975-1979	King of motorcycles
2	1980-1983	The Interstate of the ART
3	1984-1987	Leading where no one can follow
4	1988-2000	An Extraordinary touring performance
5	2001-2017	Gold Wing is the gold standard of touring

excites, and deeply moves you the second you touch, feel and straddle it" as the coloring theme.

4. Gearing Up to Implementing Coloring Theme

4.1. Integrated Color Management

Due to the approach to manage the entire coloring scheme in an integrated manner, the parts were to be given textures to meet their respective roles.

Most of the parts used in the Gold Wing are developed for exclusive use, allowing for expressions and surface treatments of parts to be optimized for the model. These are luxuries that can only be commanded by the Gold Wing, the one and only. Specifically on the upper half of the body comprised of many colored parts, much care and detailed attention were to be given to the texture, feel and color of the parts where people would touch, in addition to using high-quality paints.

For the lower part of the motorcycle comprised



Fig. 5 Precursors of the Gold Wing

mainly of mechanical parts, the focus was on accentuating the presence of each part that supports the function and performance, creating a functional beauty that is distinctively the Gold Wing. The contrast between the upper and lower areas in appearance itself creates a high-quality feel of a flagship model, as well as the “Presence like no other” targeted (Fig. 6).

4.2. CMF

A study was done also on color expressions, as well as materials and finishes that would take one’s breath away at first glance.

For coloring expression, colors that exude quality have been developed for the Gold Wings in the past. With this development, however, the envelope had to be pushed further to make the coloring design to have a “Presence like no other.” The coloring must leave a deep impression on those who see the model at first glance. The coloring itself must be able to evoke an emotional response.

Going beyond the coloring, much attention was to be given to the materials and finishes as well.

The seat surface skin should be supple and soft, high in quality and beautiful in color, with a texture pleasant to touch, leaving an impression by its color and feel.

The metal parts should be given various treatments from buffed to plated, even clear-coated for depth in paint color. These differences in finishing would contribute to creating the feel of quality and style that cannot be created by hues alone.

In this development, the coloring theme was executed from an integrated CMF perspective.

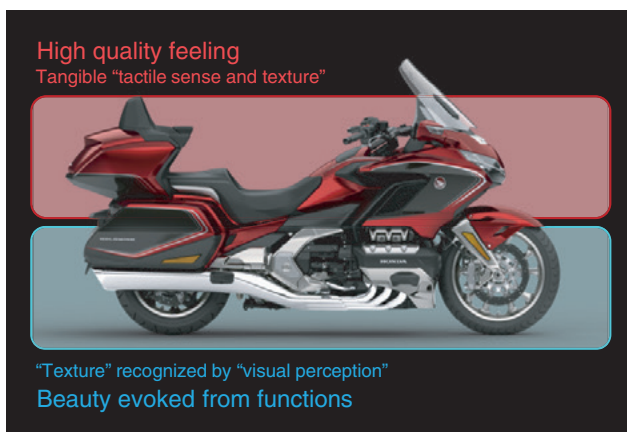


Fig. 6 Defining characteristics clearly separated in expressions of exterior color arrangements

5. Specifics of Methods Applied

To think of hues that give dramatic impressions, the team first looked into the movements and body postures specific to motorcycle. Motorcycles are often seen tilted,

such as when going round a curve or when parked on the roadside using the side stand. The coloring itself needed to create a “Presence like no other” so as to immediately give those who look at it a vision of a scene with the motorcycle.

5.1. Creating Dramatic Impression Through Paint Surface Expression

For the development of paints to be used on the Gold Wing, an in-depth study was carried out on how the paint surface expressions can make each and every scene involving the motorcycle a dramatic one.

Ideally, a paint color should have a wet-like depth, a high-saturation brilliance almost like a highlight, and a shade that dips deep down. The look shifts, the paint surface expression even changing dramatically, by the shape of the part or vehicle movement. This would accentuate the three-dimensionality of the motorcycle’s body to give a dramatic impression.

Based on this concept, two new colors were developed exclusively for the Gold Wing: CANDY ARDENT RED and PEARL STALLION BROWN. The details are illustrated below.

5.1.1. Development of new color CANDY ARDENT RED

(1) Meaning and target of color red

Red is an essential color to Honda whose history has been built from sport, passion and challenge. In this development of making the flagship for a new era, the objective was to develop a red that goes beyond the reds of the past. The color must be a red that is high quality and alluring that would deeply move a person the moment it is seen. The hue was to be the reddest of red, not leaning towards yellow nor blue.

(2) Creating expression through paint structure

The current trend in the metal flakes used in high-end automobiles are mostly using relatively small particles, not large particles that dazzle, for its effect of giving the product a delicate, high-quality feel. With this development of the Gold Wing, the aim was to apply the same approach to create dramatic yet elegant colors.

To accentuate the variety of stylized forms and shapes, a clear cover coat was to be applied to maintain the saturation level and show the smooth shift in color value of the painted surfaces. With the shaded surfaces that the light would not reach, the color value should dramatically drop to show the beautiful contrasts the three-dimensional shapes make. These requirements were to be satisfied by a triple-layer candy paint application for adding depth to the color and give a high-end feel suitable for a flagship model (Fig. 7). Under this color design, color-mixing was done while using new pigments and metal flakes. The “candy paint” refers to the painting specification of a base color with metallic flakes with a clear cover coating.

(3) Confirmation and evaluation

The color in the process of mixing was applied to

mockup models for confirmation of appearance on vehicle. Paint colors vary in appearance by the area and shape of application and therefore it is essential to do a confirmation by applying to models having the actual size and shape of the motorcycle. This three-dimensional verification was carried out repeatedly to check if the coloring design was able to best show the new styling of the model and create the “Presence like no other.” As such, there was also the need of verifying whether the color expression can leave a dramatic impression on people who see the model from a distance.

At the last phase of color mixing, other styling designers were invited to a confirmation with a mockup model placed outside. Their first reaction upon seeing the new red was a very vocal “wow,” facial expressions being that of a surprise. The surprise immediately turned to a smile with words such as “good.” Seeing such changes in facial expressions was a confirmation that we were able to create the targeted “Presence like no other.” Figure 8 shows the conventional candy color, and Fig. 9 the newly developed red.

(4) Specification and effect of finalized paint

To the base coat, next-generation high-brilliance tinted aluminum flakes were added for their thin, smooth surfaces and high reflecting power to realize a stronger, sharper brilliance. The transparency of the clear cover coat was enhanced by applying nano-pigment particles, dramatically increasing the amount of light reaching the base coat (Fig. 7). By applying these materials, the red was able to have a highly saturated transparency for a defined bright highlight and deep shade which could not be achieved with the previous candy paint.

These technologies created a wet-like depth of color and highly defined three-dimensional appearance through the strong contrast, giving the Gold Wing the “Presence like no other” befitting the premier tourer. We believe that a red that is high in quality, alluring, and having a dramatic impression that would excite and deeply move

a person at first glance was successfully developed (Figs. 10, 11, and 12).

5.1.2. Development of new color PEARL STALLION BROWN

PEARL STALLION BROWN is the other new color with an agile and light image, developed for exclusive use for the Gold Wing model without the trunk. The image envisioned in preparation for the development was that of the dynamic beauty of a thoroughbred horse dashing under the sun, its body shimmering with every movement.

Motorcycles are often referred to as iron horses for their

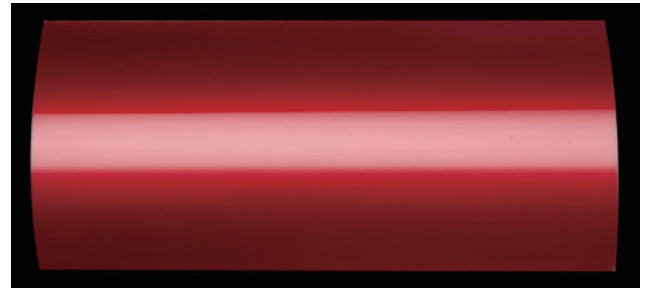


Fig. 8 Conventional candy color

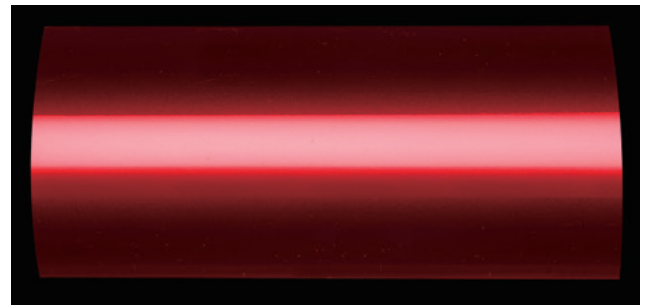


Fig. 9 Developed “CANDY ARDENT RED”

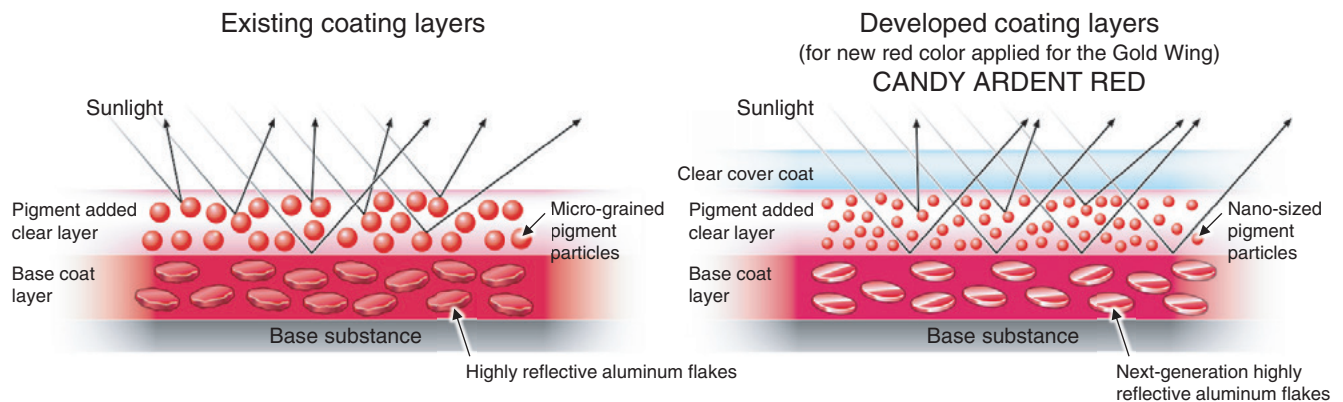


Fig. 7 Schematic drawings of paint layers comparing existing method and developed method applied for CANDY ARDENT RED

similarities with the thoroughbred racing horses. Looking at their lean bodies, it is easy to imagine their performance in a race. The color was mixed to look like the beautiful coat of a stallion, moving and shining as the powerful muscles move under its skin.



Fig. 10 CANDY ARDENT RED in rider's view



Fig. 11 CANDY ARDENT RED in front diagonal view



Fig. 12 CANDY ARDENT RED applied on trunk

The approach taken to develop CANDY ARDENT RED was also applied here: the color should be a dramatic, high-saturation and deeply shaded one. Small-particle metal flakes were chosen to create a feel of high quality through a continuous and smooth color transition.

The trunk-less Gold Wing also uses dark colors in the frame and suspension areas for sportiness and powerfulness. The details on this portion will be described in Chapter 6.

The overall vehicle color management made it possible to strongly differentiate the two Gold Wing variations (Figs. 13 and 14).

5.1.3. Development of two-tone graphics

The Gold Wing's top grade model with an airbag was given a two-tone finish of the Gold Wing exclusive CANDY ARDENT RED and a black metallic color with depth, giving the model the stylish, luxurious presence that it deserves. The added pin stripe graphics highlight the distinctive lines and forms to showcase the beauty of the model.

The Gold Wing is a flagship model and therefore must have a feel of an unparalleled quality and presence, and also embodying the model's legacy while also being new, and this was the case even for the added exclusive graphics.



Fig. 13 PEARL STALLION BROWN



Fig. 14 Looks of PEARL STALLION BROWN in driving scene

However, the initial trial of drawing stripe lines along the ridges of the character lines did not yield the result initially envisioned.

The role of the graphics such as stripes is to accentuate the beauty of the body's shape and add value to it. To identify the ideal keyline for the model's styling, the team turned off the lights of the studio to project light directly onto the clay model. The light source was moved slowly, changing the way the clay model is shone, to observe how and when the line's appearance changes.

The observation was this: the strongest light condenses not on the ridgeline projecting out the most (Line 1), which the team believed as being the main character, but rather on the depression in the deep end of a downward-looking surface (Line 2) (Fig. 15). Based on this finding, Line 2 was defined as the keyline and sketches were reworked (Fig. 16).

With the implementation of this, the graphics design was able to further accentuate the model's styling and express the beautiful fluidity of its proportion. This meant that we were able to realize the stylish and luxurious presence that was the graphic design theme worthy of a top-grade motorcycle (Figs. 17 and 18).

For the pinstripes of the model, a 53 μm -thin stripe sheet was used. Compared to the usual materials with thicknesses of 80-135 μm , this extremely thin material makes it hardly

noticeable when touched, giving it a feel of being well integrated into the body.

5.2. Expression through Materials and Finishes

5.2.1. Development of seat surface skin with enhanced quality and feel – Study of skin emboss design –

A feel of high quality is another important factor of making a "Presence like no other." In this development, in order to realize a high quality touch suitable for the Gold Wing, there was no compromise made even for the plastic parts and emboss design of the seat surface skin.

A new texture pattern was developed for the seat surface skin with a particular consideration to the feel of it, such as suppleness and the temperature felt by the hand, in addition to having a new look. Polyvinyl chloride (PVC) material was chosen as with many other motorcycles, and the above-mentioned quality enhancement with an excellent feel to the touch were to be made.

The seats of the Gold Wings in the past often used large embossed patterns on the surface skin (Fig. 19). The current trend, however, is using mid-sized embossed patterns for a more elegant feel (Fig. 20). For this model, a new seat surface skin emboss design with a high quality



Fig. 15 Deliberation in pursuit for effective key-line



Fig. 16 Defined key-lines for decorative graphics



Fig. 17 Fixed key-line for decorative graphic on middle cowling



Fig. 18 Appearance with finalized decorative graphics

feel was considered to meet the current trend.

A seat surface's feel of quality changes by the suppleness and the temperature felt by the hand. Since this is mainly due to the way the hand comes in contact with the fine unevenness created by the texture on the surface, an effort was made to optimize the emboss pattern for a quality feel.

Whether or not a seat surface skin is high in quality also largely depends on the visual information. Even if genuine leather is used, when the polish level is excessively high, it would be perceived as a cheap vinyl product through our vision. It is therefore necessary to have a surface treatment to create a more matte, elegant appearance.

Motorcycles are used outdoors, therefore the seat is exposed to the elements and used in various, if not severe, weather and usage conditions. Since the surfaces are bound to become damaged at various levels through normal use, it is ideal to have a seat surface skin that would make scratches as unnoticeable as possible. Full matte would not achieve this goal. The team created a new skin texture

design after repeating the cycle of detailed adjustments of polish level and texture pattern design size as well as how it feels to the touch, while also meeting the conditions mentioned earlier (Fig. 21). The result was the completion of a seat surface skin that is high in quality and elegant in appearance, which could become the standard for future high-end products.

5.2.2. Expression of functional beauty in lower body area

This clause explains the surface treatments and other finishes applied to the lower area of the vehicle body where the model's functional beauty is displayed.

The first study was on how to show the metallic texture. The lower body is quite complex, having the engine and many other parts using various materials such as metal and plastics. From the perspective of color management, the team chose to give this area a cohesive look with metallic look.

In the following process of identifying the best method to achieve this, various products other than motorcycles were studied. In this group of objects was a certain high-end single-reflex lens (SRL) camera which caught the eye. It was predominantly black, but metallic finishes were used effectively in some areas of the body and parts. Although metal was only partially used, metal had a stronger presence compared to products showing metal overall. This experience gave a realization that a precise management of the relative placements of black and metal creates the visual effect of accentuating the metal. Meticulous attention was given on what placement of metallic materials would be most effective, down to a bolt placed in a black area. The area ratio of black and silver was also determined based on above observations. The decision on how to do styling



Fig. 19 Large texture design of leather applied for the previous Gold Wings



Fig. 20 Medium-sized texture design of leather that makes the elegance of the current trend



Fig. 21 PVC seat leather with grain patterns developed this time

design for the lower vehicle body was made: the method as explained above would be used (Fig. 22).

5.2.3. Styling design for new horizontally opposed 6-cylinder engine

To showcase the new, smaller engine, a study was carried out on how to make its head cover, the most prominent feature in terms of appearance, can be shown most beautifully. The conventional surface treatment method is “buff clear” with a look of chrome plating, but for this model it was going to be finished with satin-buffed hairline treatment (Fig. 23).

Previous models had plated parts all over for a gorgeous, luxe look. In contrast, this model was to have a styling design meeting the design preferences of new customer groups such as Generation X and following the current trends. The surrounding parts, such as the frame and suspensions, would have a matte and subtle metallic look to show their functional beauty. Further, these were to be treated with a finish evoking the image of artisanal hand work, such as satin-buffed hairline finish, to give customers another reason to love the product.



Fig. 22 Lower area of vehicle body with coloring design having intention to make metallic feel stand out



Fig. 23 Head cover with hairline treatment

6. Differentiating Images by Character Differences

As touched on in Clause 5.1.2., development of new color PEARL STALLION BROWN, the Gold Wing series being developed at this time has a version that does not come equipped with a rear trunk. Also as mentioned earlier, the trunk-less Gold Wing looks light and agile and styled to stress its sportiness. This version was given a different CMF and coloring approach to create a visible difference from the other, even with the functional parts such as the frame and suspension parts.

For this version, most of the parts in the lower vehicle body area were designed to be in dark metallic gray or blacks with different textures, with minimal accent coming only from the metal of bolts and caps. The finished look is a combination of dark, low-contrast color tone with matte textures, enhancing the powerful styling of the product. Figure 24 shows the difference between the two versions with their own distinctive finishes in the vehicle's lower body area.



Fig. 24 The Gold Wing Tour and the Gold Wing



Fig. 25 Precious time spent with the Gold Wing

It is our hope that these two versions would resonate with the various customer groups (Fig. 25).

7. Summary

This paper gives the overview on the concept set forth for the coloring design and the actual development and application process for the Gold Wing, a motorcycle going through its first full-model change in 17 years. In this process, the colors, materials and finishes were developed and applied after considering the quality of appearance for the overall vehicle, even attempting at visually creating the presence that the product has. The coloring design was created so it would appeal to all senses, portraying the “Presence like no other.”

It is my sincere wish that the coloring design with the intention mentioned above would make the moment a person and the Gold Wing meets to be a special one, leading to deeply moving road trips, and the time the rider spends with the Gold Wing an even more enriching one.

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■ Author ■



Midori KATSURAGAWA

Styling Design for 2018 Gold Wing

– Power unit –

Akihiro SAWABE¹

ABSTRACT

In designing the power unit of the 2018 Gold Wing, we focused on mechanical lines in efforts to express a functional beauty with its exterior design. We strove for a design that clearly telegraphs the functions of the individual parts to sate the desire of motorcycle enthusiasts interested in the function and performance of the motorcycle. In implementing these design themes, we have produced a motorcycle with an advanced feel and a power unit with a finish that satisfies the itch for owning the latest technology.

1. Introduction

We have designed a horizontally-opposed six-cylinder (F6) engine that was newly developed for the 2018 edition of Honda's flagship model, the Gold Wing GL1800. We started by assessing the engine's role in the overall vehicle design.

With a designated styling theme of "Styling with Refined Sharpness and Tension,"⁽¹⁾ first, each element of the design theme was settled with the vehicle divided into two design zones: top and bottom (Fig. 1). The top half of the vehicle was chosen to feature "Fluency and lightness, dynamic fluid-edge surface," while the bottom half would utilize "Functional beauty and advancement through mechanical lines" to showcase the functional beauty and advanced feel of the design.

The engine design forms the core for the mechanical

lines in the bottom design zone. The final sketch for this engine is shown in Fig. 2.

Thus, this engine design is expected both to portray the premium feel of Honda's flagship model and to befit its unrivaled F6 engine.

Furthermore, many users feel a strong affinity for engines as the heart of the motorcycle. Another impetus for the decision was to actively show off the engine to give the Gold Wing the feel of "a pure motorcycle,"⁽¹⁾ one of the designated keyword phrases for the design.

Air flow management around the engine was also aligned accordingly. Up through the previous generation of the Gold Wing, all but the cylinder head portions of the engine were completely sheathed with exterior parts. This approach both shaped the exterior air flow while also serving to protect the rider from engine heat.

Therefore, space was needed on the inner side of the exterior parts to vent this engine heat, a contributing factor to enlarging the vehicle body. For this design, based on the approach of actively showcasing the engine, we used minimal exterior parts with air channeling effects to vent heat, serving to both cool the engine and reduce the weight of exterior parts.

Moreover, design for engines, the soul of the functional components of the motorcycle, requires extensive understanding of how these parts function. Thus, we solicited the engine designers for their opinions in detail as the work proceeded.

With these approaches, our goal with the engine design was to express the beauty of its mechanical functions while serving as a symbol of stylish progression. The engine's prominence should satisfy the many aforementioned engine-loving users and provide them a greater sense of ownership.

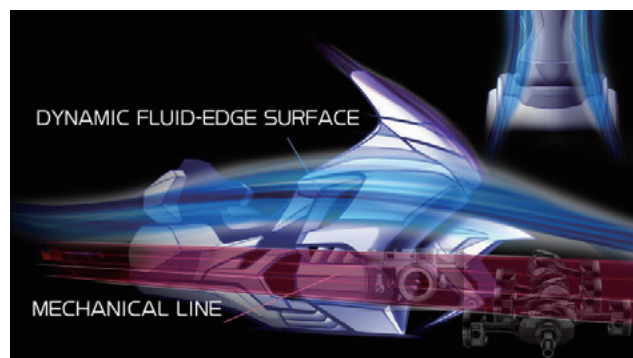


Fig. 1 Two design zones and their designated themes

¹ Motorcycle R&D Center

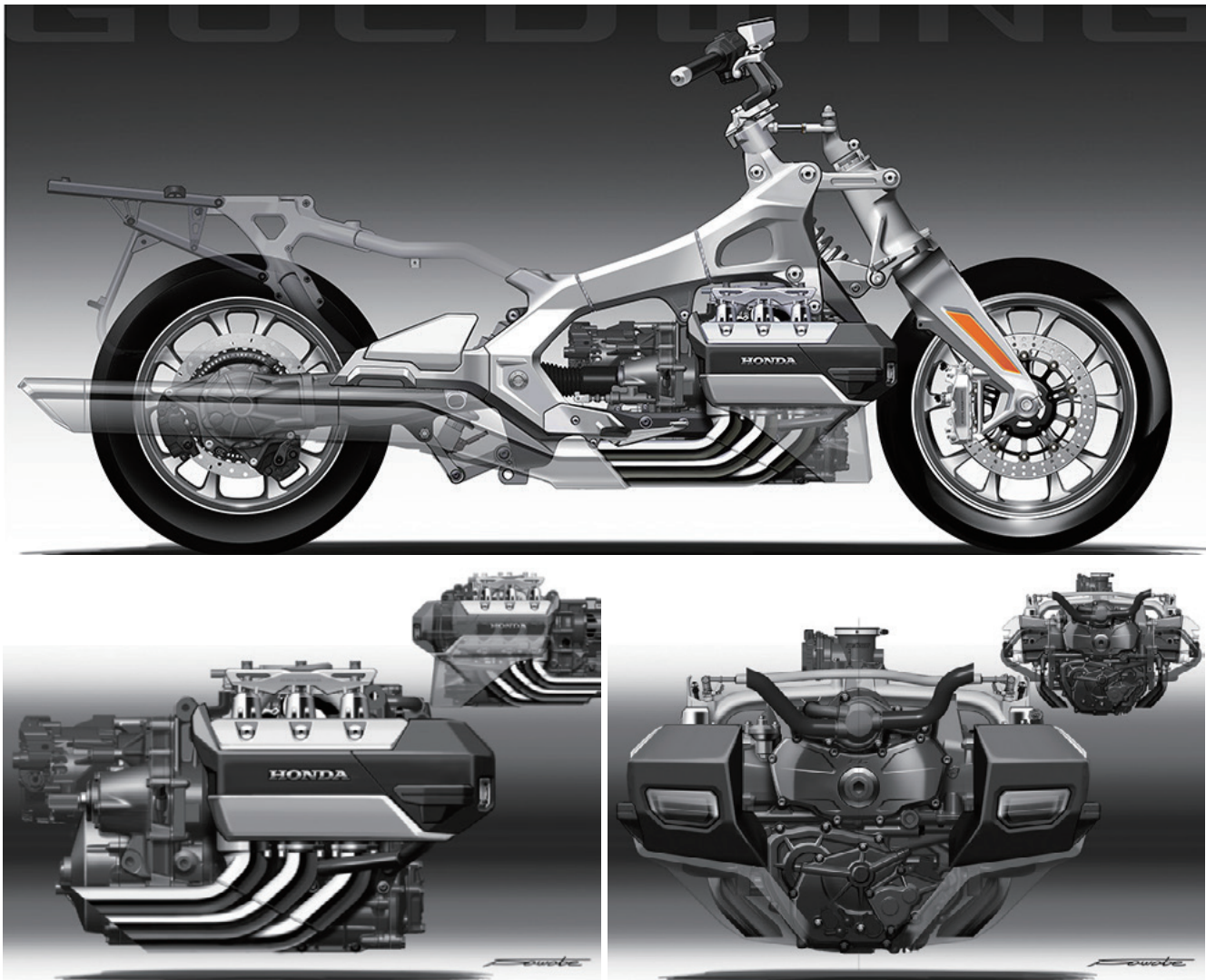


Fig. 2 Engine situated in center of mechanical line

2. Mechanical Expression: An Appealing Machine

Generally, manmade mechanical models take on inorganic shapes comprising arcs and lines (Fig. 3). Thus, in design as well, inorganic elements can be used to transparently convey a mechanical theme.

Conversely, beings in the natural world, such as plants and animals, have organic shapes with no simple arcs or lines (Fig. 4).

For this design, it was consciously decided to actively incorporate inorganic shapes to express the themes set for this design zone: functional beauty and advancement through mechanical lines.

2.1. Transparent Expression of Functionality

In a purely structural design, functional parts such as an

engine will take on complex shapes (Fig. 5). This concept was leveraged to design each part with the quality feel of a flagship model engine and, as mentioned in the previous section, to transparently convey the roles and structure of each part to users infatuated with the engine's appearance.

The below are some of the design features in this development project which model structure and function. By associating the design with internal structure, in addition to their standard roles, the case and covers were used as a medium for expressing the mechanical concept.

2.1.1. Outline of cam chain line

Indentations were added to outline the shape of where the cam chain fits, extending from the front cover at the center of the engine's front across the cylinders and cylinder heads on each flank. These indentations are illustrated in Fig. 6 by red gradations.

2.1.2. Straight lines from intake to exhaust

The intake manifolds and exhaust pipes were intentionally aligned in a straight line cutting from top to bottom. In engines through the previous model, the intake and exhaust were staggered slightly front to back due to

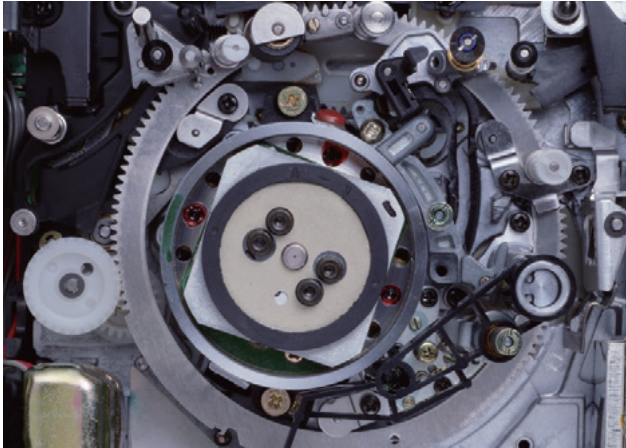


Fig. 3 Objects having mechanical and/or artificial shapes are commonly recognized as geometric shapes



Fig. 4 Shapes of things that exist in nature are commonly recognized as organic shapes

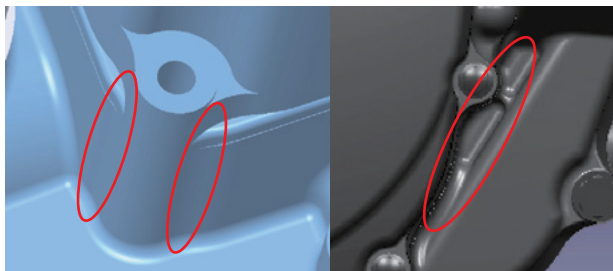


Fig. 5 Examples of things that give sense of inconsistency

the placement of the valves. This was offset by shifting the position of the head cover bolts and other adjustments for a cleaner look (Fig. 7). Meanwhile, as this stagger between intake and exhaust was removed from the developed engine, straight lines were emphasized in the design (Fig. 8).

Furthermore, a simple, functional appearance was targeted due to the arrangement with 3 exhaust pipes converging to one side.

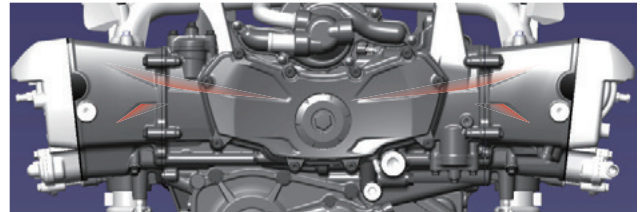


Fig. 6 Front cover design that makes viewer imagine movement of cam chain

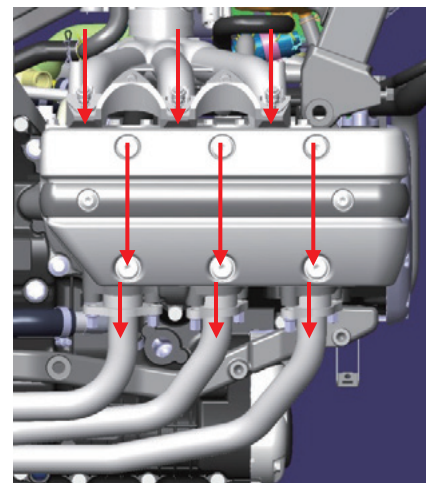


Fig. 7 Design applied to previous Gold Wing

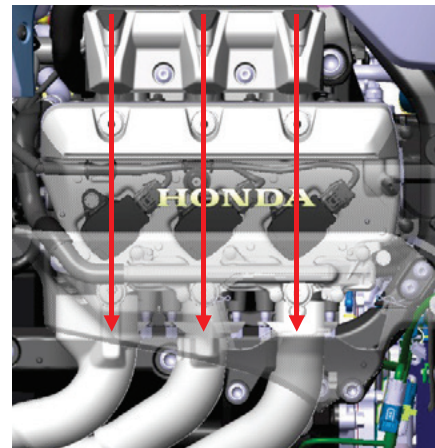


Fig. 8 Design applied to developed Gold Wing

2.1.3. Suggestive expression of intake manifold cover

The intake manifold covers forming part of the straight lines from the previous section are shaped to visually represent the placement of the injectors and fuel pipes housed inside (Fig. 9).

2.1.4. Three drive system covers

Below the front cover are three drive system parts which are not externally viewable in complete build units: a transmission cover, shift motor cover, and reduction gear cover. These covers were designed to maintain the engine design image even with the exterior parts removed, such as during maintenance.

The covers are functional components which support the internal drive system parts and are reinforced to the required strength with ribs inside the cover. These ribs were drawn outward to the extent possible and utilized as exterior design features to contribute to the mechanical image without adding any unnecessary weight (Fig. 10).

2.1.5. Wiring inside cylinder head side cover

Care was also taken in the placement of the electrical components inside the cylinder head side cover. Close attention was paid to the inclination of the top coil plug and the layout for hoses and wires for a pleasing appearance when the cover is removed (Fig. 11).

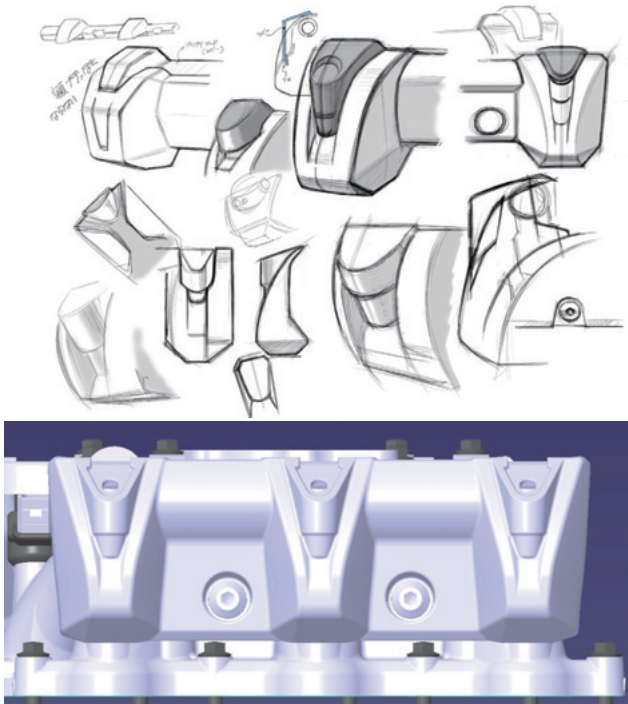


Fig. 9 Design of covering of intake manifold that makes viewer easily imagine inside structures

2.2. Polyhedrons and Styling Base Character Lines to Symbolize Function

In an attempt to manifest the mechanical image described at the beginning of this section, polyhedrons were used as inorganic shapes. This overt expression of how the parts are machine cut from large hunks of metal bares everything, down to the precision of the underlying mechanical parts. Such methods are considered a fitting expression of an engine design centered around functional beauty and advancement (Fig. 12).

Given its central presence, special attention was paid to the aluminum head cover. In order to make it possible to express metallic texture by satin buffs, the uneven shape around the tightening seating surface of the bolt and around the cam chain chamber were reduced as much as possible to make the shape of a simple surface (Fig. 13).

The polyhedron-based design employed in this development, shown in Fig. 14, can be contrasted with a typical design featuring organic shapes as shown in Fig. 15.

Also, these engine-centered mechanical lines form the front-to-back horizontal styling base character lines so key to the proportions of the Gold Wing. In designing engine

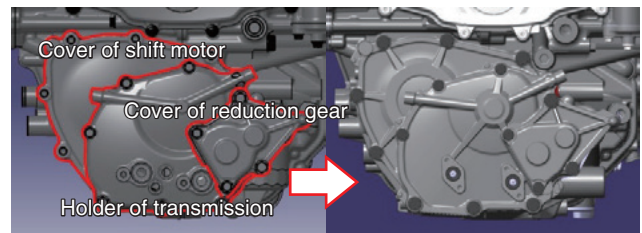


Fig. 10 Covering of drive system that is divided into three pieces

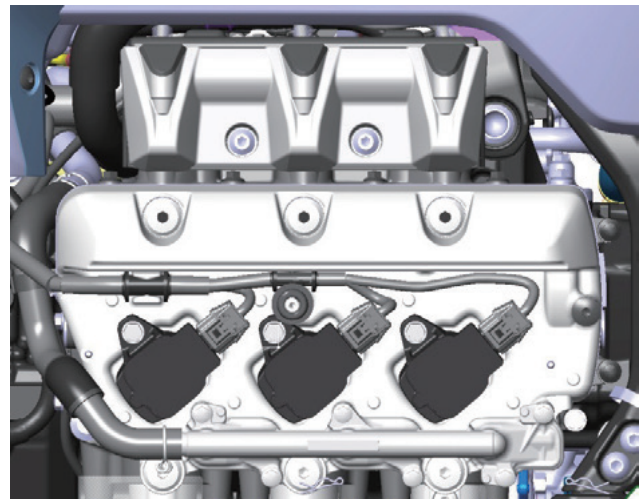


Fig. 11 Consideration on appearance when covering is removed

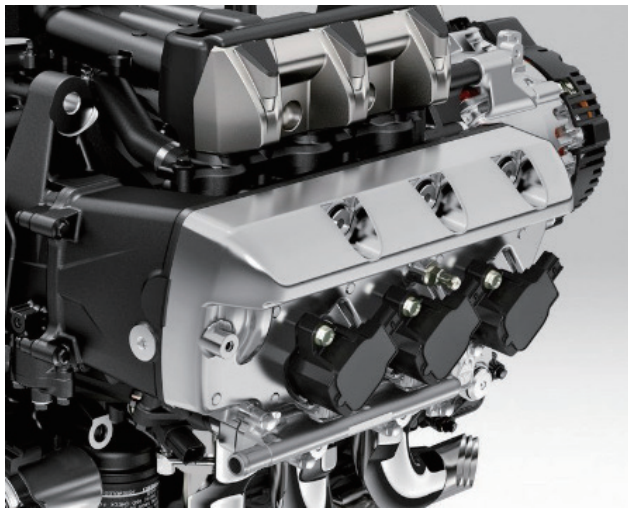


Fig. 12 Engine parts constituted by polyhedrons

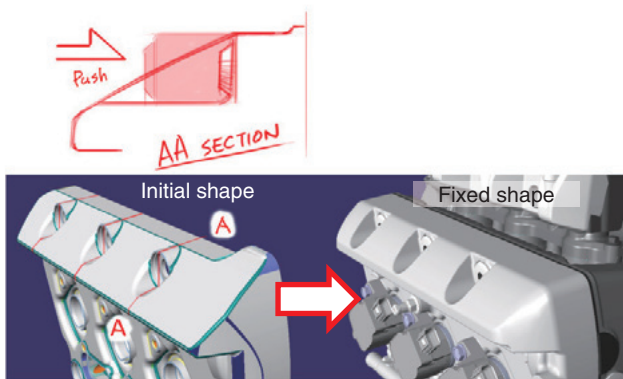


Fig. 13 Simplified surface shape for “polishable shape”

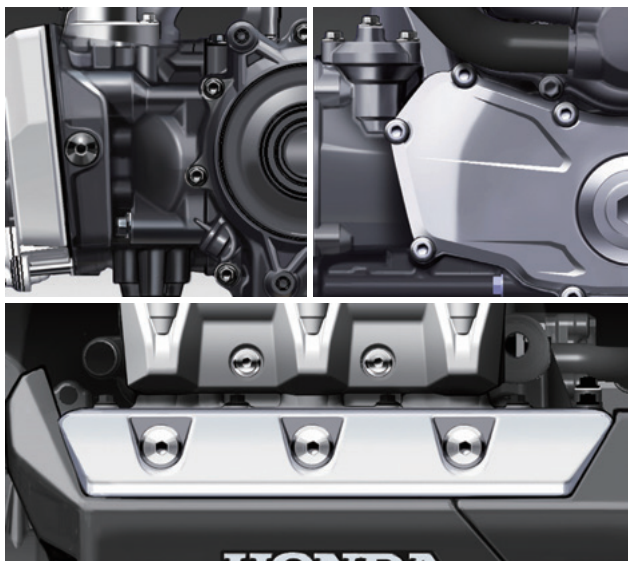


Fig. 14 Designs applied to developed Gold Wing

parts, it is important to align the base components of each section with the vehicle's overall styling character lines (Fig. 16). Doing so gave the vehicle an overall sense of unity. It kept the design from getting too complex and also tied into the bottom half design themes of functional beauty and advancement.



Fig. 15 Example of design using organic shape elements



Fig. 16 Integrating components with base character line of the vehicle design

3. Auxiliary Elements to Emphasize Engine Design: Attention to Details

3.1. Shape of Receptacles for Case Tie Bolts

In development for this engine, shapes were even revisited for one of the smallest of details: the bolt receptacles. Previously, these bolt receptacles, of which there were 20 on the engine case surface, were a standard rounded hemispherical shape. For this development, however, the receptacle ends were given a machined conical

shape to match the sharp lines in the engine area with its many polyhedrons (Fig. 17). While this change may not stand out on its own, it is an important consideration in terms of bringing the total design together.

3.2. Bolt Selection

Flange bolts with concave bolt heads were intentionally used for the new M6 bolts. The sharp shape left after cutting this dead material contributes to the overall mechanical feel and, while minor, also serves as a weight reduction (Fig. 18).

3.3. Inconspicuous Changes: Size Reduction

The engine and pannier case guards for protecting the engine and body were also designed inline with the mechanical lines of this model. In the previous generation Gold Wing model, the guards were all matched in chrome plating. In the new design, these guards were left alone functionally but with the pipe diameter reduced to the bare necessities for a more compact cover (Fig. 19). The covers are simply shaped to blend in with the surrounding

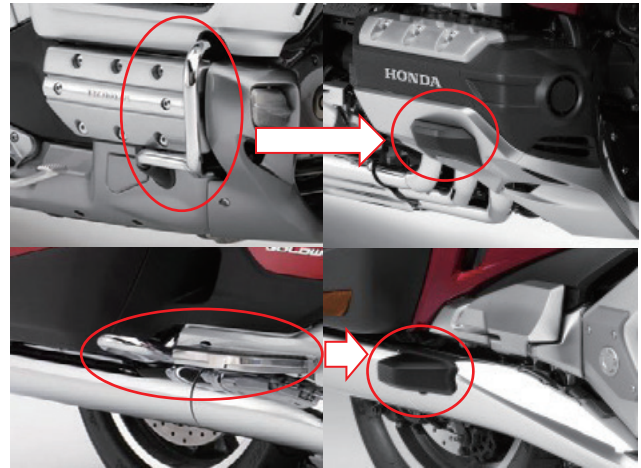


Fig. 19 Design making components inconspicuous

design elements and colored in a subdued black. Rubber was selected for the guard material to avoid generating any debris when the guards come in contact with the road surface.

4. Conclusion

With this design, we expressed a functional beauty and advanced feel to fit the unrivaled F6 engine equipped on Honda's flagship model, the Gold Wing. As the heart of the motorcycle, we designed the engine with intention and a clear design theme, from the external appearance down to the finest parts not outwardly visible in normal conditions. We also added some designer touches for users to notice during maintenance.

Through the engine design for the new Gold Wing, it is our hope that the designers' message will reach users.

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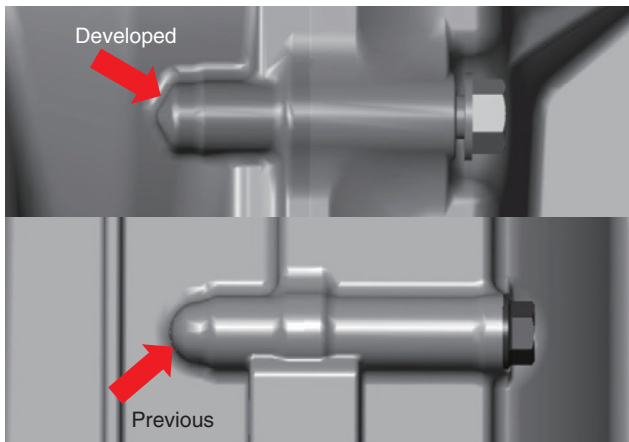


Fig. 17 Example of design applied to fine part (Shape of receptacles for bolts used for fastening engine case)

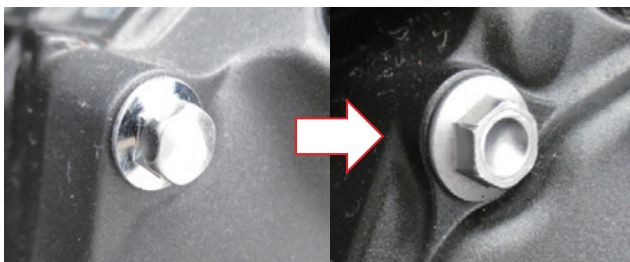


Fig. 18 Adoption of flange bolt contributing to the mechanical appearance and weight reduction

■ Author ■



Akihiro SAWABE

Styling Design for 2018 Gold Wing

– Lighting system –

Daisuke KURIKI¹

ABSTRACT

We created a design for the lighting system of the 2018 Gold Wing motorcycle. To express a sense of innovation in terms of both function and appearance, we attempted to use multiple-eye LED headlights to create a “facial expression” for the motorcycle. In addition, we re-created the “wing line,” the pattern which represents an important part of the brand identity of the Gold Wing, using the new lighting system. We unified the impression given by the overall body of the motorcycle by incorporating the wing line pattern in the designs for both the front and the rear of the body. Our new lighting system design values both innovation and tradition, and it represents a big contribution in the development of the new design of the Gold Wing.

1. Introduction

One important requirement for the design of the lighting system for the 2018 Gold Wing (Fig. 1) was to give the motorcycle a new and unique sense of personality while expressing the essence of the Gold Wing at the same time.

The front fairing represents the face of the Gold Wing and features a design in which the placement of the headlights and turn signals makes it appear as if the wings are spreading out to both sides (Fig. 2). We named this shape the “wing line.” It has been inherited as part of the design identity previously developed for the Gold Wing.

As it is in the other styling design creation of the Gold Wings, it was sought to create expressions having the personality and to adopt the technologies that symbolize the



The Gold Wing Tour DCT Airbag (2018)

Fig. 1 The 2018 Gold Wing Tour



Fig. 2 The Gold Wing in former generations

¹ Motorcycle R&D Center

status fitted to the latest era while inheriting its identity.

Moreover, in the design of the rear combination light, we challenged the unity that reflects the image given by the front part also in the rear part. We describe our approach to designing a lighting system that embodies the styling theme for this model, “Styling with Refined Sharpness and Tension,”⁽¹⁾ in the following sections.

2. Front Design

The Gold Wings have been the motorcycles that are making the advanced features come into prominence and symbolizing the each era, by applying the styling designs utilizing the latest technologies. Moreover, novelty has even become a part of the Gold Wing’s unique identity.

Therefore, we decided to use Light-Emitting Diodes (LEDs), the light source which recently started to appear in the headlights for motorcycles. Our approach was to use the LEDs to create a new wing line and a new face to represent the Gold Wing, our flagship model.

2.1. Key Concept Behind the Headlight Design: Inheriting and Evolution of the Wing Line

When LED lamps are applied to vehicles, especially when they are applied as main lights, they are generally installed with reflectors. When they are used as position lights, they are usually installed with light guides. In contrast, for the head lights of the developed Gold Wing, low beam configuration that has the total of 10 lenses, 5 for each of right and left sides, was adopted applying multiple-eye illumination method to represent the impression of advancement in the equipment. In addition, we chose to create the trim line using light guiding lenses, which created a three-dimensional sense of depth and light.

The world’s first adoption of multiple-eye type headlights is on a motorcycle. We wanted to express the Gold Wing’s unrivalled sense of presence in the design of its lighting system as well by giving it a sense of character that is symbolic (Fig. 3).

Our goal was to give the Gold Wing a facial expression that exudes a sense of vitality and status with dignity and trust befitting of our flagship model. We considered how to achieve this goal through the design. The headlights, which serve as the “eyes” of the motorcycle’s facial expression, play an important role.

2.2. Research into Creating the Facial Expression through Multiple-eye LEDs in Two-lamp Type Headlights

2.2.1. A study regarding the differences in the impressions given by two-eye and multiple-eye lights in two-lamp system headlights

(1) The limit of two-eye lights

Before the advent of LED headlights, headlight designs were composed of projector lamps or reflector type lamps. For two-lamp headlight systems with headlights on the

left and the right, the headlights are composed of two-eye headlights with one eye in each headlight (hereinafter referred to as the two-eye type). The lamps are a crucial element in forming the facial expression. For two-eye type headlight systems in particular, people tend to think of the lamps as the “eyes” at a subconscious level⁽²⁾. Therefore, for the two-eye type design, the light sources serve as the pupils of the eyes, and the front often looks like the facial expression of an animal. There is a limitation in terms of creating a novel impression.

(2) An attempt of using multiple-eye lights

When multiple-eye configuration is adopted, in which the light sources are distributedly located, the center points, which draw attention like pupils, are lost, even though the headlights are composed like two-lamp-configured headlight. That creates the impression of some strange objects, which have never seen before and look inorganic or like compound eyes of insects, which are totally different from facial expression of animals. We have noticed that aforementioned specific characteristics multiple-eye configuration has some potential of creating something new, and studies exploring of that possibility began.

We conducted investigations, in order to create a lighting system design as if having a mind like an organic object, making challenge to apply a motif utilizing multiple-eye configuration, which usually leads to give inorganic expression.

(3) Examples of two-eye facial expressions

As part of our investigation on the use of headlights to create facial expressions, we firstly conducted a study of facial expressions created using two-eye type headlights, which are well-suited for representing facial expressions. Figure 4 shows examples of designs created with different combinations of eye positions, eye sizes, and lens shapes (contours) for two-eye designs.

The examples illustrate that by using different



Fig. 3 Wing Line implemented in lighting system design (top: developed design, bottom: previous designs)

combinations of simple elements, it is possible to create a variety of facial expressions, ranging from those that have an intimidating appearance, to those that have a calm and gentle appearance.

(4) Examples of multiple-eye facial expressions

Similarly, Fig. 5 shows examples of designs created with multiple-eye type headlights. As you can see from the figure, a facial expression cannot be easily represented when we apply multiple-eye configuration as the parts like pupils are lost.

(5) Discovering facial expressions created by the shapes around the eyes

We conducted further investigations in order to study which elements determine the facial expression of humans and animals.

In Fig. 6, we show photographs of the faces of lions and bald eagles, including the eyes, the region surrounding the eyes, and the area that corresponds to the eyebrows, as well as the movement of the area between the eyebrows.

The close study of these images reveals that the contour of the eyes and the relationship between the positions of the pupils has a large impact on the facial expressions of these animals. However, the images also show that the facial expressions are formed not only by the eyes, but by the shapes of the elements around the eyes as well, such as the eyebrows and the area between the eyebrows, and that these elements play an important role.

Therefore, to create the facial expression of the Gold Wing, we decided to make effective use of the surrounding design elements in addition to the headlights, in order to work on the design of the entire face.



Fig. 4 Examples of facial expressions constituted by binocular lighting designs

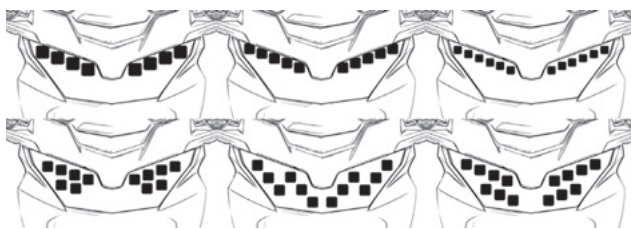


Fig. 5 Examples of expressions constituted by multiple-eye lighting designs

2.2.2. Use of Kumadori

As a part of the study described in the previous section, we decided to focus on the art of *Kumadori*, which refers to the patterns painted onto the faces of Kabuki actors. We studied it as an example of how to create facial expressions using elements placed in the area around the eyes.

Kumadori is the stage makeup drawn on the actors' faces in order to emphasize the muscles and veins of the face. Kumadori enable audience members sitting far away from the stage to recognize the facial expressions of the actors at a glance (Fig. 7).



Fig. 6 Examples of facial expressions of animals



Fig. 7 Kumadori (shadings on face)

Among the design elements that make up the Kumadori, the most important elements are the lines that dramatize the facial expressions. The Kumadori serves as an example that shows that it is possible to represent facial expressions using the structures of lines arranged around the eyes, not the pupils of the eyes themselves.

Therefore, in addition to designing the outline of the headlight lens, we also used the trim line made out of a light guiding lens on the interior of the headlights in order to represent the facial expression. The lines form the facial expression on the front of the motorcycle (Fig. 8).

2.2.3. Creating the high beams

We selected reflector type lights for the high-beam lights. Normally, reflector type lights are bright and stand out because they reflect their surroundings like a mirror.

Moreover, we placed reflectors behind the light guide lenses so that they reflect the black extension of the bottom part of the multiple-eye lens. In this way, we emphasized the multiple-eye lens and the light-guide lens by blacking out the reflectors (Fig. 9).



Fig. 8 Styling design sketches of vehicle front



Fig. 9 Difference in appearance due to difference in structure of reflector

2.2.4. Creation of parts that compose the multiple-eye LED headlight

We also put special care into the design of each part that composes the headlights as well as into the design of the overall lamp (Fig. 10).

Additionally, we paid special attention to the details of the design for the low beam lamps, which are composed of multiple-eye lenses as well. We carefully designed the shapes of the extensions that surround each lens to give a three-dimensional impression and designed the shape of the area to which we applied surface texturing.

Furthermore, we created a design for the light guide lenses. Although the light guide lenses are subject to many optical constraints, we created a design that achieves an even and uniform illumination with a sense of depth. The light guide lenses represent a Kumadori that is beautiful when viewed from any angle.

2.3. Completion of Two-lamp Multiple-eye Headlights

We decided on a final design for the headlights which uses a multiple-eye illumination method with 5 lenses on each side, for a total of 10 lenses.

The multiple-eye LEDs arranged on the left and right sides along with the contour of the lamps, the shape of the area between the eyebrows, and the shape of the optical guide plates achieve the same effect as the Kumadori on an actor's face. Together, these elements represent the "eyes" of the motorcycle and create a facial expression that is full of vitality.

As a result of the study we conducted, we were able to develop a new method for creating the facial expression of the Gold Wing with multiple-eye LED headlights through the use of the lines surrounding the headlights.

In addition, the Kumadori that was formed by the light guide lenses also forms a part of the wing line that extends to the left and the right sides along with the position lights. The tips of the wing lines were placed as far out as possible towards the outside of the motorcycle. The tips of the wing line are located outside the vehicle as much as possible, contributing to the enhancement of the visibility from other vehicles (Fig. 11).



Fig. 10 Drawing showing emitted lights and sketch showing individual components



Fig. 11 Front view of finished design

3. Integrated Tail Lights

3.1. Uniformity with the Design of the Front

We used the sense of character imparted by the wing line formed by the headlights for the integrated tail light as well.

Although the front lamps tend to receive more attention than the tail lamps in terms of determining the impression that viewers receive from the facial expression of the motorcycle, the tail lamps are also important. When you suddenly notice a motorcycle passing by on the street, although the front of the motorcycle passes by in an instant, the rear of the motorcycle can be seen for a longer period of time and appears to trail after the front. In addition, when vehicles are driving one after another, the rear of the motorcycle ahead is continuously visible from the vehicles that follow behind. Therefore, the rear of the motorcycle is in view for longer periods of time.

Therefore, the facial expression created by the rear of the motorcycle is just as important as the front one for determining the impression imparted by the motorcycle.

For the Gold Wing, we incorporated the wing line motif in the design of the integrated tail lights as well. This is

because we thought it was important to consider the impact that the rear of the motorcycle has on the viewer — when the Gold Wing motorcycle that is heading towards the viewer passes by, after which only the rear is visible. We attempted to create a design that makes it look as if the light emitted from the wing line is showing through the chassis from the back. A viewer looking at the rear of the motorcycle after it has passed by would feel as if they were seeing an afterimage of the wing line that was seen on the front.

We wanted to create a design for the integrated tail lights that leaves a strong impression and that makes the viewer want to continue following the motorcycle with his eyes for extended (Fig. 12).

We were able to achieve this design on the Gold Wing since it has panniers on the left and right (Fig. 13).



Fig. 13 Styling sketch of vehicle rear

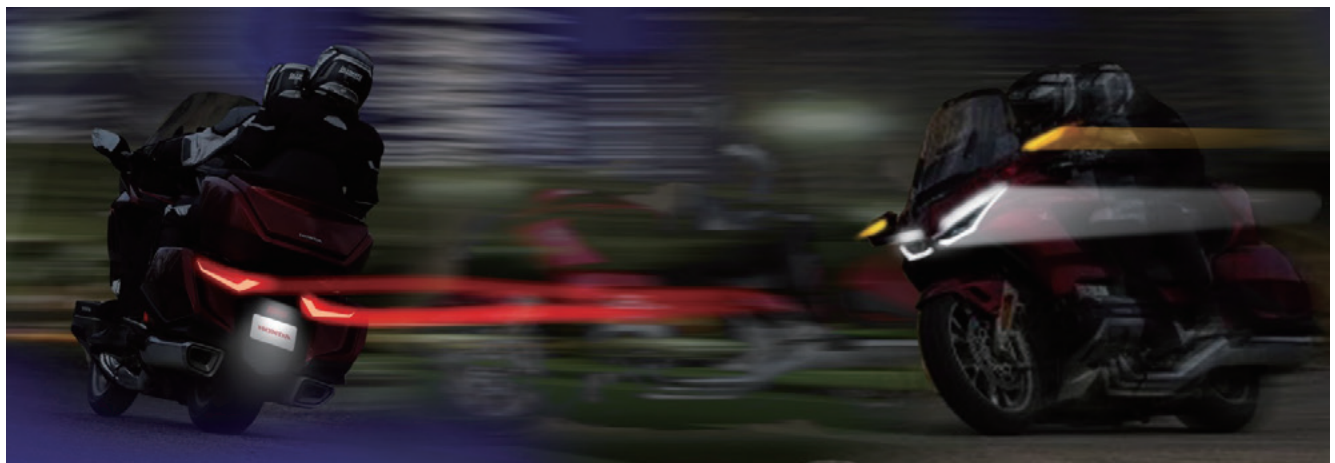


Fig. 12 Expression created by light emissions when vehicle has travelled away

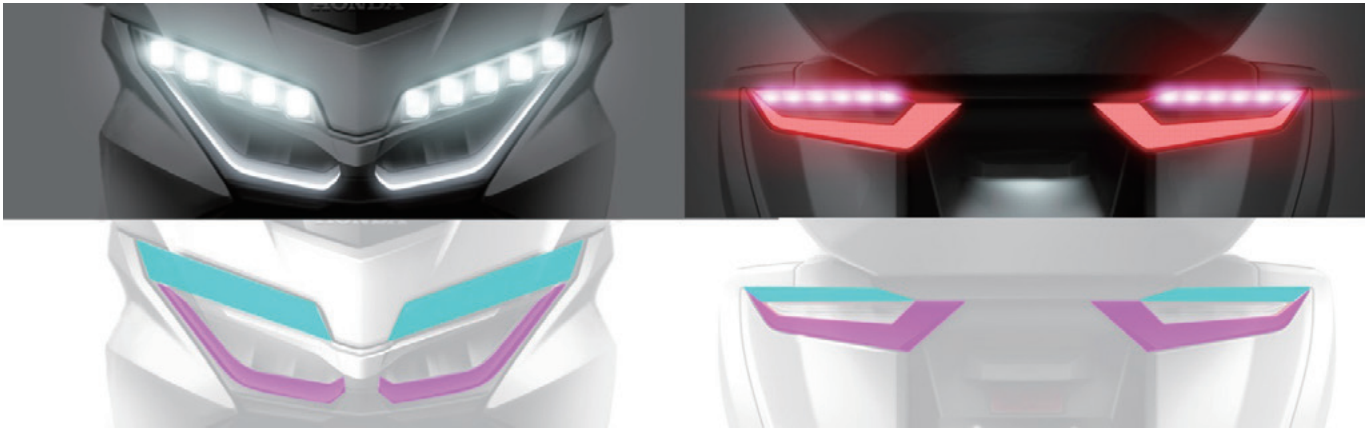


Fig. 14 Unified characteristic impression applied to front and rear lighting systems

3.2. Uniformity of Shine

We incorporated the elements that were used to create the facial expression of the front of the motorcycle, such as the two-lamp multiple-eye lamp and the Kumadori, into the design for the integrated tail lamps as well. In this way, we were able to unify the appearance of the front and the back of the motorcycle (Fig. 14).

In addition, in order to give a greater sense of design uniformity, we made the shape of the lights similar to the front and made the optical structure of the interior of the lamp similar to the structure used for the front lights as well.

The multiple-eye low-beams on the headlight correspond to the brake lamps on the tail light. We represented a multiple-eye light by combining an array of multiple separate reflectors with an outer lens with an independent cut.

The three-dimensional light guide lens on the headlight corresponds to the tail lamp. By combining the reflector and the inner lens, we created a three-dimensional and uniform illumination that is similar to the front.

The high beams on the headlights correspond to the turn signal lamps on the tail lights. We selected reflector-type lamps for the turn signal lamps, similar to the lamps for the high beams (Fig. 15).



Fig. 15 Sketches of parts constructing combination light



Fig. 16 Rear view of finished design

3.3. Completion of the Final Design for the Rear

As explained above, we created the unique wing line shape on the rear as well as the front. In this way, we succeeded in creating a tail light that leaves an impression that is befitting of the new Gold Wing. In addition, we successfully created a light that appears to extend freely to the left and right. By increasing the width of the lamp area, enhancement of the visibility from other vehicles, which was one of the design objectives, was realized (Fig. 16).

4. Conclusion

The lighting system that is deserved for the 2018 Gold Wing was designed. Some of the unique design methods are described hereafter.

We created a new method for designing lighting systems. The idea is to use the lines in the area surrounding the headlights to define a new facial expression for a motorcycle with multiple-eye LED headlights. By applying lighting system designs, which are based a motif of the wing mark, for vehicle front and rear, a consistent impression arranged in front and rear areas was created.

By adopting the latest technologies, the sense of advancement is expressed together with the inherited original features. Together with other original characteristics, the wing line was inherited and it contributes to create premium status as Honda's flagship.

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Daisuke KURIKI

Development of 2018 PCX and PCX HYBRID

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ABSTRACT

In the fourth-generation model of the 2018 PCX, the basic structure of frame was reviewed to make it lighter and rigid. Weight reduction was also adapted to its wheels. These enhancements contributed to its increased dynamic performances. The engine performances were enhanced as well, and all these features made it possible to provide a high-quality riding with composure of rider's mind. In addition, we developed hybrid model PCX HYBRID that uses an ACG starter directly connected to a crankshaft as a drive assist system and realized pleasurable ride feeling with a more direct drive response.

1. Introduction

The market for small scooters has recently been expanding, mainly in Asia. The first-generation PCX, which was launched on the global market in 2009, was very successful in drastically transforming the 125 cc scooter concept through the following added values:

- Comfortable, relaxed riding position in the higher end models realized in the easy-to-handle 125 cc-size body
- High-quality feel provided by its styling package
- Comfortable, high-quality ride
- Reliable environmental performance.

The packaging design of the PCX has continued to provide all the above features. These features have led to the PCX series models being very well received by people around the globe, and it is seen as higher-class commuters in ASEAN and other countries in the region and seen as a distinguished higher grade product compared to other conventional scooters of the same class in both Japan and Europe. Since its introduction, the PCX has continuously evolved, also seeing the addition of 150 cc model, PCX150, in pursuit of an ideal packaging design for both 125 cc and 150 cc scooters.

The fourth-generation model introduced in this paper, the 2018 PCX, was developed as a full model change (Fig. 1). The main aim in developing this model was to make the PCX more attractive while at the same time retaining the core features of the previous PCX models that appeal to current consumers. When setting the design goal, we introduced five conceptual pillars: freshness, running performance, comfortability, ease of use, and economical

efficiency, with the aim of making the new model better than the previous models in all these respects.

In addition, we newly developed the world's first hybrid system for use in a mass-produced motorcycle (according to a research study by Honda), and installed it in the PCX HYBRID (Fig. 2). This hybrid system is designed to assist the vehicle's acceleration through the utilization of a drive motor directly coupled to the crankshaft. This hybrid system enables the rider to experience a very different ride sensation from that offered by conventional models of the same class. Hence, the desire of the development team to offer users a model that is more "fun to ride" was realized.

This paper introduces the new technologies that were adopted in the 2018 PCX and PCX HYBRID models.



Fig. 1 The PCX (2018)

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Fig. 2 The PCX HYBRID (2018)

2. Development Concept

Before commencing development, we conducted a market survey to gather the opinions of current users in ASEAN countries. The survey results showed that users were fairly satisfied with the PCX model as a high-grade scooter. The survey also revealed that users had strong desire to show their wealth by purchasing a PCX.

So, we therefore decided to retain the core features of the current PCX that were the most appealing and to further enhance the attractiveness of the model. Accordingly, we decided to stay with the development concept of “personal comfort saloon,” which had been inherited from the first-generation PCX.

Then, the development theme of “premium daily use scooter to satisfy user’s sense of superiority around the world” was set together with three development objectives as follows:

- High-quality, comfortable ride enabled by enhanced maneuverability
- New expression of excellence
- More convenience and user friendliness

Furthermore, a new variant was added to employ an hybrid system in order to feature more innovation, quality, and the joy of riding.

3. Development of 2018 PCX

3.1. Reduced Weight and Enhanced Maneuverability

In order to get a better maneuverability, we implemented measures to reduce the weight and increase the rigidity of the body.

So, the body frame was changed from the previous underbone frame (Fig. 3) to a double cradle frame (Fig. 4). Also, the material of the front cover stay bolted to the frame was changed from metal to resin. As a result, the total combined mass of the frame and front cover stay was

reduced by 2.4 kg compared to the previous model. As regards the rigidity of the frame, longitudinal stiffness was increased by 50.4% and torsional rigidity was increased by 2.9%, which contributed to enhanced operational performance of the suspension and vehicle stability.

The front and rear tires and wheels were also renewed (Fig. 5). The wheels were newly designed not only for wider tires but with the aim of also reducing the weight. For

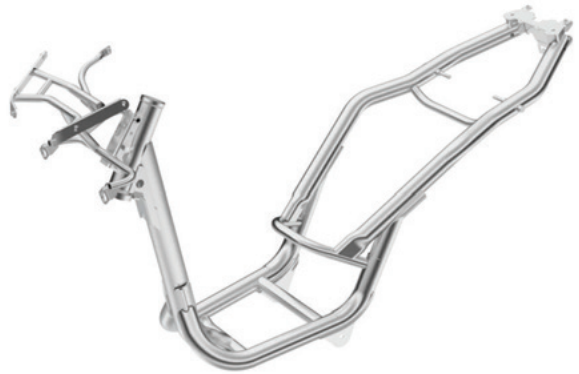


Fig. 3 Frame of previous model



Fig. 4 Frame of developed model

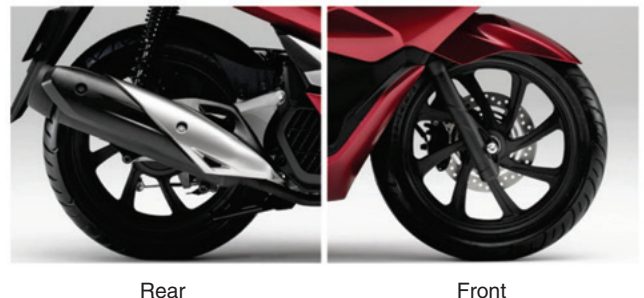


Fig. 5 Wide tire and newly designed wheel

this purpose, the wall thickness of the rim was effectively reduced by decreasing the circumferential stress, which was achieved by increasing the number of spokes from the previous 5 to 8. In addition, the front wheel hub was partly hollowed and the wall thickness of the rear wheel hub was reduced. As a result, we achieved weight savings of about 7% (-0.2 kg) for the front wheels and about 11% (-0.5 kg) for the rear wheels compared with the previous model.

Accordingly, through the above changes, smoother maneuverability was realized to give a seamless, comfortable vehicle response to the rider's actions.

3.2. Enhanced Performance of Gasoline Engine

From the engine development point of view, the objective of a "high-quality, comfortable ride" could be attained through higher engine power and such engine characteristics that could make the rider feel relaxed and comfortable while out on a ride. As increasing the engine speed to shift the belt-driven transmission increases vibration and thus reduces comfort, we focused on generating sufficient power at lower engine speed while making the engine more powerful in the higher engine speed range for smooth and seamless acceleration.

Since one of the development goals in this model was to meet Euro 4 equivalent emission regulation, we redesigned the layout of the exhaust system to accommodate a larger size catalyst unit. Then, we increased the power in the higher engine speed range by increasing the bore size (only for the 125 cc model) and by straightening the exhaust pipe structure in the muffler. Furthermore, we increased the capacity of the air cleaner case by 1 liter and optimized the flow and pressure balance in the intake line which consists of the air intake duct and connecting tube through computational fluid dynamics (CFD) analysis, as shown in Fig. 6. In this way we were able to achieve a quicker engine response to the throttle control while maintaining the same engine power as that of the previous model in the low and

medium engine speed ranges.

In addition, we adjusted the fuel injection setting, with the aim of realizing a smooth, comfortable response to the rider's input. Through these, the engine power was increased in the higher engine speed range to enable smooth and continuous acceleration while maintaining the same gear-shifting engine speed and acceleration at the lower engine speed range as the previous model, as shown in Figs. 7 and 8, to successfully achieve the desired high-quality, comfortable ride.

Accordingly, as a result of the above changes coupled with the enhanced maneuverability, the new model realizes an enjoyable and energetic ride in a wide range of applications from daily commuting to weekend touring.

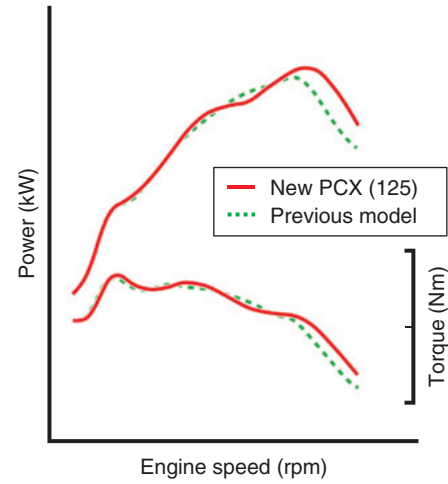


Fig. 7 Engine performance (PCX)

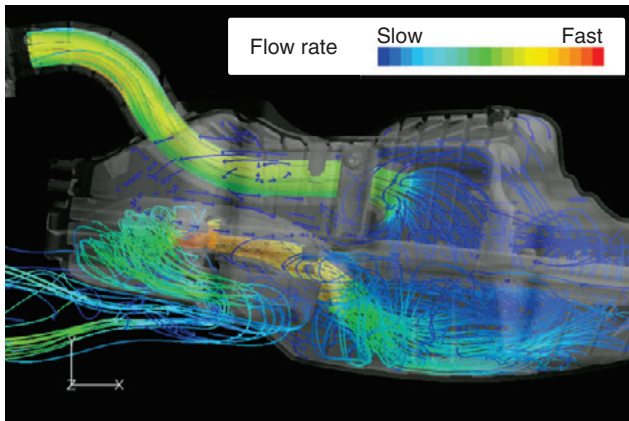


Fig. 6 Example of CFD analysis in air cleaner case

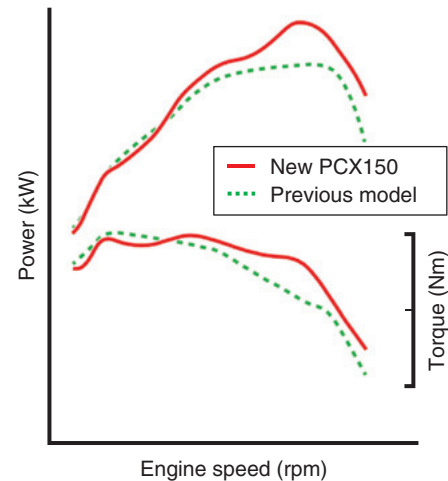


Fig. 8 Engine performance (PCX150)

4. Development of PCX HYBRID

4.1. Aim of Hybrid System

In a scooter of this displacement class, there is a slight time lag due to the characteristics of the belt converter, from the opening of the throttle to the response of the vehicle body. Therefore, a response like a manual transmission motorcycle could not be realized. This is one of the reasons why motorbike enthusiasts are not willing to use scooters. So, in developing the new model, we tried to find a solution to enhance this response to realize a more enjoyable ride.

One way to realize the desired quick response is to develop a hybrid system consisting of a gasoline engine and an electric motor, which reacts directly to the input, and hence provide a direct enjoyable ride sensation.

Note that the performance data on the PCX HYBRID presented here are those for the 125 cc engine installed hybrid model marketed in Japan. Also note that the performance data that are used for comparison are those for the 125 cc gasoline engine model, the 2018 PCX.

4.2. Outline of Hybrid System

4.2.1. Compact system layout

When designing the hybrid system, we placed the highest priority on not impairing the maneuverability expected of a motorcycle. As a hybrid vehicle needs to have a drive battery and a complicated control system, the total mass as well as the size of the vehicle body tends to increase, which then possibly lowering maneuverability. Therefore, we aimed to build a compact system that could be accommodated in the body size of the PCX gasoline engine model, to allow easy handling in town and to maintain a comfortable, high-quality ride without losing inherent mobility.

To make the system simpler so that it could be used in the same body as that for the gasoline engine model, we decided to employ a parallel drive system that utilizes the ACG starter⁽¹⁾ for drive assist. The ACG starter of the gasoline engine model, which is used to start the engine and to generate electric power, is directly coupled to the crankshaft, as shown in Fig. 9. By developing a special hybrid drive motor that uses electromagnetic steel sheets as the stator's core material, core loss was reduced and a compact unit was realized without changing the basic structure of the engine including the starter system.

Figure 10 shows the layout of the hybrid system components. The power drive unit (PDU) to control the motor assist function is integrated with the engine control unit (ECU) by reducing the size of the ECU components, increasing the thermal efficiency of the power supply, and optimizing the layout within the original size of the ECU enclosure.

The down regulator is used to supply power to the lamps, lead-acid battery, and other general electrical components. The junction unit is used to connect an external 12 V DC power supply to start the engine in the

case of an emergency. These two units and the lithium-ion battery pack (described in Clause 4.2.4. below) were placed adjacent to each other in order to reduce the length of the connecting cables.

Accordingly, the hybrid system components were installed in a compact manner without affecting the appearance of the original gasoline engine model.

4.2.2. Overview of system operation

Figure 11 shows how the hybrid system works. The motor assist function is activated when the engine is restarted after an idling stop state or when the rate of throttle control applied by the rider exceeds a threshold level. The PDU calculates an optimum assist torque from the throttle position, engine speed, and remaining capacity

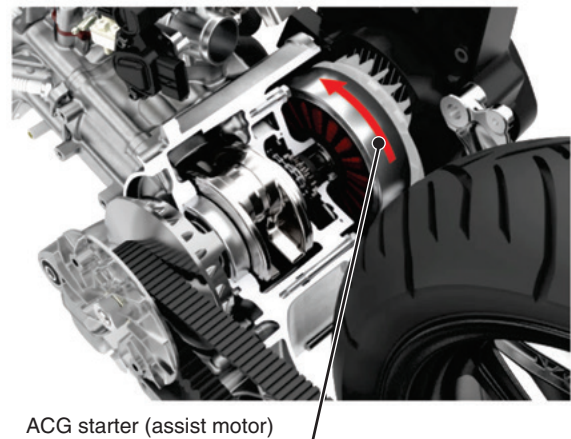


Fig. 9 ACG starter (assist motor)



Fig. 10 Layout of hybrid system parts

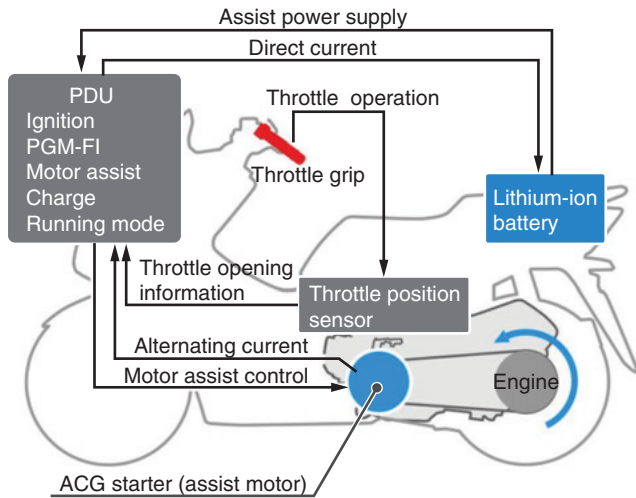


Fig. 11 Overview of hybrid system

and temperature of the lithium-ion battery to generate assist torque control commands.

Note that whenever the motor assist function is not in operation, the ACG starter is used for power generation to charge the lithium-ion battery.

4.2.3. Setting of assist duration

As the assist duration has an impact on the battery size, it was necessary to determine the minimum acceptable duration from the viewpoint of usability. For this purpose, we surveyed the use situation of Thai users, which are often accelerating rapidly, in order to measure the time from opening the throttle to starting to close it to maintain vehicle speed. The frequency results for the throttle-opening time for two different driving conditions are shown in Figs. 12 and 13. We can see from Fig. 12 that about 90% of the measurements fell into the duration of 3 seconds or less in urban areas of Thailand. Similarly, about 80% fell into the 3-second duration in the suburbs of Thailand, as shown in Fig. 13. From these results, it was determined that setting the assist duration to 3 seconds would be able to cover most of the acceleration cases.

On the other hand, we also expected that terminating the assist operation immediately after the assist time of 3 seconds would result in a significant drop in the driving force and have a negative effect on the rider's experience. To address this issue, we decided to add a 1-second interval to gradually reduce the amount of assisting power and thereby set the maximum total assist duration to 4 seconds. In addition, we also gradually increased the power generation load after the end of the assist to help prevent any uncomfortable ride sensation.

4.2.4. Lithium-ion battery

Among the hybrid system components, the motor drive

battery is the largest. Hence, there is a conflict between the compactness requirement so as not to impair the mobility of the motorcycle and the minimum size required to deliver enough assist power.

So, first we needed to select a small, lightweight battery that could be mounted on the vehicle and that met both the assist power and assist time requirements. For this purpose, we selected a cylindrical, 18 mm diameter high power lithium-ion battery cell.

As the cell voltage was 3.6 V, we connected 14 cells in series to obtain a voltage that was high enough to assist the drive up to the high engine speed range. Then, to satisfy the required engine starting output even under cold weather conditions and the low state of charge (SOC), we paralleled two series strings of 14 cells to obtain the rated voltage of 50.4 V and rated capacity of 3.8 Ah (192 Wh).

The battery pack was integrated with the battery management unit, which monitors the battery temperature and SOC to control the charge/discharge operation, in an IPX5 protection rated (IEC 60529) waterproof housing.

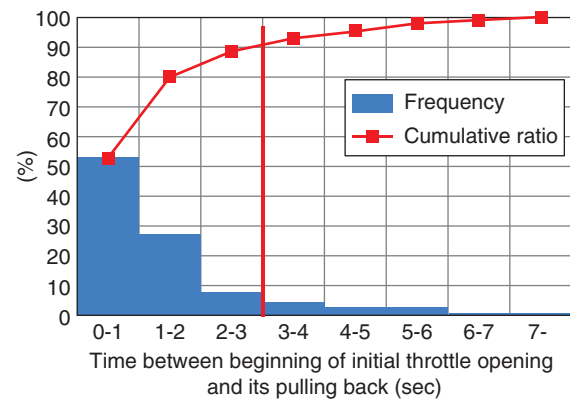


Fig. 12 Measurement results for throttle-opening time (urban area driving in Thailand)

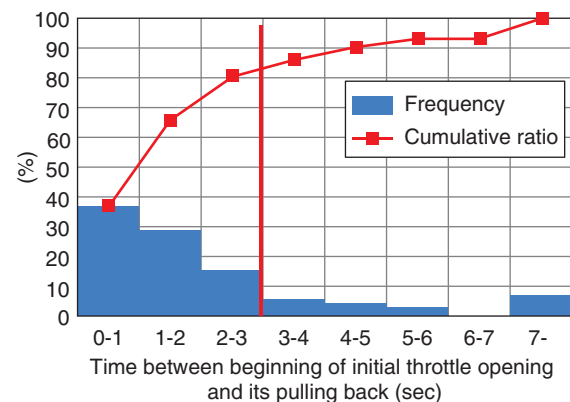


Fig. 13 Measurement results for throttle-opening time (suburban area driving in Thailand)

Figure 14 shows the resulting vehicle-mounted compact battery pack. The lithium-ion battery pack measures length 205 mm x width 134 mm x height 90 mm and weighs 2.6 kg.

4.2.5. Performance enhancement by motor assist

The motor delivers the power of 1.4 kW and the torque of 4.3 Nm at 3,000 rpm. The addition of motor assist power to the 125 cc gasoline engine increased the torque by about 33% at 4,000 rpm and about 22% at 5,000 rpm, as shown in Fig. 15 for wide open throttle (WOT); hence a very torqueful assist was realized.

Figure 16 shows the engine speed versus time when the vehicle is accelerated from a stopped state with WOT for both the gasoline engine model and the hybrid model. We can see from the graph that the centrifugal clutch is engaged at the time of the fourth combustion in the case of the gasoline engine model, whereas it is engaged at the third combustion in the hybrid model. In other words, the time from the start to clutch engagement is successfully



Fig. 14 Appearance of lithium-ion battery pack

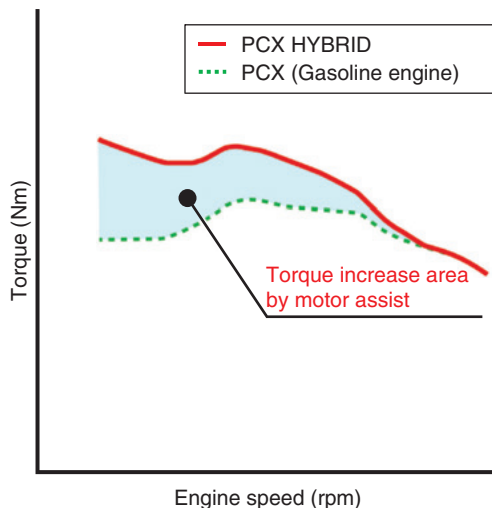


Fig. 15 Increase in torque by motor assist at wide open throttle (WOT)

reduced by about 20 % due to the quick response provided by the motor assist. These enhancements provide a feeling of direct acceleration, and the quick standstill acceleration in town and the reliable traction characteristics during cornering make for a more exciting and pleasurable ride.

Also, as shown in Fig. 17, the hybrid model can run

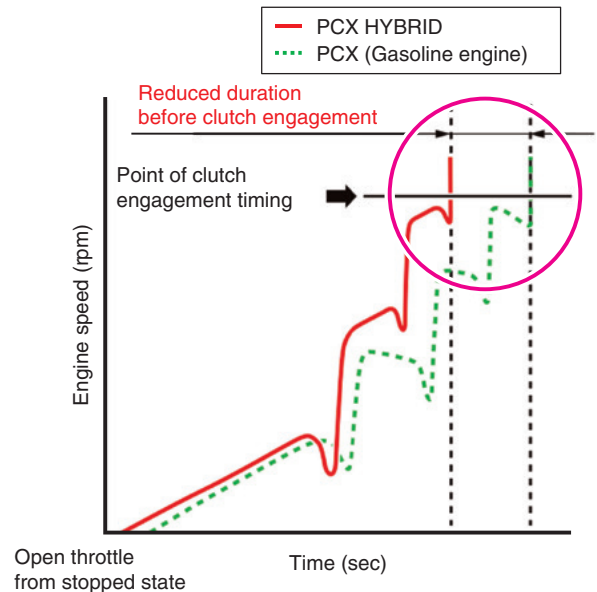


Fig. 16 Comparison of duration before clutch engagement

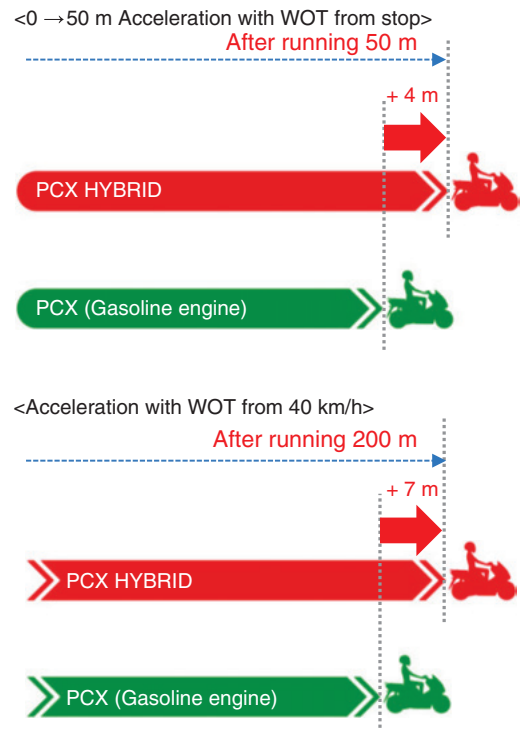


Fig. 17 Comparison of power performance

about two vehicle lengths (4 m) ahead of the gasoline engine model at a distance of 50 m from a standstill start with WOT. Similarly, in the case of WOT acceleration from 40 km/h, the difference was about 3.6 vehicle lengths (7 m) at 200 m after starting the acceleration. From the above results, we understand that the motor assist function has also enhanced the power performance.

4.2.6. Reduction of idling stop waiting time

In previous PCX model, the idling stop function operates 3 seconds after the vehicle stops. This duration was intended to reduce repetitive start/stop operations on congested roads as the restarting time lag would be annoying for the rider if the engine stopped too frequently. As the PCX HYBRID can achieve quicker clutch engagement by using the assist motor, it should be able to help eliminate or reduce this annoyance for the rider. So, we studied the possibility of reducing the idling stop waiting time. By finding a setting that struck a balance between the rider's annoyance with the time lag and the sense of security in the restart, we were able to reduce the waiting time by 2.5 seconds compared to the previous model, as shown in Fig. 18. In other words, we were able to stop the engine for only 0.5 seconds after the vehicle was stopped; this greatly contributes to reducing emissions and to enhancing engine quietness in town.

4.2.7. Run mode switching to use different assist characteristics

During the process of developing the detailed specifications, we created a prototype model that could legally run on public roads and tested it to check the suitability of the PCX HYBRID design on public roads. As a result, we found that the required assist force is different between the cases when the vehicle is on a congested road and when it is on a winding road even if the throttle position is the same.

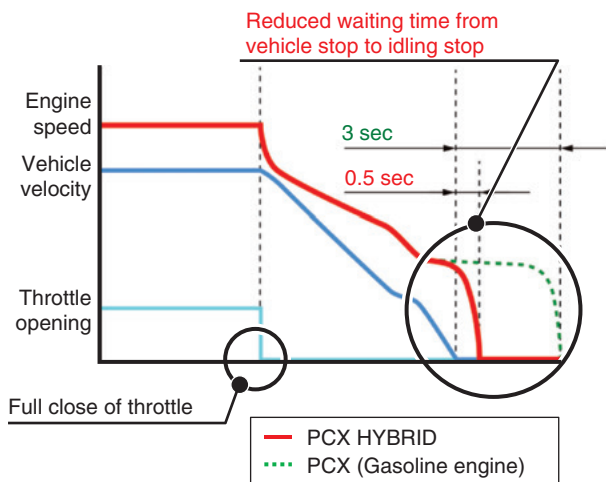


Fig. 18 Reduced waiting time for idling stop system operation

So, we added a function to enable the rider to switch the run mode to select motor assist characteristics according to the context or the rider's preference.

When the main switch is turned on, it enters D mode, where a relaxed, comfortable ride and moderate motor assist are provided at the same time. On the other hand, S mode enables a sporty run by enhancing the assist power to provide more fun when riding the vehicle. To be more specific, while the assist power is the same in both modes when the throttle is wide open, the assist power at a low to medium throttle position is different according to the mode and throttle position, as in the example shown in Fig. 19. The mode select switch is on the left handlebar (Fig. 20) so as to enable selection even during a ride, according to whether there is traffic congestion or a winding road.

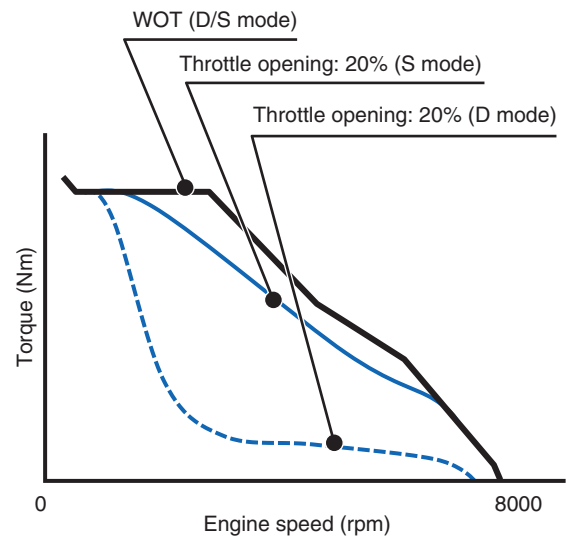


Fig. 19 Example of torque difference due to difference in assist mode

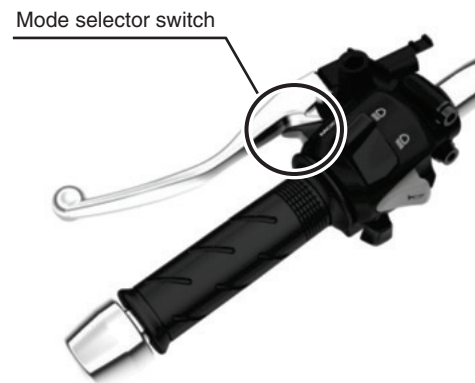


Fig. 20 Mode selector switch

4.2.8. Speedometer display for hybrid model

A special display panel was designed in order to show various types of information of hybrid system in an easily understandable way. In addition to the same display content of the gasoline engine model, such as speedometer, clock, and average gas mileage, the following indications were added specifically for the hybrid model:

- Run mode indicator (D/S/Idling modes)
- Indicator of motor assist level for engine
- Lithium-ion battery charge level indicator
- Residual capacity of lithium-ion battery
- Lithium-ion battery indicator

Figure 21 shows the center display. The assist level indicator and charge level indicator are five-segment and two-segment bar-graph displays, as shown in Figs. 22 and 23, respectively.

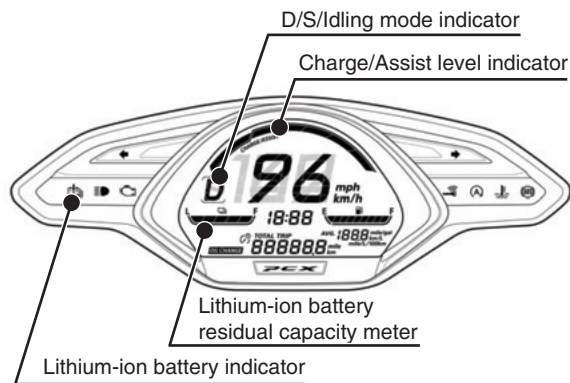


Fig. 21 Speedometer for PCX HYBRID



Fig. 22 Assist level indicator (at maximum level)



Fig. 23 Charge level indicator (at maximum level)

5. Summary

The fourth-generation model, the 2018 PCX, was developed as a full model change with a newly designed frame body and wheels and enhanced intake and exhaust systems. The new Euro 4 emission standard was satisfied, and the functions and performance greatly exceeded those of the previous model to enable a more enjoyable and energetic ride in a wide range of settings from commuting to weekend touring.

The PCX HYBRID model was designed to use the packaging of the PCX to the maximum extent possible while adding the minimum required hybrid system of a dedicated motor and optimized assist time. The quick standstill acceleration in town and reliable traction characteristics during cornering of this world-first mass production hybrid motorcycle model realized a more exciting and pleasurable ride.

We expect that this hybrid system will be well accepted by customers and that it will be further developed as one of the most attractive forms of technology applicable to motorcycles.

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Development of the PCX ELECTRIC

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ABSTRACT

We developed the electric motorcycle model “PCX ELECTRIC” that satisfies usability under the traffic environment in Japan and ASEAN’s motorcycle sales major countries. The PCX ELECTRIC features easily removable battery packs, which practically helps eliminate the waiting time associated with charging the battery. The compactly designed EV system, which is efficiently packaged in the vehicle, uses two removable 48 V battery packs connected in series to realize a 96 V system suitable for driving the electric motorcycle. The EV system mounted on the body of the 2018 PCX achieves a motor power of 4.2 kW, top speed of 60 km/h, and cruising range of 41 km (at a steady 60 km/h).

In addition, we developed a highly-convenient battery attaching system that enables fixing of the battery to the vehicle body and engaging of the connectors with a single action operation.

1. Introduction

In order to reduce CO₂ emissions intensity in products by 30% from compared with 2000 levels by 2020, Honda has been focusing on developing more electric vehicles as a means to achieve this goal.

As regards electric motorcycles specifically, in 1994, Honda developed and marketed the “CUV-ES⁽¹⁾” for use by government agencies and local municipalities. Then, in 2010, we also marketed the “EV-neo^{(2), (3)}” for use mainly by delivery businesses, targeting the Japanese market for small motorcycles, i.e., Class I motorcycles that have a displacement of up to 50 cc or rated power of up to 0.6 kW. Through these efforts, we have identified some issues inherent to electric motorcycles, such as long charging time and insufficient cruising range.

To overcome these issues, we have developed the “PCX ELECTRIC” to offer an unprecedented electric motorcycle experience to people around the world. As a concrete mean, we developed and employed a removable battery system to not only reduce charging waiting time, but also to increase the cruising range. Figure 1 shows an image of the developed PCX ELECTRIC model.

This paper introduces the new technologies used in the PCX ELECTRIC.



Fig. 1 The PCX ELECTRIC

2. Aim of Development

2.1. Development Concept

We defined the development concept as “e-Comfort Saloon for Enhanced EV Experience.” Comfort Saloon is a concept that the base model 2018 PCX⁽⁴⁾ inherited from the

¹ Motorcycle R&D Center

² R&D Center X

original model. That means that it is a model with a sense of higher quality. The attraction of the electric motorcycle is also added to the development concept of this model. This expresses our wish to offer many customers wonderful experience of PCX ELECTRIC.

The earlier EV models, the CUV-ES and EV-neo, were marketed only in Japan. However, we observed that interest in reducing CO₂ emissions is increasing not only in developed nations such as Japan, but also in developing countries.

We therefore decided to market the new PCX ELECTRIC not only in Japan, but also in three ASEAN countries, i.e., Thailand, Vietnam, and Indonesia.

However, the 50 cc (0.6 kW) class motorcycles that are specific to Japan have not been marketed in these ASEAN countries. Rather, there is a popular market demand for mainly 125 cc models, which are equivalent to Japanese Class II motorcycles of up to 125 cc or rated power of up to 1.0 kW. Accordingly, we aimed to achieve a motor power that would enable the riders in these countries to travel easily and safely among other Class II equivalent motorcycles and automobiles and to provide a cruising range sufficient for daily use.

2.2. Removable Battery System

The two previous EV models use a built-in battery system where the batteries are fixed in the vehicle. In the case of the EV-neo that is used for delivery services, we initially assumed that the battery could be recharged before it is fully discharged during the standby time between delivery jobs. We therefore provided both normal and quick chargers for such businesses so that they could choose to employ either one according to their specific needs and service conditions.

However, it is not easy for delivery business operators to predetermine their vehicle operating hours, especially in the case of food delivery services. Such businesses must quickly respond to delivery requests even when the vehicle's battery is being charged and thus the amount of charge can be insufficient for such operations. We also presumed that this issue could also arise in the vehicle models intended for general users.

So, for the PCX ELECTRIC, we decided to employ a removable battery system (instead of a quick charger) to allow the use of fully charged standby batteries to thereby practically help eliminate the waiting time associated with charging the battery.

Another advantage of using a removable battery system is that you can more freely choose the charging location. Once the battery is detached from the vehicle, you can charge it almost anywhere that has a charging point with a special charger. So, even if no power source is available near the vehicle parking spot, such as in a parking area of an apartment house or condominium, you can use such a vehicle without having to face the issue of installing a power supply system.

In fact, Honda exhibited a prototype removable battery at the Tokyo Motor Show 2015 (TMS 2015) to demonstrate that the concept could be applied to various Honda products in the future, as shown in Fig. 2.

Therefore, based on this concept, we defined the basic specifications for the removable battery by also considering its possible future application in handy batteries and other general-purpose energy products in addition to its mobile use in small motorcycles or ultra-compact four-wheel EVs as follows:

- (1) Volume: about 7 liters (to take into account the limited installation space of small motorcycles)
- (2) Capacity: 20.8 Ah
- (3) Power: 2.5 kW, continuously for 10 minutes or longer (to consider sufficient hill-climbing performance for small motorcycles)
- (4) Voltage: 50.4 V (to satisfy the safe low-voltage requirement defined in UNR 136)

Based on the above basic specifications, we continued our research to further define detailed specifications with the aim of moving toward achieving the goal of “practically zero waiting time and practical cruising range.”

2.3. Power Performance

In order to increase the power of electric motorcycles, a larger motor, a larger battery for the power source, and a larger power control unit (PCU) for motor control are required. The issue is that this directly leads to a heavier vehicle weight and a higher sale price.

Also, as the basic battery specifications have already been defined, we need to use multiple battery packs to increase the power. For this reason, the PCX ELECTRIC adopted a solution that uses two battery packs connected in series to increase the voltage to reduce the discharge current, and help avoid the use of large-diameter wires at the same time.

In this way, we successfully achieved a maximum motor power of 4.2 kW, as described later in the paper. On the assumption that this solution would be utilized in our model design, we further researched the power performance requirements for the EV model by taking into consideration the usability required in the target markets.

To begin with, to understand the running speed



Fig. 2 “Honda Smart Mobility City” at TMS 2015

distribution of small motorcycles in urban areas, we conducted a survey to measure the running speed of manual transmission motorcycles and CVT scooters in Bangkok in Thailand, Hanoi in Vietnam, and Jakarta in Indonesia. The resulting running speed distributions are shown in Fig. 3.

Although we observed some differences between countries, we found that for approximately 60% to 70% of the time the running speed ranged from 20 to 50 km/h and that for more than 90% of the time the running speed was 60 km/h or less.

Based on this survey result, we decided that, as our power performance goal, the vehicle should be able to run at a speed of at least 60 km/h.

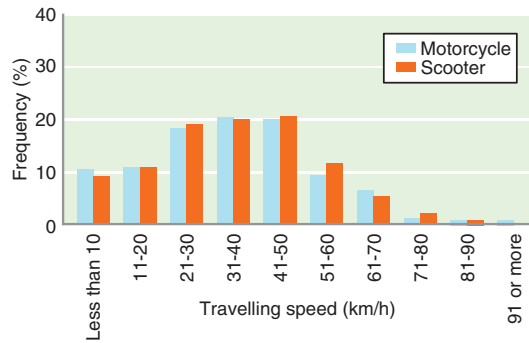
2.4. Cruising Range

Each country has its own standard for how to indicate the cruising range of electric motorcycles in catalogs and other

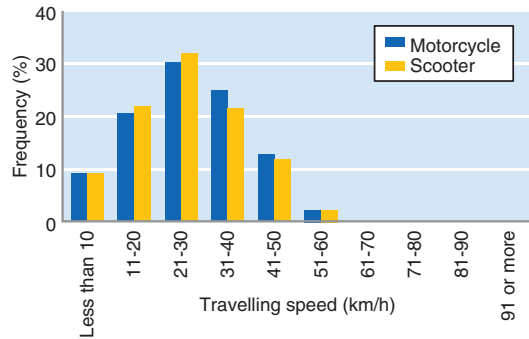
publications. While the cruising range of Class I motorcycles in Japan is indicated for a steady 30 km/h run, the actual cruising range performance deviates significantly from such measurements as it largely depends on how the vehicle is used. This is because the power consumption rate is significantly affected by the pattern of repetitive acceleration and deceleration, in contrast to a steady-speed run. Therefore, we decided to set a target using WMTC mode, which is one of the emission measurement modes used for vehicles with internal combustion engines, as the condition for measuring the cruising range, because it includes more practical acceleration and deceleration scenarios.

Similarly to the case of power performance, we conducted a survey in the three cities by interviewing users about their daily running distance. Figure 4 shows the resulting distributions of daily running distance.

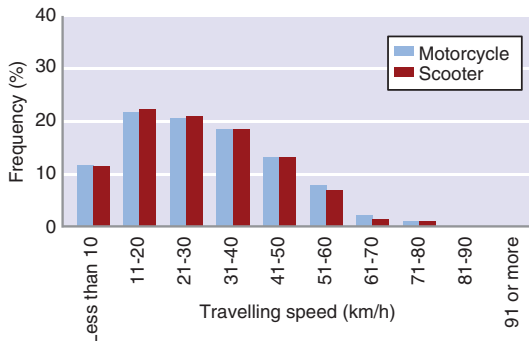
Despite some differences between countries, we can see



(a) Thailand (Bangkok)

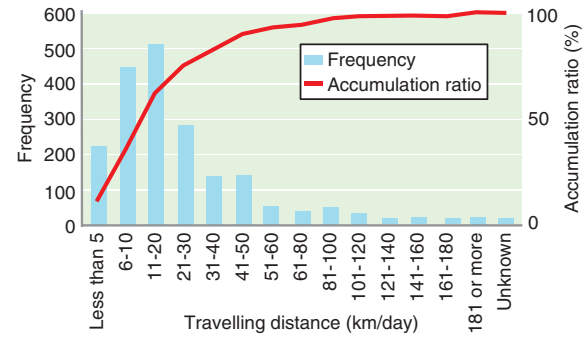


(b) Vietnam (Hanoi)

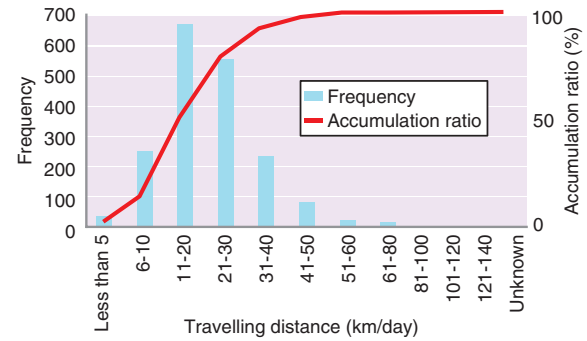


(c) Indonesia (Jakarta)

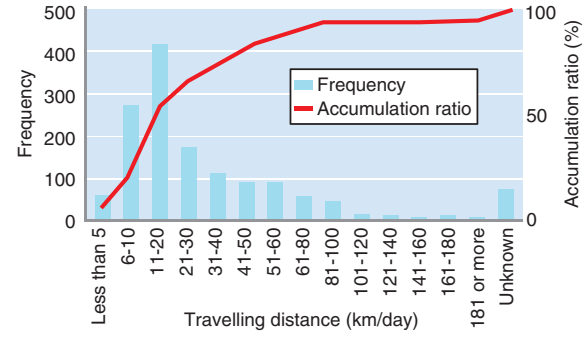
Fig. 3 Distribution of running speed in three countries



(a) Thailand (Bangkok)



(b) Vietnam (Hanoi)



(c) Indonesia (Jakarta)

Fig. 4 Daily running distance in three countries

that 80% or more users in each country have a daily running distance of 50 km/day. Therefore, we targeted a cruising range of 50 km or more after a full charge, assuming internal test criteria equivalent to the corresponding WMTC mode.

2.5. Vehicle Packaging

On the assumption that a global model would be marketed in the three ASEAN countries and Japan, and also taking into account future local assembly operations in these countries, we selected the 2018 PCX⁽⁴⁾ as the base model.

As a scooter of its class, the PCX model is highly supported worldwide, especially in Japan and Southeast Asia, due to its compactness and easy handling, comfortable riding position, sense of higher quality, and the fun riding experience.

We therefore believed that a PCX model with an electric power unit would make a superb electric motorcycle that would be well supported by many people around the world. Accordingly, we aimed to make the EV system as compact

as possible for installation in the existing gasoline engine-based model with minimum modifications. Figure 5 shows the layout of the major EV components.

This approach not only helped to make the system compact, it also helped to prevent a cost increase due to the inclusion of additional miscellaneous parts other than the essential EV components that needed to be newly developed.

In order to provide opportunities to contact electric motorcycles more widely, we examined vehicle specifications from the viewpoint of what should be a model suitable for small commuter users in Japan and ASEAN countries. As a result, we set the aim as a completed vehicle as follows.

To innovate in order to differentiate the EV from engine-based models:

- Newly developed EV system
- Styling items specific to the EV

To provide convenience through simple and user-friendly operation:

- Enjoyable run in a mixed urban traffic
- Simple operation

To incorporate functionality in order to provide a sense of security:

- Sufficient cruising range to cover one day's running distance
- Removable and portable battery packs
- Onboard charger for on-the-spot charging.

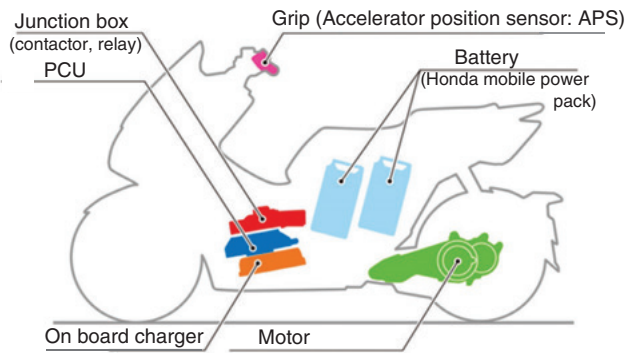


Fig. 5 Layout of EV components

3. EV System

3.1. System Overview

Figure 6 shows a block diagram of the EV system. We designed the EV system to offer the same operability as that

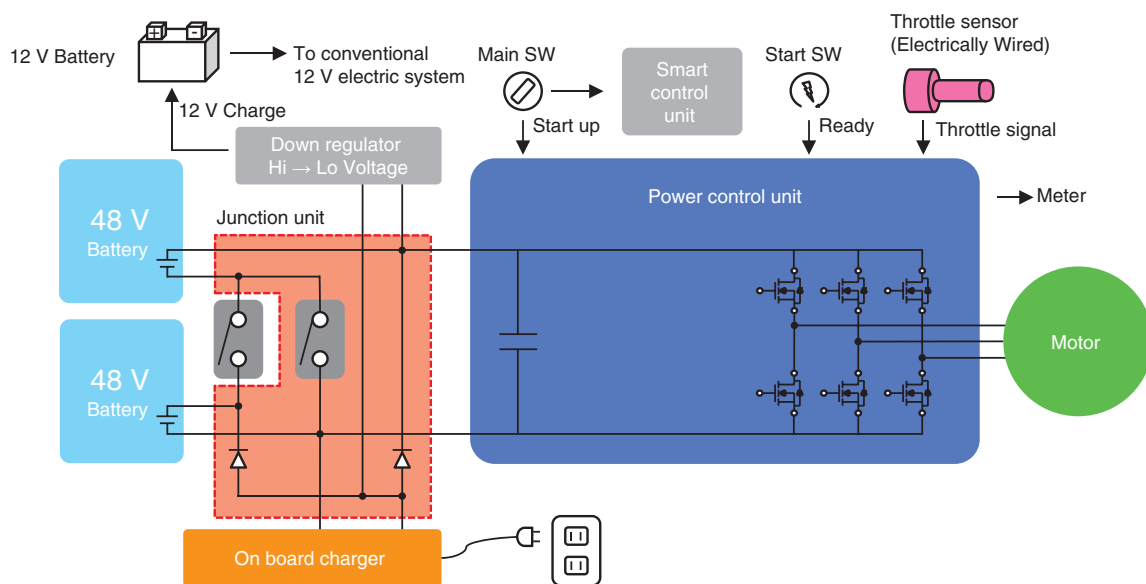


Fig. 6 EV system diagram

of the gasoline engine models, including the use of a main switch to activate the system and a handlebar accelerator grip.

The EV system has two different startup sequences for the run and battery charge modes that are detailed in the following paragraphs. Figure 7 shows a comparison of the two startup sequences. The startup sequence for the run mode is as follows:

(1) Startup of PCU and meter unit

When the user turns on the main switch, a 12 V battery voltage is applied to the PCU and meter unit.

(2) Startup of BMU and communication

The PCU starts up the 48 V battery management unit (BMU) to initiate communication between various components of the EV system. Figure 8 shows the CAN bus line used for information exchange between the EV components.

(3) System standby

The PCU checks for any malfunctions in the components listed in Table 1 and then puts the high-voltage system into its standby state (for details, see Section 3.2. “PCU”).

(4) Start running

Pressing the start switch makes the system ready to run. Then, the user can ride the vehicle using the grip control.

The startup sequence for the onboard battery charge mode is as follows:

(1) Startup of PCU and meter unit

Connecting the charge plug to an outlet (100 - 250 VAC) starts up the PCU and meter unit.

(2) Startup of BMU and communication

Same as in the run mode.

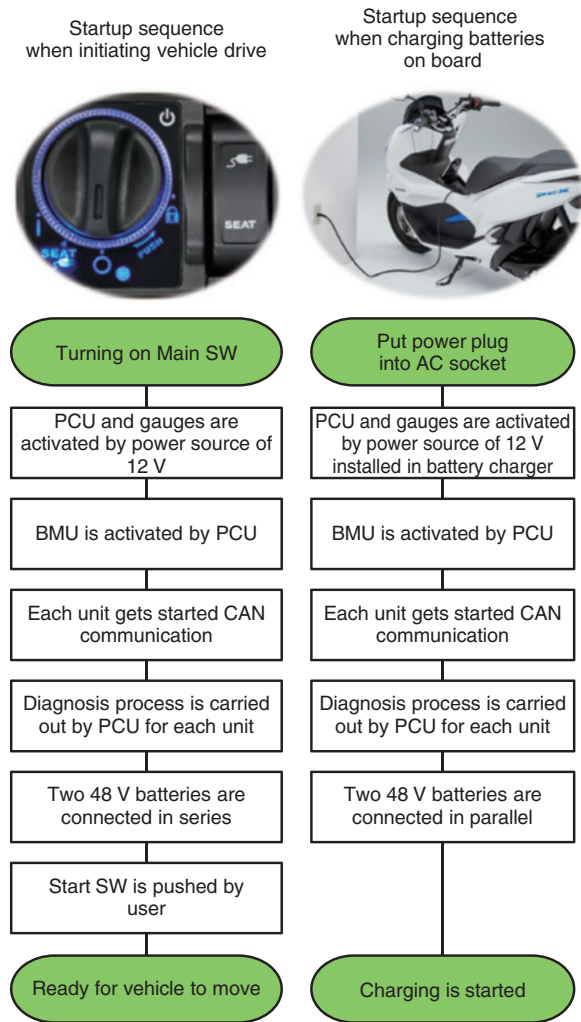
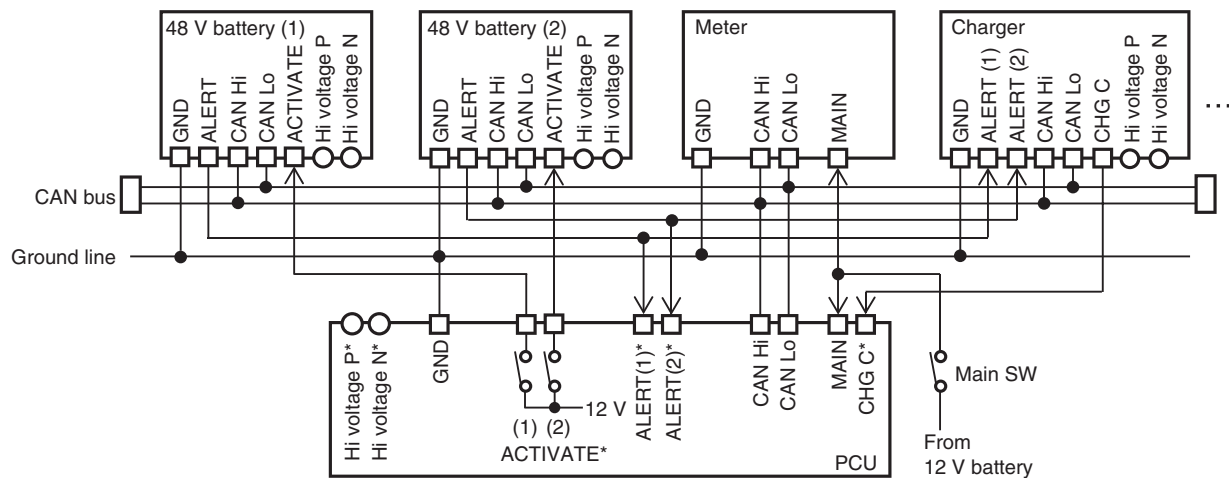


Fig. 7 Comparison of startup sequences



* Details

ACTIVATE: 12 V startup to battery from PCU

ALERT(1)/(2): Detect Battery(1)/(2) connection

CHG C: 12 V startup to PCU from charger

Hi Voltage P/N: Hi voltage positive/negative (connection not shown)

Fig. 8 CAN bus and 12 V system

Table 1 Malfunction detection during run and charge startup sequences

Subjects of monitoring	When initializing for vehicle running	When initializing for charging
Throttle sensor malfunction	✓	
Functional flaws of PCU	✓	✓
Malfunctions of motor sensors	✓	
Functional or communication flaws of charger		✓
Unusual conditions of 48 V batteries	✓	✓
Malfunctions of junction unit	✓	✓
Unusual conditions of down regulator	✓	

✓: to be checked

(3) System standby

The PCU checks for any malfunctions in the components listed in Table 1 and then puts the high-voltage system into its standby state (for details, see Section 3.2. “PCU”).

(4) Start charging

Charging of the two 48 V batteries connected in parallel commences.

As mentioned above, the system uses 48 V batteries to supply the drive power, while the PCU controls the entire power system of the vehicle in the run and charge modes.

3.2. PCU

The following paragraphs give the details of the PCU functions.

In run mode, the PCU controls the main contactor to series-connect the two 48 V batteries to provide a system voltage of 96 V, as shown in Fig. 9. As this system can reduce the drive current compared to a 48 V system of the same power, it has the following advantages:

- The power loss in the high-voltage cable that connects the battery to the PCU is reduced by about 60%, contributing to the overall efficiency of the system.
- The cross-section of the cable is reduced by about 25%, contributing to weight and space reduction.

When charging from an external power source, the PCU controls the relays to connect the two batteries in parallel to set up the 48 V system voltage, as shown in Fig. 10. In this way, uniform charging is made possible even when the remaining charge in the two batteries differs.

Although two batteries of the same specification are

used as previously mentioned, it is necessary to individually monitor the condition of each battery, e.g., remaining charge and temperature, in order to properly adjust the motor power.

For this, the PCU assigns a CAN ID to each battery during the vehicle startup sequence to enable identification of the data transmitted from each battery. Figure 11 provides the flow chart of battery ID assignment.

Thus, the PCU continuously monitors the status of each component and controls the motor power, provides vehicle safety controls, and sends information to meter unit, thereby providing centralized control of the entire vehicle system.

3.3. Motor

In order to enhance the efficiency of the motor over a wide rotation range, we used an interior permanent magnet (IPM) structure consisting of both magnetic torque and reluctance torque. This is because very high performance is required of the motor of the PCX as compared to the motor of the EV-neo which has the same rotor-stator configuration,

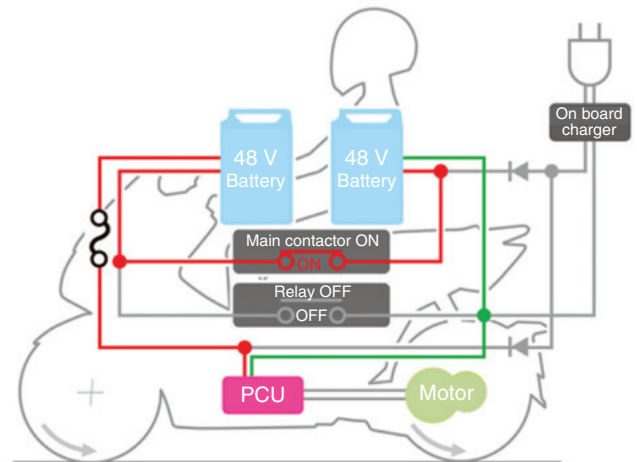


Fig. 9 Diagram of 96 V system

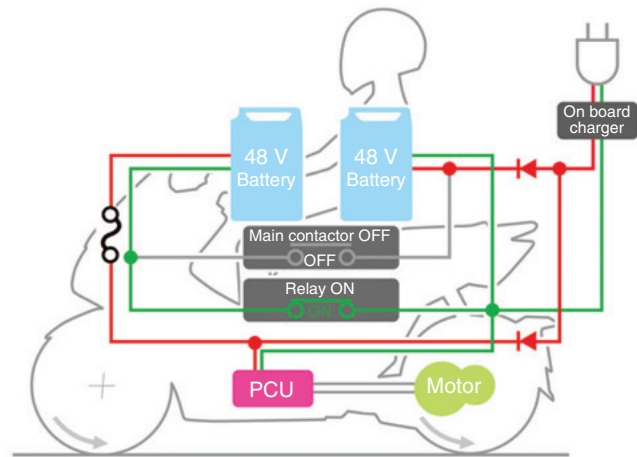


Fig. 10 Diagram of 48 V system

Table 2 Comparison of motor specifications

	EV-neo	PCX ELECTRIC
Rated power (kW)	0.58	0.98
Maximum power (kW)	2.8	4.2
Maximum torque (Nm)	11	18

as show in Table 2. We enhanced the performance by changing the stator coil diameter, number of coil turns, and core thickness and by using the new battery system described later in the paper in order to achieve a maximum motor power of 4.2 kW.

In general, high-power motors require a proper cooling system that consists of additional components such as an oil

pump, radiator, clutch, and so on. However, as our aim was to realize a compact and lightweight motor for this model, we managed at a system without such a motor cooling system, as shown in Fig. 12.

As shown in Fig. 13, a motor torque of 18 Nm is assumed for the low rotation range to help ensure sufficient startup acceleration and hill-climbing power. As the phase current is generally proportional to the torque, a very high phase current delivered during a low-rotation run or prolonged motor stalling can excessively raise the motor temperature and result in damage to the motor.

To help prevent this, we used a thermistor at the stator's coil end to enable the PCU to sense the coil temperature and reduce the output power when the temperature exceeds a threshold, as the first-stage protection. Then, if the coil temperature further increases, the PCU cuts off the power as the second-stage protection.

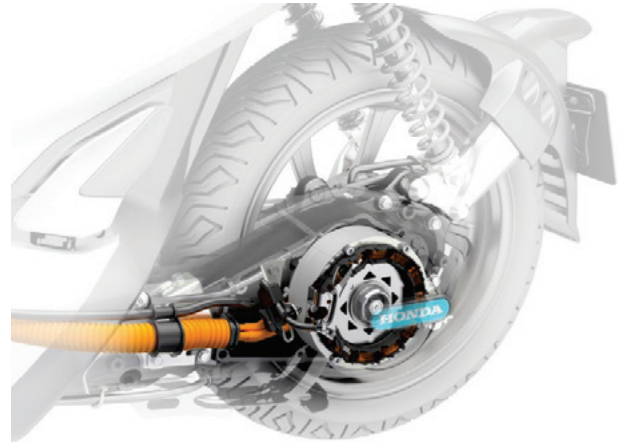


Fig. 12 Motor structure

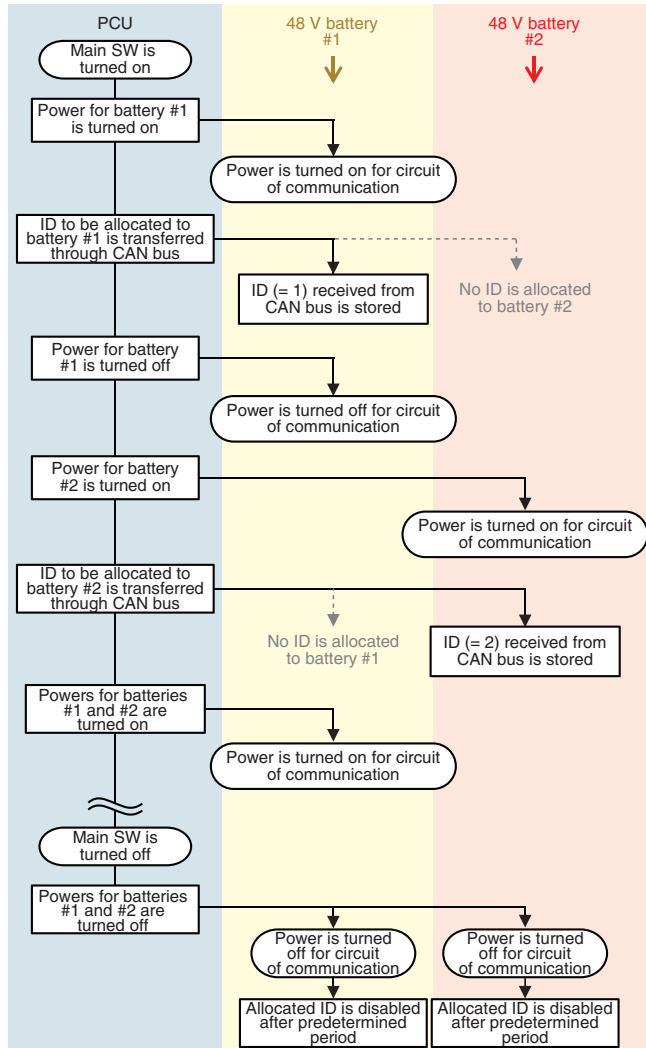


Fig. 11 Flow chart of battery ID assignment

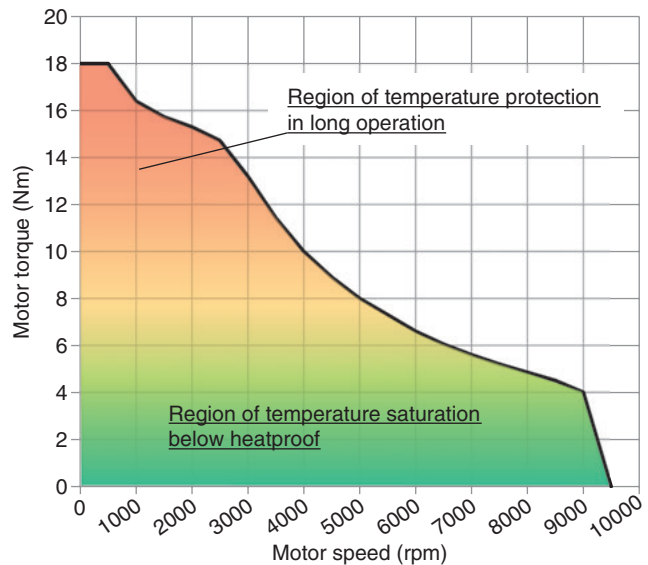


Fig. 13 Torque characteristics of motor

For this, we used a simple bolt-on structure to secure the thermistor for easy maintenance. As shown in Fig. 14, the flat spring structure of the thermistor stay presses the temperature sensing point of the thermistor against the motor coil to realize reliable temperature sensing.

3.4. Battery

We developed a new removable battery “Honda Mobile Power Pack™” which is compact, robust, and stylish as well (Fig. 15). Table 3 provides the basic specifications for

Table 3 Basic specifications of removable battery

Voltage	50.4 V
Capacity	1,052 Wh Min
Volume	7.1 L
Outside dimension (H × W × D)	296 mm × 178 mm × 155 mm
Weight	10.9 kg Max

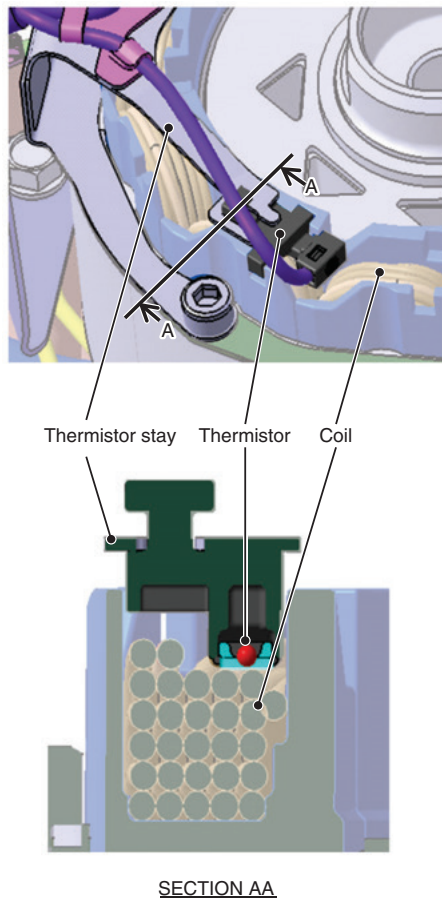


Fig. 14 Motor thermistor structure



Fig. 15 Honda Mobile Power Pack™

the removable battery.

As shown in Fig. 16, we tripled both the volumetric energy density and gravimetric energy density of the battery of the EV-neo through the efficient layout of the cells, battery connector, BMU, and other components. In this way, we realized a compact battery size for easy accommodation in the body of the PCX EV. For a smart appearance without exposed nuts and bolts, we used a three-piece structure consisting of an aluminum extrusion housing and top/bottom covers. In addition, for convenient hand-carrying of the batteries, we added a T-shaped handle to allow the unit to be held in a variety of ways, as shown in Fig. 17.

The connector is required to pass a large current while withstanding frequent engagement and disengagement operations. To satisfy these tough requirements, we newly developed a multiple-contact connector that can allow self-adjustment of the contact pressure, mating position, and insertion angle, as shown in Fig. 18. This connector showed stable electric characteristics even after exceeding the engage/disengage test of 10,000 cycles defined in IEC 62196, which specifies the requirements for battery-charging connectors of electric vehicles, giving it a high durability compared to that of typical connectors of the

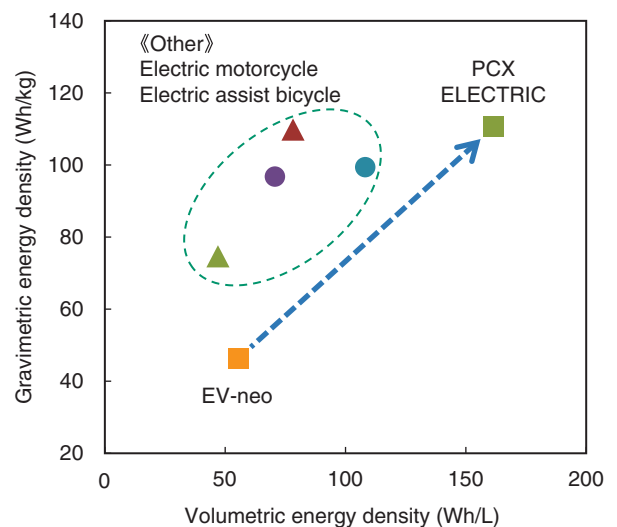


Fig. 16 Comparison of energy densities

same shape. We also achieved a connector current-carrying capacity of 50 A.

Furthermore, due to the nature of portable batteries, a waterproof, anti-drop housing was also required for the battery unit itself.

Therefore, we provided a waterproof structure inside the housing so as not to lose waterproofness even if the housing were damaged and, in order to protect the battery from the shock of being dropped, we applied the measures described in the following paragraphs.

To reduce the shock on the internal battery cells and BMU substrate that could be received through the external housing, we used a shock-absorbing structure inside the battery pack. To help avoid the addition of separate shock-absorbing devices that would make the unit less compact, we used a shock-absorbing structure that had slits in the



Fig. 17 Methods of hand-carrying battery

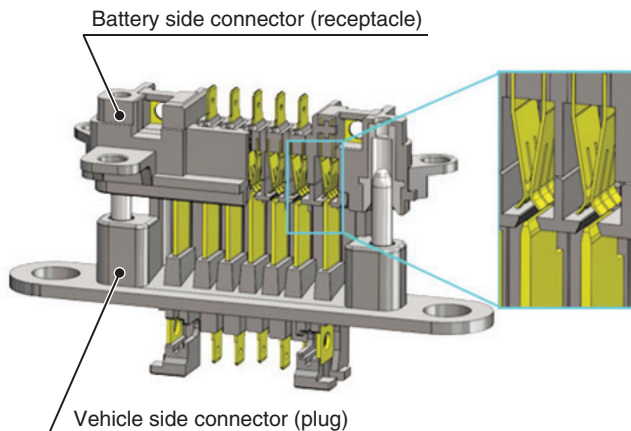


Fig. 18 Internal structure of connector

outer shell of the cell holder of each lithium ion cell, as shown in Fig. 19(a). It was also important to help prevent any internal resonance due to vibration during running. However, the issue is that shock absorption and avoidance of resonance are mutually contradictory. To address this issue, we used a CAE analysis to determine the shock absorption characteristics due to slit deformation and the results of actual vibration/resonance tests to derive the spring characteristics (spring constant) that could satisfy both the shock absorption and resonance avoidance requirements. Accordingly, we realized the desired spring characteristics by properly setting the width and spacing of the slits. Figure 19(b) shows an example of the CAE analysis of the slit deformation. As a result, in the 1 m drop test prescribed in UN R 136 Part 2, no fire or smoke was generated, so that safety could be secured and durability against running vibration was realized at the same time.

As it is not easy for a compact portable battery to have a built-in cooling system, e.g., forced air cooling, self-heating due to charging and discharging would be issues. For this, we optimized the cell layout, the positioning of thermal conductive sheets, and the amount of potting to realize highly efficient heat dissipation through the aluminum housing. Through these efforts, we realized a natural air cooling system that can allow a power output of 2.5 kW for a continuous 10 minutes at an ambient temperature of 40 °C, as shown in Fig. 20.

An additional and significant benefit of this cooling system is the extended service life of the battery, in terms of charge/discharge cycles, due to the reduced cell temperature.

3.5. Battery Attaching Mechanism

The battery attaching mechanism must have functions to secure the battery in place and to help ensure reliable mating of the connectors. These two functions are detailed below.

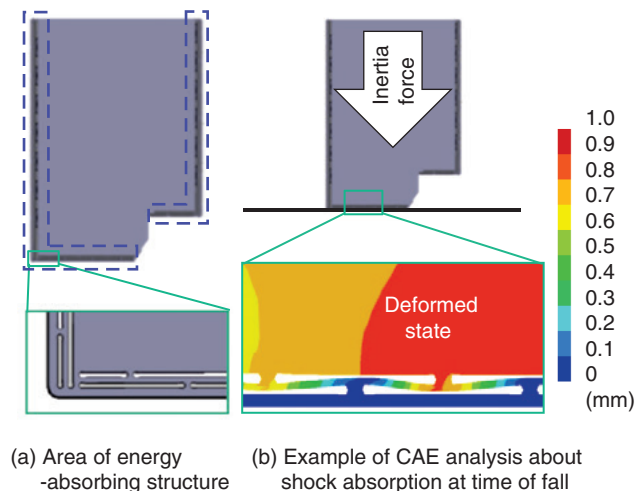


Fig. 19 Shock-absorbing structure for battery

3.5.1. Securing the battery on the vehicle

Figures 21 and 22 show the battery attaching components and their principles of operation. When the user rotates the lock plate around its pivot, the interlocking battery holder also rotates and presses down the battery to secure it in place.

To help prevent the lock plate from being rotated back by the force on the battery due to vibration during running, we set both pivot axes at right angles to each other and made a flat contact surface between the lock plate and

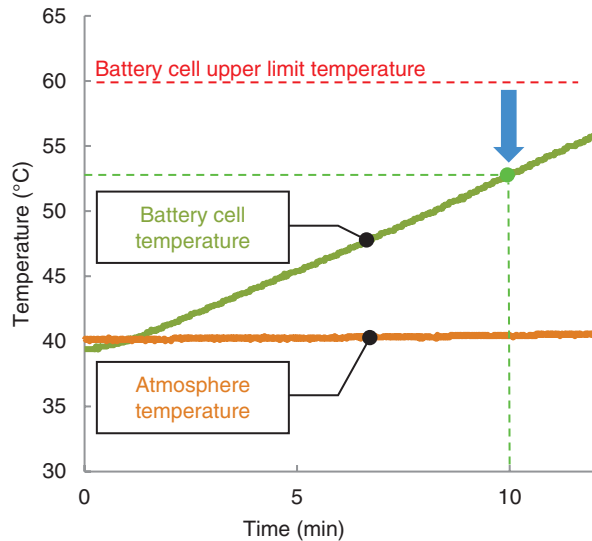


Fig. 20 Temperature of battery cell at 2.5 kW discharge for 10 min

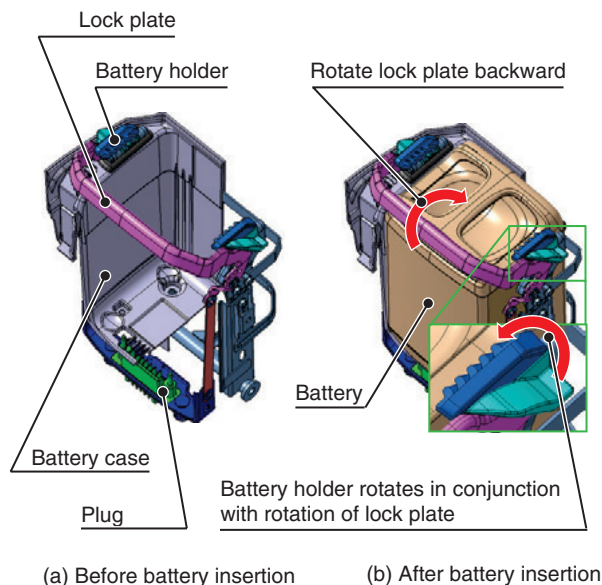


Fig. 21 Structure and operating principle of battery attaching system

battery holder when the battery is secured in place, as shown in Fig. 23.

3.5.2. Connector engagement

Figure 18 shows how the battery connector (receptacle) is mated with the connector (plug) on the vehicle. In order to help prevent the load when inserting the battery from being applied to the plug and the receptacle, the plug is disposed below the bottom of the battery box. Consequently, no mating action can take place when the battery is inserted.

When the lock plate is rotated, the interlocked plug holder moves up to engage the plug and receptacle for the first time as shown in Fig. 24. The plug is float-mounted onto the plug holder via springs to absorb positional errors due to the mechanical allowances of various components, as shown in Fig. 25. In addition, as the springs will always press the plug onto the receptacle, a reliable connection is maintained during running.

With the mechanism described above, we successfully implemented a single-action operation of the lock plate to secure the battery in place with the battery holder and reliably mate the connectors by raising the plug holder at

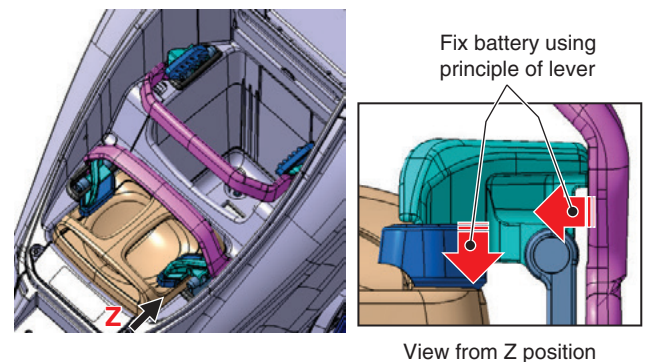


Fig. 22 Operation of lock plate to secure battery in holder

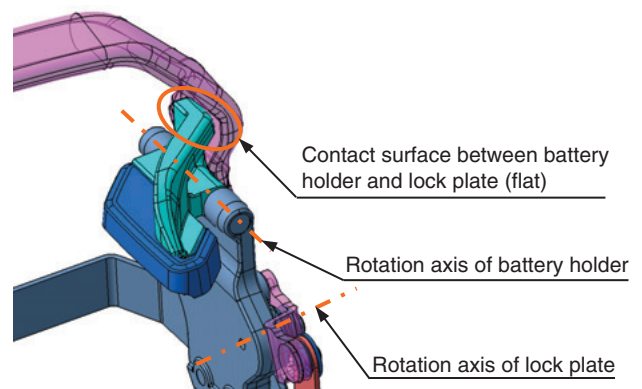


Fig. 23 Battery holder and lock plate pivoting axes and their contact surface

the same time. We also added under-seat stoppers to help prevent the lock plates from being disengaged while the seat is closed. These stoppers provide added reliability in securing the batteries in place and in constantly mating the connectors as shown in Fig. 26.

3.6. Charging System

We provided two methods for charging the batteries.

The first method involves charging the batteries while they are mounted on the vehicle by connecting the AC cable contained in the body to an external power source, as previously mentioned. Using this method, it takes about six hours to fully charge the two batteries connected in parallel.

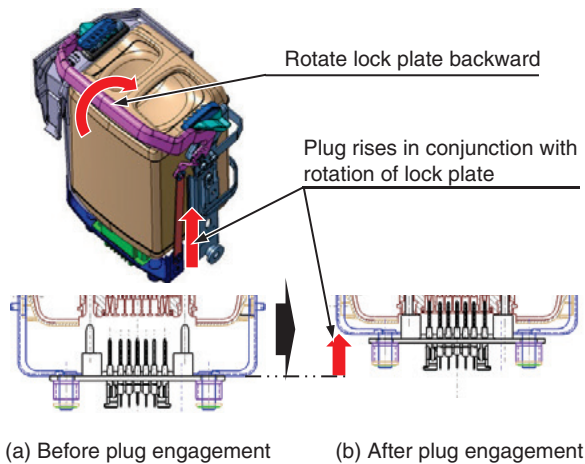


Fig. 24 Connector engaging operation

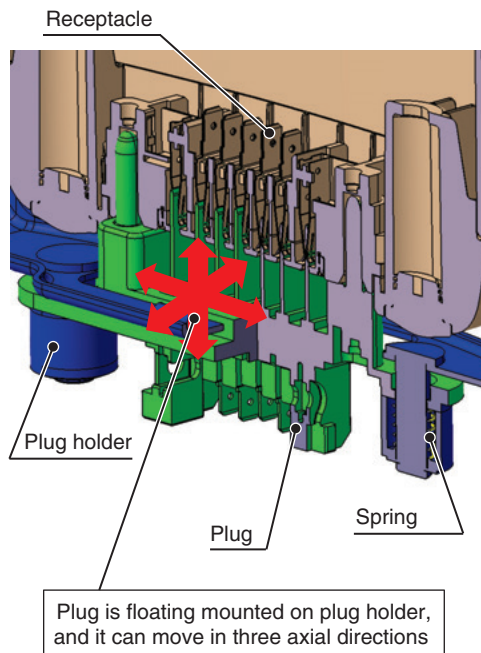


Fig. 25 Floating mount system of plug

The charging status can be checked with the indicator of the meter unit.

The second method involves charging the batteries after removing them from the vehicle. In this case, the removed batteries are connected to the special charger shown in Fig. 27, which is connected to an external power source. This method takes about four hours to fully charge a battery. Charging status can be checked with the special charger indicator. To help prevent unwanted loading on the plug and receptacle during insertion of the battery into the special charger, we used a movable bottom plate supported by oil dampers. As these oil dampers allow the inserted battery to slowly descend to the bottom, the plug and receptacle can be engaged without being subjected to excessive force, as shown in Fig. 28. Similar to the onboard connector mating mechanism, the plug of the special charger is float-mounted.

By providing the above two charging methods, we enabled users to freely choose either method according to their lifestyle, i.e., onboard charging using an outdoor AC

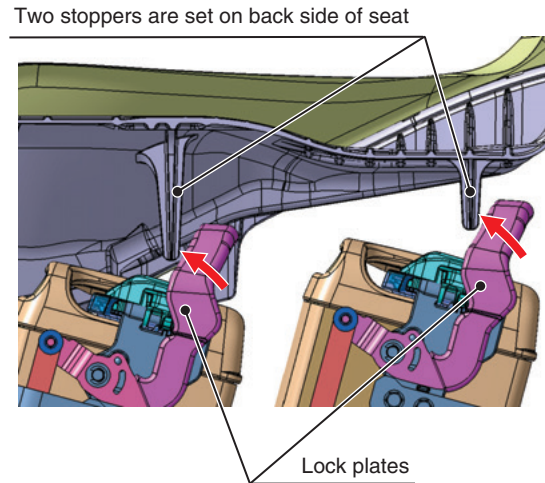


Fig. 26 Under-seat stoppers of lock plates



Fig. 27 Special charger for Honda Mobile Power Pack™

outlet, if available, or indoor charging of batteries removed from the vehicle.

3.7. Vehicle Packaging

By implementing a compact EV system, we were able to integrate the system in an equivalent body size to that of the PCX gasoline-based model to provide a comfortable, high-quality ride.

3.7.1. Dimensions and riding position

In order to retain the comfortable riding position of the existing PCX models, we used the same body cover and seat, placing the two batteries in tandem under the seat and installing the battery removal mechanism in the vehicle frame. In addition, to help ensure that there would be enough space between the rear battery and swinging rear wheel, we increased the wheelbase by 65 mm compared to that of the gasoline-based PCX model. Despite this modification, we only increased the overall vehicle length by 35 mm because we specially designed an unsprung rear fender for better handling in push-walking and for running the motorcycle in urban areas. Table 4 provides the main specifications of the PCX ELECTRIC.

3.7.2. Frame and power unit hanger

In order to use the frame manufacturing facility for

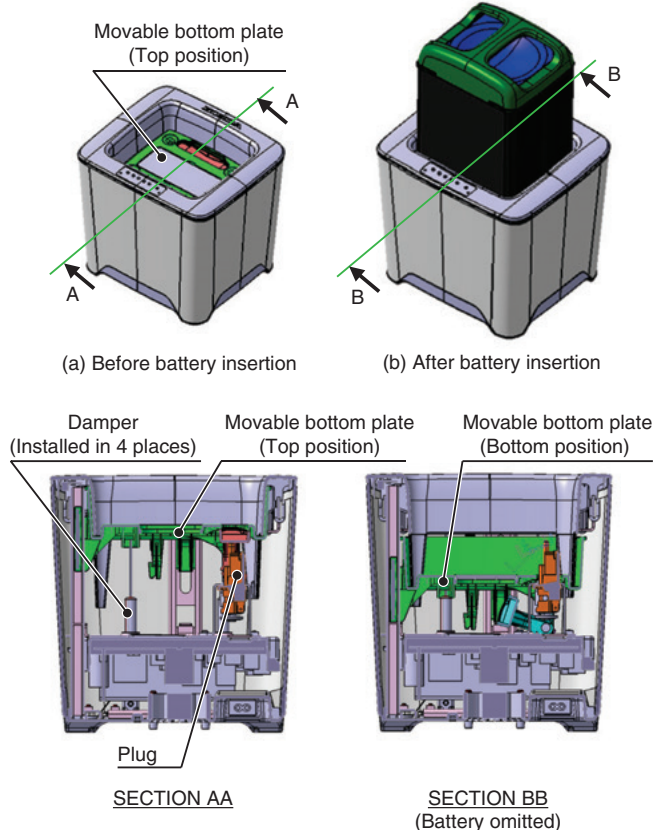


Fig. 28 Structure of special charger

Table 4 Specifications for PCX ELECTRIC

Dimensions L x W x H (m)		1.960 x 0.740 x 1.095
Wheelbase (m)		1.380
Ground clearance (m)		0.132
Seat height (m)		0.760
Vehicle curb mass (kg)		144
Rated power (kW)		0.98
Maximum power (kW/rpm)		4.2/5,500
Maximum torque (Nm/rpm)		18/500
Cruising range at 60 km/h (km)		41
Main battery	Type	Lithium ion
	Battery (V) / (Ah)	50.4 V / 20.8 Ah x 2
Tire size	Front	100/80-14M/C 48P
	Rear	120/70-14M/C 55P

the PCX for the PCX ELECTRIC as well, we retained the positions of the pivot on the frame, bottom of the head pipe, and rear suspension mount to maintain the basic structure. Also, as it was also our intention to maintain the same handling performance despite the 65 mm extension of the wheelbase and weight increase of 13 kg, we specially designed the power unit hanger shown in Fig. 29 from which to suspend the minimized-size power unit. For this, we also used rubber bushings for the fore and aft mounts to absorb inputs from the road surface. In addition, we further optimized the rigidity of the frame and setting of the front and rear suspensions in order to offer high-quality riding comfort by making the most of the inherently low-vibration EV power unit and the excellent handling performance that is equivalent to that of the PCX. Above all, we were able to achieve a maximum speed of 60 km/h and cruising ranges of 57 km (according to an internal test equivalent to the WMTC mode) and 41 km (at a steady 60 km/h).

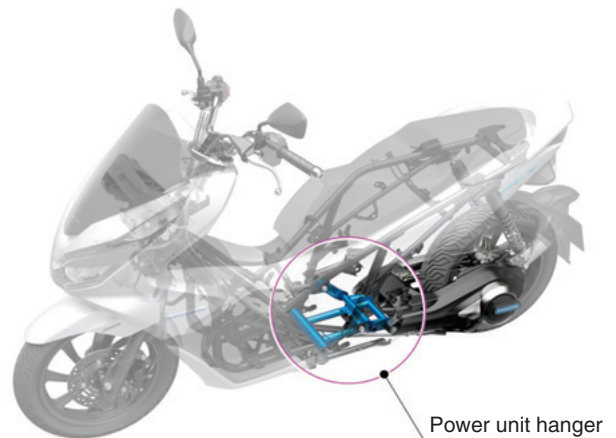


Fig. 29 Power unit hanger

4. Styling Design

4.1. Styling

We retained the styling of the 2018 PCX and PCX 150. Accordingly, based on the styling concept “beautiful and powerful,” we took the main body color portion as a single large form and incorporated tension and softness into it to represent high quality and innovation, as shown in Fig. 30.

In addition, in order to add a unique feature to the PCX ELECTRIC, we applied a special design around the power unit, as shown in Fig. 31.

The round-shaped motor cover, which was designed to symbolize and stress the presence of the electric motor, together with the special plastic rear fender supported by aluminum parts mounted on the unsprung portion emphasize the specialness of the EV among the other PCX series models.

4.2. Color

In order to represent the cleanness and specialness of the EV, we selected pearl white as a special coloring and candy blue as an accent color.

4.2.1. Lamps

The headlight (Fig. 32) and tail lamp (Fig. 33) are the same as the ones used for the PCX HYBRID. However, we used a blue color for the bracket on the back side of the signature lights for the headlight and for the inner lens



Fig. 30 Side view



Fig. 31 External view of power unit

of the stop lamp in order to show the blue color when the lamps are turned off.

4.2.2. Emblem

We used candy blue for the PCX emblem to be recognized immediately as the Honda EV, as shown in Fig. 34. We also used an exclusive emblem for ELECTRIC, as shown in Fig. 35.



Fig. 32 Headlight



Fig. 33 Tail light



Fig. 34 Emblem of PCX



Fig. 35 ELECTRIC exclusive emblem

5. Summary

We developed the electric motorcycle model “PCX ELECTRIC” with the aim of offering better usability in urban areas of Japan and three ASEAN countries, i.e., Thailand, Vietnam, and Indonesia.

By using a removable battery system, we practically helped to eliminate the traditional issue of the waiting time associated with charging the battery. Also, by using a 96 V EV power system to connect two 48 V battery packs in series, we achieved a maximum speed of 60 km/h and a cruising range of 57 km (according to an internal test equivalent to the WMTC mode) and 41 km (at a steady 60 km/h). Through these efforts, we were able to develop an advanced electric motorcycle for Japan and ASEAN countries that meets UNR 136.

Lastly, we would like to mention that the PCX ELECTRIC will be used in various field trials in Indonesia and other countries. We will also continue our efforts to verify the concept in order to move toward a world that can “generate, connect, and use”⁽⁵⁾ electricity through the use of the Honda Mobile Power Pack™.

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Downsizing Technology for FC Cooling System Installation under Front Hood

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ABSTRACT

Technology for downsizing the fuel cell cooling system was developed in order to realize installation of the fuel cell power plant under the front hood of the CLARITY FUEL CELL. The fuel cell stack was downsized by accurately estimating the amount of corrosion current by using technology for predicting corrosion of the metal separator, decreasing the conductivity of the coolant, and removing the insulation rubber from the cell. For the fuel cell cooling device, the conductivity of the coolant was set within a range that would enable piping to be shorter and not necessitate the large-scale coolant pump used when a pressure drop increase occurred. In the fuel cell cooling system, the conductivity of the coolant was decreased within the range that would make a large contribution to downsizing the fuel cell stack and the fuel cell cooling device. In order to decrease the conductivity of the coolant, a fuel cell cooling system was built that would decrease ion dissolution from parts, inhibit degradation of the coolant, and constantly remove dissolved ions. These measures achieved a fuel cell cooling system that was downsized 20% over the previous model and succeeded in realizing the world's first five-passenger fuel cell vehicle in a sedan package.

1. Introduction

The CLARITY FUEL CELL, a new model fuel cell vehicle (FCV) introduced in 2016, was developed with the aim of achieving the first five-passenger FCV in the world to offer a sedan package identical to vehicles with an internal combustion engine (ICE). For that purpose, the fuel cell (FC) power plant was downsized from the 2009 model year (09MY) so that it could be relocated from under the floor to under the front hood⁽¹⁾ (Fig. 1). That advantage enabled realization of a five-passenger vehicle in the same way as ICE vehicles, and also eliminated the necessity



Fig. 1 Schematic drawing of FC power plant for new CLARITY FUEL CELL

for development of a dedicated FCV car body. Achieving this necessitated downsizing the FC power plant while enhancing the shock resistance to a level four times greater than in the 09MY. This was highly challenging in terms of technical difficulty⁽¹⁾.

This paper introduces the downsizing of the FC cooling system as one of the technologies applied in downsizing the 2016 model year (16MY) FC power plant.

2. FC Cooling System Downsizing Target and Issues

2.1. FC Cooling System Configuration

Figure 2 shows a diagram of the FC cooling system, including the FC stack installed in the CLARITY FUEL CELL.

The FC cooling system is made up of FC stack and FC cooling devices for radiating the heat generated in the FC stack to the outside.

2.1.1. FC stack

Figure 3 shows the configuration of the FC stack examined in this paper.

The FC stack shown in (a) was constructed with

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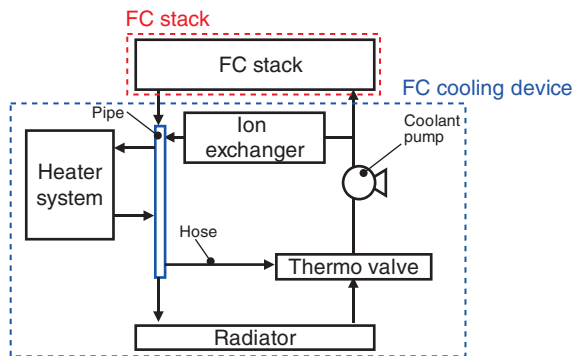


Fig. 2 Schematic diagram of FC cooling system

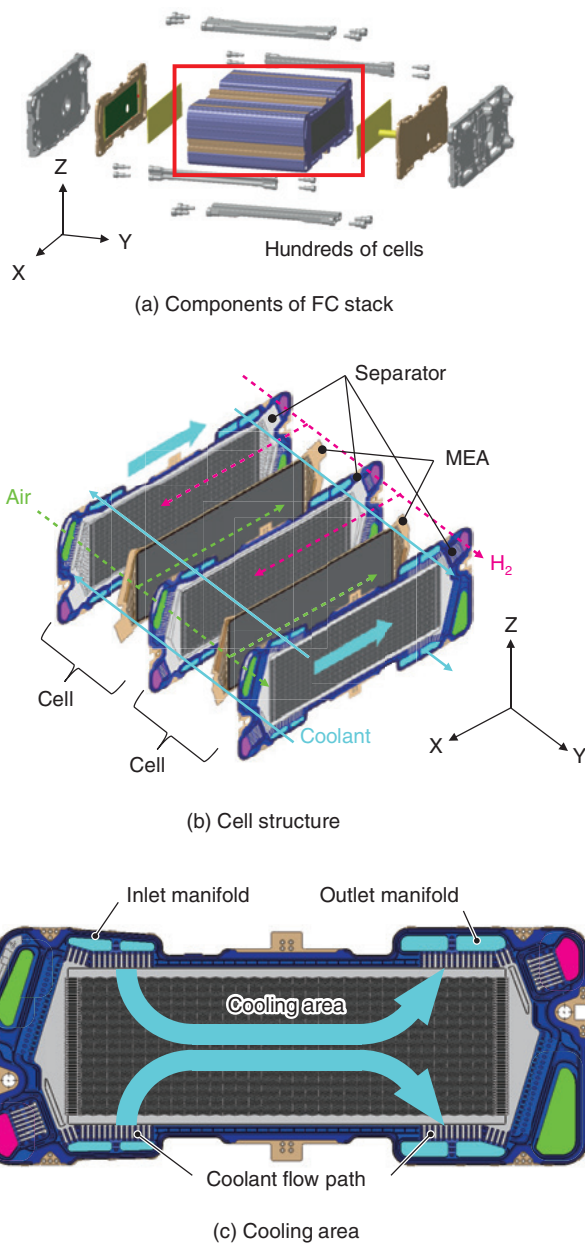


Fig. 3 Inside of FC stack, cell component, and cooling area

hundreds of cells stacked in layers in order to supply the electric power needed to assure the vehicle's dynamic performance. The cell structure shown in (b) has two membrane electrode assemblies (MEA) held in place by three metal separators⁽²⁾. A structure that has coolant flowing through every pair of cells was adopted.

The polymer electrolyte fuel cells adopted in the FCV form a system that uses electrolyte membranes to cause an electrochemical reaction between the hydrogen from the fuel and oxygen from the air, and converts the resulting chemical energy directly into electrical energy. The heat generated during the electrochemical reaction is exchanged with the coolant that is circulated in the cooling device by means of the metal separators and the heat is discharged. As shown in (c), the coolant passes from the coolant manifold on the inlet side through the coolant flow path, is supplied to the cooling area, then passes through the coolant flow path to the coolant manifold on the outlet side and is discharged.

2.1.2. FC cooling device

As shown in Fig. 2, the FC cooling device was configured with a coolant pump that circulates coolant, a radiator that radiates heat to the outside, and a thermo valve that switches the circuit between the radiator and a radiator bypass circuit. An ion exchanger has been adopted from before to help assure electrical safety in the vehicle and help prevent corrosion of the FC stack by removing ions that are in the coolant. It is a device that is widely adopted in fuel cell cooling systems. The exhaust heat recovery circuit is installed for the purpose of raising fuel economy at lower temperatures by recovering heat from the FC stack through the coolant and supplying it to the heater system circuit.

2.2. Target and Means of Accomplishment of FC Cooling System Downsizing

In order to make it possible to install the FC power plant under the front hood, the aim of making the FC power plant volume the same as that of a V6 engine was adopted⁽¹⁾. Therefore the work of downsizing the FC cooling system was examined in terms of approach both from structure and from function. The aim of decreasing the volume of the FC stack by 20 percentage points from the 09MY by revising the coolant flow path structure while maintaining the functionality of the FC cooling system was adopted.

The FC stack is made up of hundreds of cells. Decreasing the cell thickness contributes greatly to downsizing. Therefore, attention was focused on removing the rubber insulation covering that is a component of cell thickness.

Figure 4 shows the coolant flow path structure in the 09MY and 16MY FC stack. A front view of the 09MY and 16MY cooling area is shown first. The change in the height of the cooling flow structure and the change in the coolant flow path distance from the manifold due to the rubber insulation covering are shown next.

The 09MY coolant flow path was built to help prevent

corrosion of the metal separator by covering the left and right sides and top and bottom of the coolant flow path with insulation rubber. The structure of the 16MY coolant flow path, by contrast, has reduced the insulation rubber placed on the top and bottom. The height h_{16MY} of the coolant flow path was also set to be the same as the height h_{09MY} . As a result, cell thickness has been decreased by two layers of rubber covering without increasing the pressure drop in the coolant flow path.

With regard to cell area, too, the length l_{16MY} from the manifold to the metal surface that is covered by insulation rubber in 16MY is shorter than the length l_{09MY} in 09MY. This reduced the cell area.

These revisions of structure realized a 20% downsizing of the FC stack volume.

2.3. FC Cooling System Function

Table 1 shows the three functions demanded of the FC cooling system together with parameters influencing those functions and the issues involved in downsizing.

FC stack cooling performance is determined by the coolant flow rate into the FC stack and radiator and by the amount of heat radiated to the outside, which is determined by the heat exchange efficiency of the various parts. When downsizing measures are taken with the coolant pump and radiator, the coolant flow rate and the amount of heat

Table 1 Three functions for FC cooling system

Function	Parameters	Issues of downsizing
Stack cooling	• Coolant flow • Heat exchanger rate	Decrease in cooling performance
Insulation	• Insulation resistance • Coolant conductivity	Decrease in insulation resistance
Corrosion resistance	• Cell thickness • Insulation distance • Coolant conductivity	Increase in metal corrosion

radiated to the outside are reduced, which lowers cooling performance. Therefore it was decided not to implement downsizing at the component level, but rather to achieve it by shortening the piping length.

The FC cooling system needs to have insulating properties that maintain the electrical safety of the vehicle. These depend on the length of the piping that connects the FC stack and the ground and on the conductivity of the coolant. As noted above, downsizing shortens the piping length and this lowers the insulation resistance value. In order to assure the needed insulation resistance value, therefore, the coolant conductivity has to be made still lower than in the previous model.

The oxidation-reduction reaction that occurs in the coolant flow path on the metal separator, shown in Fig.

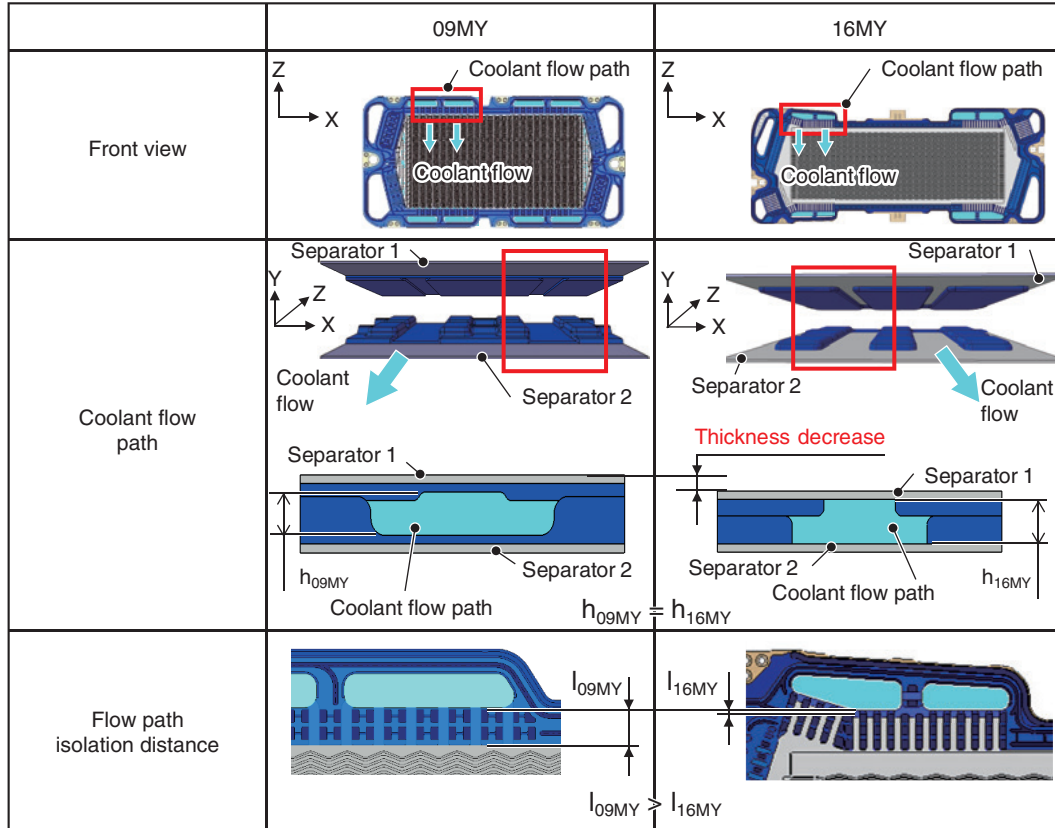


Fig. 4 Detail of coolant flow path

5(a), causes corrosion of the metal separator. The corrosion resistance of the FC separator inhibits that corrosion, and this is needed to maintain the strength of the separator.

The coolant flow path, shown in Fig. 3(c), contains coolant, which is an electrical conductor. It is, therefore, not possible to help prevent the formation of a circuit by structural means.

As shown in Fig. 5(b), corrosion of the metal separator occurs where there are exposed stainless steel portions along the coolant flow path. The main reaction is to cause dissolution of steel, which is the principal component of stainless steel, on the high potential side (1), while hydrogen is generated by the oxidation-reduction reaction on the low potential side (2).

Reaction formula on high potential side: $\text{Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^-$ (1)

Reaction formula on low potential side: $2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2$ (2)

As dissolution occurs in the stainless steel material in the coolant flow path, the strength of the material is diminished so that deformation may occur due to the pressure differential and pitting corrosion may occur.

When cell thickness and insulation distance are decreased for the purpose of downsizing the FC cooling system, the electrical resistance in each part is reduced so

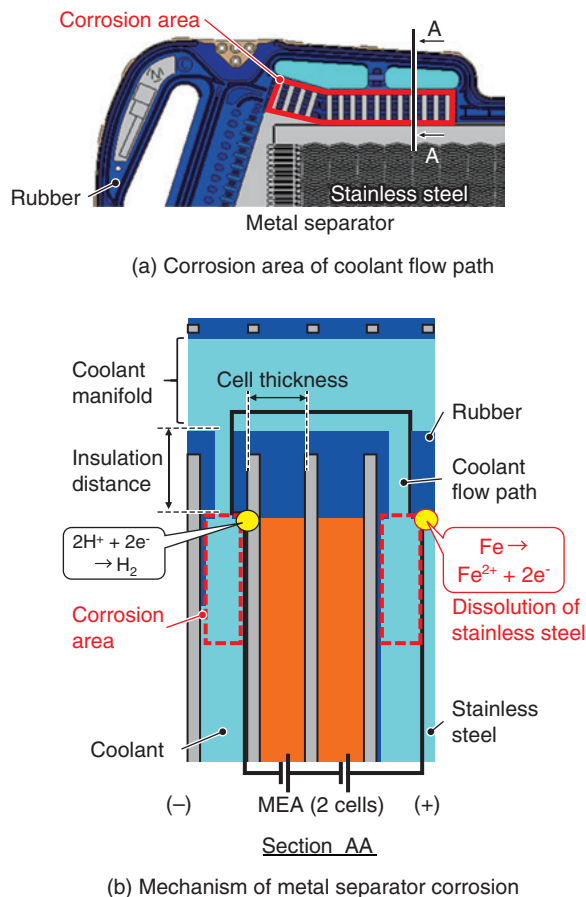


Fig. 5 Outline of metal corrosion

that the amount of corrosion current flowing in the coolant flow path is increased. This accelerates corrosion of the metal separator. Lowering the coolant conductivity would be useful for realizing downsizing and effective corrosion resistance in the metal separator.

Figure 6 shows an equivalent circuit diagram that was considered for the purpose of accurately calculating the amount of corrosion current in this FC stack.

The current flowing in the coolant manifold is designated I_A , the current flowing in the coolant flow path I_B , the resistance of the coolant manifold R_A , and the resistance of the coolant flow path R_B .

This equivalent circuit was used to calculate the largest corrosion current, $I_{B(n+1)}$ ⁽³⁾. Figures 7, 8, and 9 show the cell thickness ratio, insulation distance ratio, and coolant conductivity ratio on the horizontal axis, and the corrosion current ratio on the vertical axis, to show the influence of the former on the latter when 09MY is taken as 100%. Figure 7 indicates that when the cell thickness that is subject to downsizing in the Y direction, shown in Figs. 3 and 4, is decreased 20 points, the resistance R_A becomes smaller so that the corrosion current $I_{B(n+1)}$ increases 14 points. Figure 8 indicates that when the insulation rubber is removed so that downsizing can take place in the Z direction shown in Figs. 3 and 4, and the insulation distance is decreased 79 points, then the amount of corrosion current will increase 113 points. The increase in the corrosion current is brought about by these decreases in cell thickness and insulation distance. The influence of the number of layers in the FC

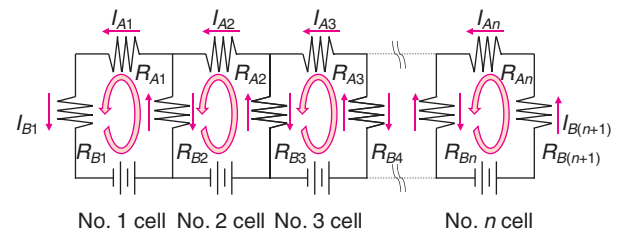


Fig. 6 FC stack circuit diagram

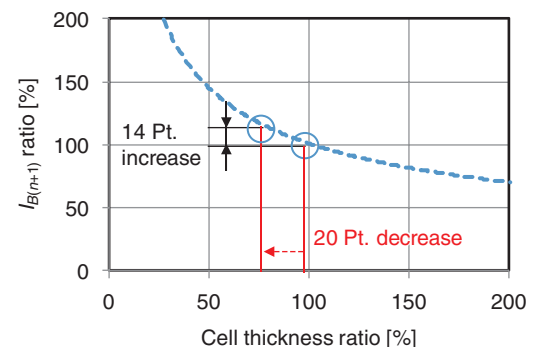


Fig. 7 Influence of cell thickness ratio on $I_{B(n+1)}$ ratio

stack, the sectional area of the coolant manifold, and the operating environment also cause the amount of corrosion current to increase. In order to bring about these decreases, it will be effective, as shown in Fig. 9, to lower the conductivity of the coolant, which contributes greatly to the corrosion current. Therefore the 16MY target was set as a reduction of 59 points in coolant conductivity ratio relative to the 09MY where the corrosion current was increased by the decrease in cell thickness and insulation distance, and a reduction of 37 points in coolant conductivity ratio relative

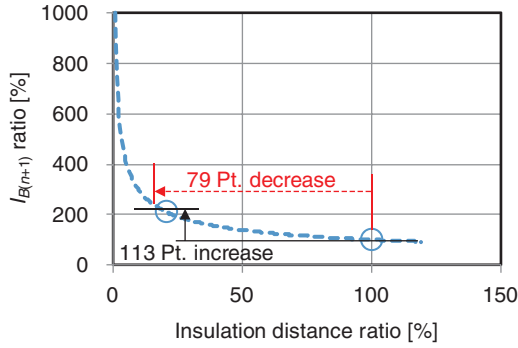


Fig. 8 Influence of insulation distance ratio on $I_{B(n+1)}$ ratio

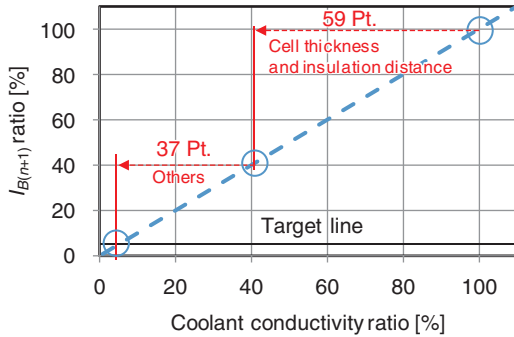


Fig. 9 Influence of coolant conductivity ratio on $I_{B(n+1)}$ ratio

to the 09MY in order to reduce the other amount of increase in the corrosion current.

It was ascertained from the above that the conductivity of the coolant, which influences the volume of the FC stack and the FC cooling device, is a crucial parameter for the purpose of meeting the functional requirement from the FC cooling system. Figure 10 shows the coolant conductivity ratio with respect to 09MY on the horizontal axis while the vertical axis on part (a) has the FC cooling device volume ratio and the vertical axis on part (b) has the FC stack volume ratio. The 09MY is taken as 100% for both the horizontal and vertical axes, and graphs express the contribution that the decrease in coolant conductivity makes to the downsizing of the FC cooling device and FC stack.

As shown by range (1) in Fig. 10(a) for the FC cooling device, when the conductivity ratio is reduced from 100%, the insulation resistance value increases so that the piping length can be shortened, and the volume decreases at a gentle rate. In order to construct an FC cooling system with a coolant conductivity ratio of less than 4% as shown in range (2), it is necessary to place an ion exchanger at the FC stack inlet to remove the ions in the coolant immediately before it flows in. However, placing an ion exchanger at that location causes the pressure drop to increase so that a large coolant pump becomes necessary and, as shown in range (2), the volume of the FC cooling device increases.

Similarly with the FC stack, as shown in range (3) of Fig. 10(b), when the coolant conductivity ratio is reduced from 100% to 4%, the insulation resistance value of the parts where cell thickness and insulation distance are major factors can be decreased. This means that the amount covered by insulation rubber can be reduced and the volume of the FC stack becomes smaller. In range (4), where the coolant conductivity ratio is 4% or less, only the corrosion of the metal separator is decreased and the contribution to downsizing is slight.

Therefore it was decided to achieve the downsizing target for the FC cooling system by setting the coolant conductivity within the range where the contribution to downsizing would be greater.

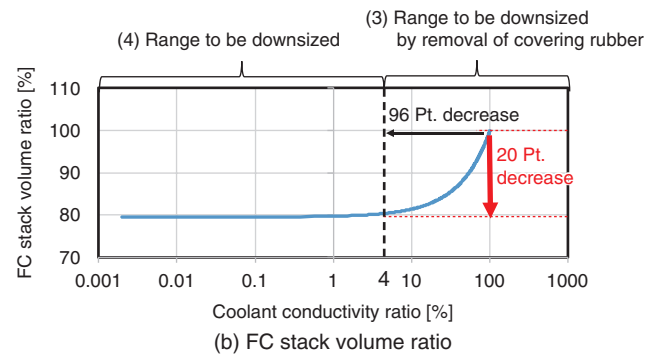
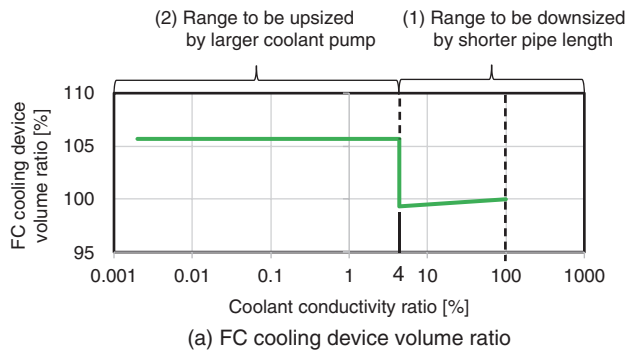


Fig. 10 Volume ratios of FC cooling device

3. Construction of an FC Cooling System with Low Conductivity

The main cause of ion dissolution in coolant is from cooling system parts and heater system parts and generation of ions by degradation of the coolant. Even if measures were taken to decrease the amount of ion dissolution, the dissolution of ions from parts and the generation of ions by degradation of the coolant would occur constantly. In order to maintain the low conductivity of coolant in the FC cooling system, therefore, it will be necessary to address two issues simultaneously.

- (1) Decrease ion dissolution from parts and limit the degradation of coolant
- (2) Build the FC cooling system to constantly remove dissolved ions

3.1. Limit Ion Dissolution Amount

Measures to limit the ion dissolution amount from parts used in the FC cooling circuit were already being implemented in 09MY. The methods are shown in Table 2. Manufacturing methods that involves less ion dissolution were adopted for the radiator. Materials that are subject to less ion dissolution were selected and adopted for the piping and other resin parts and rubber hose. For the coolant, oxidation inhibitor was added in order to limit ion dissolution caused by thermal decomposition.

In contradistinction to the 09MY, the 16MY added a system to take waste heat from the FC stack and make effective use of it for heating. Measures to reduce conductivity thus also became needed for heater system parts. The methods used are shown in Table 3. Here, in contradistinction to ICE specification vehicles, the heater core has low ion dissolution measures taken by means of manufacturing methods while materials that experience less ion dissolution were selected for the piping and other resin parts and rubber hose and adopted as in those other FC cooling parts.

By means of these measures, items that are subject to ion dissolution were successfully reduced by 75 points in the 16MY relative to cases where heater system parts from ICE specification vehicles were adopted. The ion dissolution amount for the FC cooling system as a whole was held down to the same level as the 09MY (Fig. 11).

3.2. Constant Removal of Dissolved Ion Material

When only the measures described above for limiting dissolved ion material are used, maintaining conductivity at a low level is no simple matter. This is particularly the case when a vehicle is left unused for a long time, since dissolved ions build up inside every part. Then when the vehicle is started, coolant with a temporarily high conductivity flows into the FC stack. The necessity to remove ions promptly and lower the conductivity still remains even in such cases. A bypass system configured to keep the coolant constantly flowing through an ion exchanger was adopted as the means

Table 2 Electric conductivity reduction method of FC coolant system

Parts	Method
FC radiator	Adopt flux reduction
Resin parts	Adopt low ion dissolution material
Hose	Adopt low ion dissolution material
Coolant	Add oxidation inhibitor

Table 3 Electric conductivity reduction method for heater system parts

Parts	Method
Heater core	Adopt flux reduction
Resin parts	Adopt low ion dissolution material
Hose	Adopt low ion dissolution material

for accomplishing this aim.

When an ion exchanger is arranged in series with the FC stack, the pressure drop increases in the system as a whole. However, when the ion exchanger is arranged in parallel with the FC stack, as shown in Fig. 2, the pressure drop is reduced so that a smaller coolant pump can be selected. This approach successfully decreased the coolant pump volume by 40 points.

One advantage of configuring a system for constant ion removal is that when the vehicle is warming up, the ions

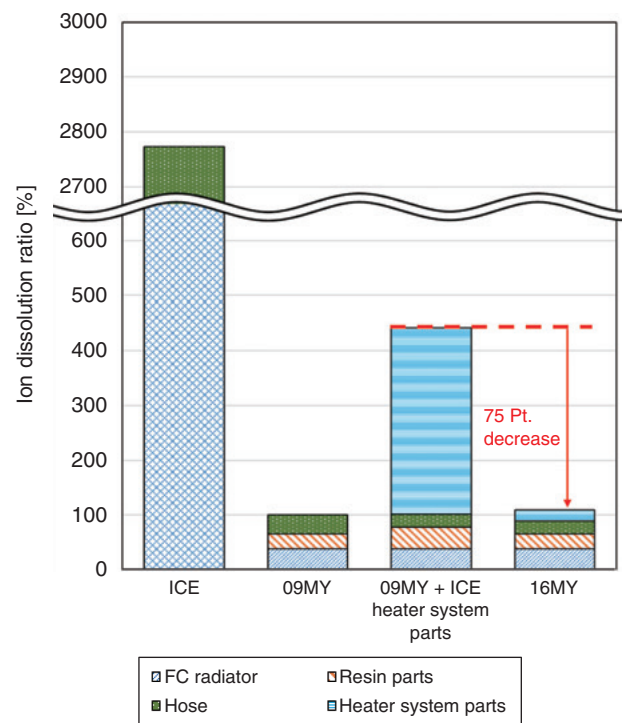


Fig. 11 Ion dissolution ratio in FC cooling system

already inside the radiator bypass circuit can be removed. This means that even if there is an inflow of ions from the radiator circuit after warming up, that inflow can be mixed in so that the range of the increase will be limited.

3.3. Performance in Maintaining Low Conductivity

Figure 12 shows how the FC cooling system incorporating the measures described above performs in maintaining low conductivity. Even in cases where the conductivity rises temporarily, the system quickly restores the lower conductivity again and can maintain that state.

During warming up (Fig. 13), the dissolved ion material that has built up inside the radiator bypass circuit flows into the system immediately after the vehicle is started. This causes the conductivity to rise temporarily. However, the conductivity can be lowered quickly because the coolant is kept constantly flowing to the ion exchanger, and that lower level can be maintained.

After warming up (Fig. 13), the dissolved ion material that has built up inside the radiator circuit flows into the system so that the conductivity rises again. Since the dissolved ion material is constantly removed after that, low conductivity is quickly restored and that lower level can be maintained.

The system is configured to switch between the radiator

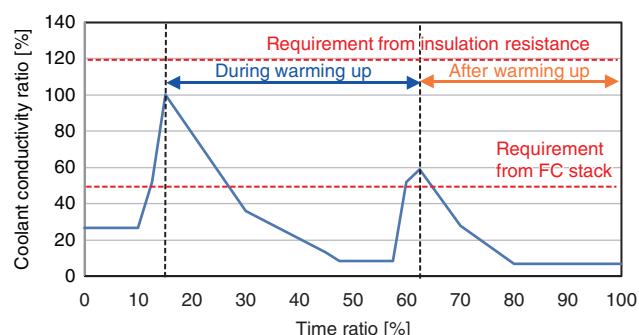


Fig. 12 Performance of keeping low coolant conductivity

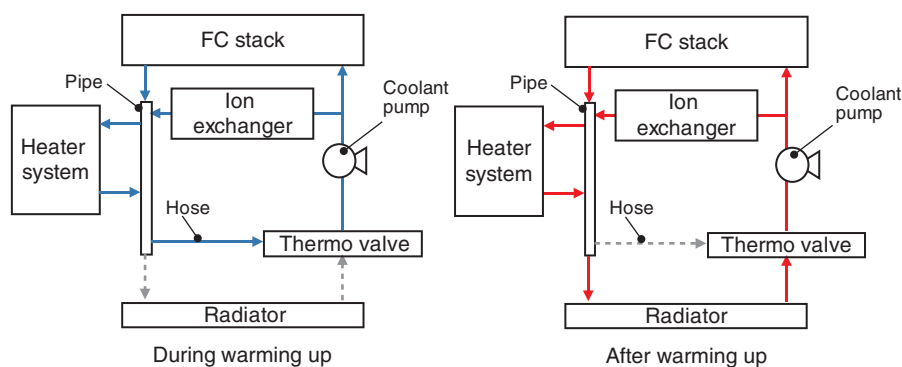


Fig. 13 Diagram of FC cooling system

bypass circuit and the radiator circuit by a thermo valve when the vehicle is warming up and after it has finished warming up. Therefore the dissolved ion material inside the radiator bypass circuit can be removed before the vehicle finishes warming up. Consequently, even if dissolved ion material flows into the system from the radiator circuit after warming up is finished, that material mixes with the coolant, which has a low level of dissolved ion material, so that the range of the increase in conductivity can be limited.

4. Conclusion

- (1) Technology for predicting corrosion of the metal separator was used to accurately estimate the amount of corrosion current and the FC stack was downsized by lowering the conductivity of the coolant and removing insulation rubber from the cells.
- (2) Downsizing of the FC cooling device was achieved by shortening the length of pipes and by setting the coolant conductivity within the range where the pressure drop increase does not necessitate use of a larger coolant pump.
- (3) An FC cooling system was developed to decrease the conductivity of the coolant within the range that would make a large contribution in downsizing the above FC stack and FC cooling device, to decrease ion dissolution from parts, to inhibit degradation of the coolant, and to constantly remove dissolved ions.

The above measures achieved downsizing of the CLARITY FUEL CELL FC cooling system by 20% over the previous model. This made it possible to install the FC power plant under the front hood and thereby to realize the world's first five-passenger FCV in a sedan package.

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Torque Steer Simulation Technology for Performance Design in Model Based Development

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ABSTRACT

A differential gear model was devised that can be used to examine torque steer when the vehicle is launching from standstill in MBD performance design. The model was expanded to enable reproduction of the transient left-right torque bias ratio, which was previously treated as a constant, by adding an element that takes into account the left-right difference in rotational speed derived from uneven torsional stiffness of driveshaft. Conventional methods needed a complex model using a multibody dynamics model. The proposed method uses a simple essential model to express the torque steer mechanism. This enabled analysis of the contribution due to the difference in transient drive torque in MBD performance design. As a result, countermeasure methods could be quantitatively and efficiently examined in performance design in the initial stages of development. The proposed method was applied to development of 2016 model year mass-production vehicles, and its usefulness was confirmed.

1. Introduction

In addition to the basic performances of running, turning, and stopping, automobiles face increasing demands for safety, environmental, and other performances in order to achieve environmentally conscious motorization. However, the mechanisms and structures used to meet these demands are becoming increasingly complex, and shorter development periods and cost reduction are also demanded in automotive development. This is increasing the importance of model-based development (MBD) as a means for efficiently promoting development⁽¹⁾. Figure 1 shows a graphic representation of the mass-production vehicle development process as a V-model. The items for examination in the MBD area enclosed by the red border can be expanded by incorporating the elements of each automotive component into the simulation model⁽²⁾⁻⁽⁴⁾.

Vehicles that use a small displacement turbo engine (compact T/C) in the power unit or which are equipped with an electric motor, such as an EV, are becoming popular as means of enhancing environmental performance. Figure 2 shows an example of the torque performance of these power units. Compared to the conventional naturally aspirated engine, the compact T/C features a supercharging effect that enables production of high torque from a low rotational speed. In addition, the electric motor can produce even higher torque from lower rotational speeds compared to the

internal combustion engines.

In a front wheel drive vehicle, high drive torque when starting from a standstill may pull the steering wheel in a direction not intended by the driver, with the result that the vehicle attempts to turn. This phenomenon is called torque steer, and is generally an anxiety factor for drivers. Typical methods for reducing this torque steer include making the left and right drive shafts the same length, reducing the left-right difference in drive shaft torsional stiffness, reducing the left-right difference in the drive shaft and axle joint angles, shortening the king pin center offset, and so on^{(5), (6)}. In addition, geometry that shortens the king pin center offset

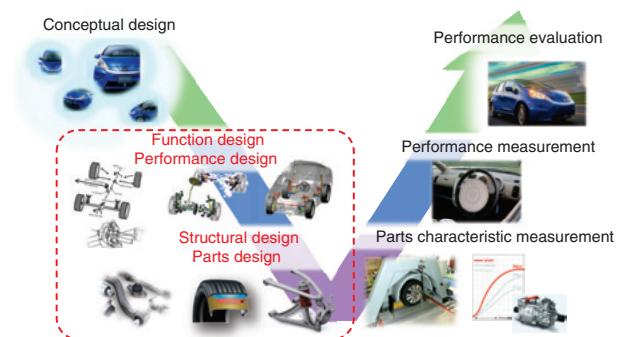


Fig. 1 Positioning of MBD in V-Model process

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is sometimes added to the suspension in vehicles equipped with high torque engines^{(7), (8)}.

In vehicle development, replacement with a compact T/C and mounting an electric motor can enhance both fuel economy and standing start performance, so these trends are continuing to increase. As a result, models with torque steer issues are expected to increase. This calls for development of simulation technology that enables stimulation of the influence of torque steer and formulate countermeasures in the initial stages of development in order to enhance development efficiency.

Torque steer characteristics are simulated by full vehicle model calculations using a multibody dynamics model such as shown in Fig. 3^{(9), (10)}. In analysis using a multibody dynamics model, high calculation accuracy can be obtained by creating detailed component models. However, it takes

much time and work to collect the information needed for modeling and to reflect it in the calculations. Furthermore, it is not easy to get all the information needed for modeling and to change the characteristics of the multibody dynamics model in the initial stages of development.

The left-right torque bias ratio of the differential gear can be treated simply as a constant. In this case, however, the difference in the drive torque distributed to the left and right wheels becomes larger than that in an actual vehicle. This makes it a challenge to simulate the influence of torque steer at the same accuracy as that of other performance design items in mass-production vehicle development.

Therefore, a differential gear modeling method that can be applied to performance design in the initial stages of development was studied by understanding the intrinsic mechanisms by which torque steer is caused.

2. Torque Steer Mechanism

Uneven torque around the king pin axis due to the uneven drive torque of the left and right wheels is transmitted to the steering wheel, resulting in torque steer. The following three mechanisms are the main factors causing uneven drive torque:

- (a) Left-right difference in drive shaft and axle joint angles
- (b) Left-right difference in drive shaft torsional stiffness
- (c) Left-right difference in torque distribution by the differential gear

The drive shafts are normally coupled with the axle via a universal joint so that they can track the motion of the suspension. If drive torque is transmitted in the condition with a joint in the angled condition, then torque component force is generated on that joint around the axis orthogonal to the axle. Figure 4 shows a schematic expression of the joint between the drive shaft and the axle.

If the drive torque distributed to the left and right drive shafts is T_i and the angle of the joint between the drive shaft and the axle is θ_{o_i} , then the torque M_{o_i} around the axis orthogonal to the axle is expressed by Eq. (1)⁽¹¹⁾ ($i = L$ or R).

$$M_{o_i} = T_i \cdot \sin \theta_{o_i} \quad (1)$$

In addition, if the king pin inclination angle is θ_{z_i} , then the torque $M_{KP_1_i}$ around the king pin axis is expressed by Eq. (2).

$$M_{KP_1_i} = M_{o_i} \cdot \cos \theta_{z_i} \quad (2)$$

Here, the joint angle and the king pin inclination angle vary according to the oscillation of the suspension and the power train. The left and right θ_{o_i} differ in many cases, and the left and right M_{o_i} also differ, so this causes torque steer.

The torque output from the power train is distributed to the left and right drive shafts via the differential gear. If there is a left-right difference in the drive shaft torsional stiffness at this time, then a transient left-right difference

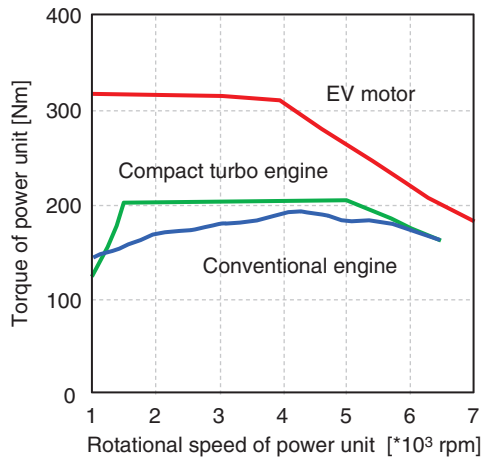


Fig. 2 Typical torque characteristics curves of different power units

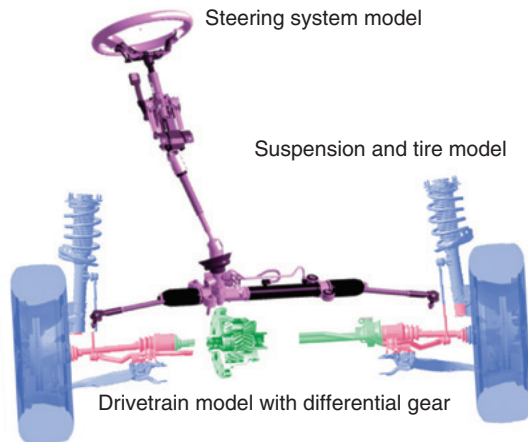


Fig. 3 Schematic image of component models for full vehicle torque steer simulation

in the rotational speed occurs. Ideally, the difference in the rotational speeds of the left and right driving wheels should be absorbed and equal drive torque should be transmitted to both tires. However, an actual differential gear has internal friction elements such as gear friction, so a left-right difference occurs in the torque distributed by the differential gear, within the range that the differential is limited by this friction. This torque difference becomes a left-right difference in the driving force, and a left-right difference also occurs in the torque around the king pin axes. This torque is called the torque around the king pin axis due to transient drive torque difference, and is a factor causing transient torque steer. Figure 5 shows a schematic expression of the drivetrain including the differential gear. If the tire radius is R and the king pin center offset is ζ_z , then the torque M_{KP_2-i} around the king pin axis due to transient drive torque difference can be expressed by Eq. (3).

$$M_{KP_2-i} = \frac{T_i \cdot \cos \theta_{o-i}}{R} \cdot \zeta_z \cdot \cos \theta_{z-i} \quad (3)$$

That is to say, when simulating torque steer, the simulation model should take into account the torque around the king pin axis due to the left-right difference in drive torque resulting from the differential gear and the left-right difference in drive shaft stiffness. The torque transmitted to the steering geometry can be calculated using the total force produced on the steering rack shaft (F_{Rack}), which is determined from the torque around the king pin axis and the link efficiency⁽²⁾. In order to reduce torque steer, it is necessary to reduce the maximum value of F_{Rack} .

In full vehicle model calculations using a multibody

dynamics model, the transient left-right torque bias ratio can be accurately reproduced by creating a detailed model of the differential gear geometry. However, even a multibody dynamics model is unable to reproduce the torque around the king pin axis due to transient drive torque difference if the left-right torque bias ratio is treated as a constant.

Therefore, a differential gear model was examined that can reproduce the left-right torque bias according to transient differences in drive shaft rotational speed, at an accuracy equivalent to that of a multibody dynamics model.

3. Differential Gear Model

3.1. Model Outline

If the drive torque distributed to the left and right drive shafts is respectively T_l and T_r , then the drive torque T and the left-right difference in drive torque ΔT are expressed by Eq. (4) and Eq. (5).

$$T = |T_l + T_r| \quad (4)$$

$$\Delta T = |T_l - T_r| \quad (5)$$

In addition, ΔT is expressed by Eq. (6) and Eq. (7) using the torque bias ratio (TBR), which is the ratio of the torque of the low rotational speed side to the torque of the high rotational speed side of the differential gear.

$$TBR = \left(\frac{T}{2} + \frac{\Delta T}{2} \right) / \left(\frac{T}{2} - \frac{\Delta T}{2} \right) \quad (6)$$

$$\Delta T = T \frac{(TBR-1)}{(TBR+1)} \quad (7)$$

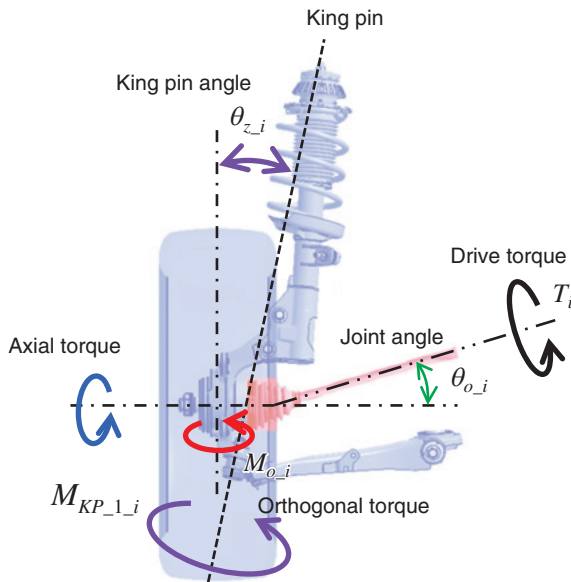


Fig. 4 Schematic expression of drive torque components around wheel hub

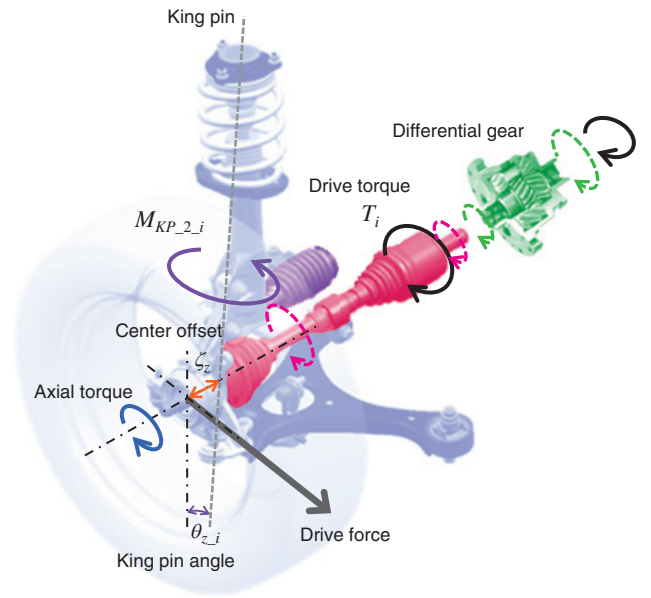


Fig. 5 Schematic expression of transient torque around king pin due to drive shaft stiffness

In a differential gear model without internal friction, the drive torques T_l and T_r , distributed to the left and right sides, are the same, and TBR is 1. In an actual differential gear, however, the differential is limited by internal friction, so a left-right difference occurs in the drive shaft rotational speeds. As a result, T_l and T_r are not the same, and TBR is a value greater than 1.

Meanwhile, the drive torque T_i , distributed to the drive shafts, produces a torsional angle θ_i in accordance with the drive shaft torsional stiffness k_i as shown in Eq. (8).

$$\theta_i = \frac{T_i}{k_i} \quad (8)$$

Here, if the left and right torsional stiffness differ, then a difference also occurs in the torsional angle, and a left-right difference occurs in the drive shaft rotational speed. From Eq. (8), this transient difference in rotational speed is the time series change in the torsional angle difference $d\Delta\theta/dt$, as expressed by Eq. (9).

$$\frac{d\Delta\theta}{dt} \approx \frac{1}{2} \frac{dT}{dt} \left(\frac{1}{k_l} - \frac{1}{k_r} \right) \quad (9)$$

Equation (9) shows that the transient difference in rotational speed $d\Delta\theta/dt$, depends on the time series change in the drive torque dT/dt . That is to say, the left-right difference in drive shaft torsional stiffness becomes a difference in rotational speed $d\Delta\theta/dt$, which causes fluctuations in the difference in drive torque ΔT . As a result, the previously described TBR also fluctuates, making a coupled issue that is a challenge to solve analytically.

The proposed differential gear model was modeled on the assumption that TBR changes in accordance with the difference in rotational speed when the left-right difference in drive shaft rotational speed is smaller than the boundary rotational speed difference N as shown in Fig. 6. In addition, the model that treats TBR as a constant is also shown for comparison.

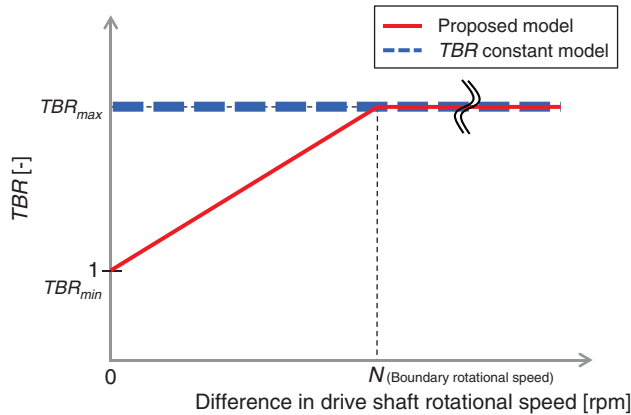


Fig. 6 Proposed TBR characteristic of differential model

Table 1 Calculation parameters and conditions

Weight: 1400 kg, Wheel base: 2.6 m, Center offset: 50 mm

Items	Note
Proposed method	TBR is variable depending on differences in rotational speed ($1 \leq TBR \leq 2.25$)
TBR constant	TBR is constant at design specification value ($TBR = 2.25$)

In contrast to the constant TBR case, the TBR of the proposed model varies according to the left-right difference in drive shaft rotational speed. TBR is the lower limit value at a rotational speed difference of zero, and increases linearly together with the rotational speed difference until it reaches the upper limit value at the boundary rotational speed difference N , after which it remains constant.

Given the above assumption, TBR is expressed by Eq. (10) as a function of $d\Delta\theta/dt$, and the left-right drive torque difference ΔT is expressed by Eq. (11).

$$TBR \left(\left| \frac{d\Delta\theta}{dt} \right| \right) = \begin{cases} \frac{(TBR_{max}-1)}{N} \cdot \left| \frac{1}{2} \frac{dT}{dt} \left(\frac{1}{k_l} - \frac{1}{k_r} \right) \right| + 1 & \left(\left| \frac{d\Delta\theta}{dt} \right| < 1 \right) \\ TBR_{max} & \left(\left| \frac{d\Delta\theta}{dt} \right| \geq N \right) \end{cases} \quad (10)$$

$$\Delta T = T \cdot \left[TBR \left(\left| \frac{d\Delta\theta}{dt} \right| \right) - 1 \right] / \left[TBR \left(\left| \frac{d\Delta\theta}{dt} \right| \right) + 1 \right] \quad (11)$$

Equation (11) shows that ΔT increases together with T , and Eq. (10) shows that TBR increases together with dT/dt . Therefore, the maximum left-right difference in drive torque is produced when T^*dT/dt is the maximum value. The torque $M_{KP,2}$ around the king pin axis due to transient drive torque difference can be obtained from Eq. (3) by using the left-right difference in drive torque ΔT . With regards to the drive torque distributed to the left and right wheels at this time, the side with high drive shaft torsional stiffness becomes the high torque side.

3.2. Verification of Effects

Torque steer simulation results obtained by a model that embeds the proposed model in an MBD performance design tool and the conventional model that treats TBR as a constant were compared with the calculation results obtained by a full vehicle model. Table 1 shows the calculation conditions.

Figure 7 shows the time series response of the drive torque used in the calculation T^*dT/dt , and F_{Rack} obtained using the proposed model. The maximum F_{Rack} is produced after around 1.4 s when T^*dT/dt is the maximum value.

Figure 8 shows a graph with the relationship between the difference in rotational speed and TBR at the maximum F_{Rack} in the MBD performance design tool and full vehicle model calculation results, superposed on the characteristic

assumed in Fig. 6. This shows that the results obtained by the MBD performance design tool using the proposed model are nearly the same as the results obtained by the full vehicle model.

Figure 9 compares the F_{Rack} produced by the drive torque in each model. Here, the contributions of the drive torque difference and the drive torque transmission of the axle joint to F_{Rack} are indicated by different colors for each mechanism. This shows that the calculation results using the proposed model match the calculation results of the full vehicle model, which indicates that torque steer can also be quantitatively calculated in the MBD performance design tool.

In contrast, when TBR was treated as a constant,

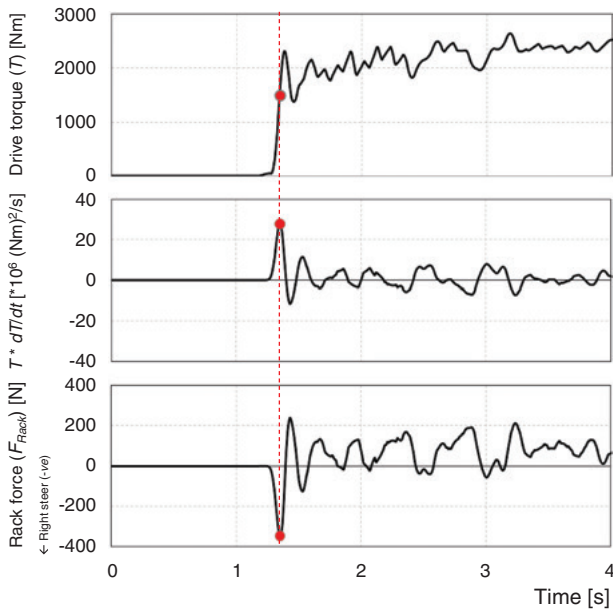


Fig. 7 Input torque (upper), proposed index (middle), and F_{Rack} (bottom) from proposed simulation

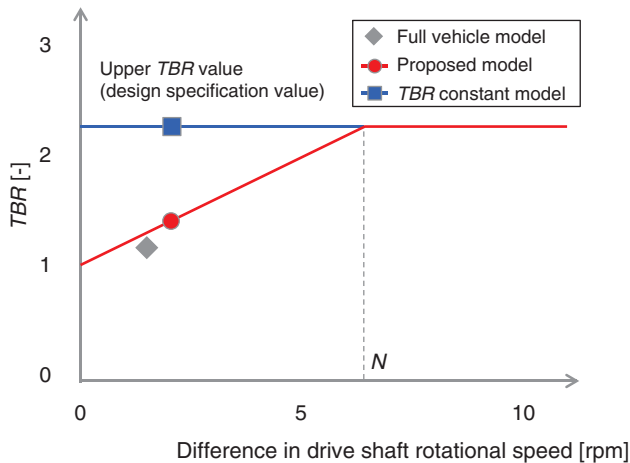


Fig. 8 TBR characteristics used in calculation

the contribution due to the drive torque difference was calculated to be larger, so F_{Rack} was larger than the detailed calculation result of the full vehicle model and the simulation accuracy also decreased. This means that TBR is assumed to be larger than the actual value in Fig. 8.

In addition, the effects of changes in the drive shaft torsional stiffness, the axle joint angle, and the king pin center offset were verified using the proposed model. Figure 10 compares the contributions to F_{Rack} with the

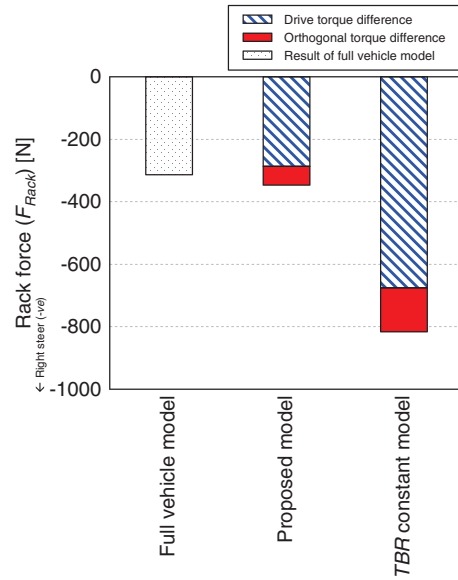


Fig. 9 Difference in F_{Rack} between proposed and TBR constant model compared with result of full vehicle model

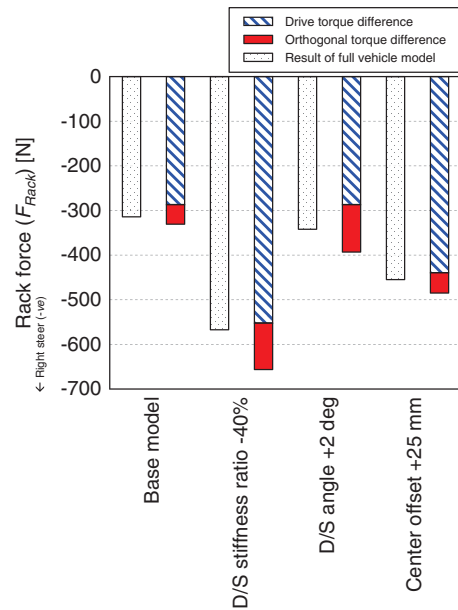


Fig. 10 F_{Rack} factor analysis results of proposed model compared with results of full vehicle model

Table 2 Calculation parameters for model verification

Weight: 1400 kg, Wheel base: 2.6 m, Center offset: 50 mm

Items	Note
D/S stiffness ratio -40% (Drivetrain effect)	Decrease D/S stiffness ratio by 40%
D/S angle +2 deg (Drivetrain effect)	Increase D/S joint angle by 2 deg
Center offset +25 mm (Chassis effect)	Increase center offset of front suspension geometry by 25 mm

D/S: Drive shaft

calculation results of the full vehicle model. Table 2 shows the calculation conditions. In each case, F_{Rack} closely matched the calculation results of the full vehicle model.

These results confirmed that the proposed model can accurately reproduce transient changes in TBR at an accuracy equivalent to that of a more detailed multibody dynamics model. In addition, it was found that a torque steer simulation model that incorporates the proposed model can accurately reproduce the left-right drive torque bias. This demonstrated that the proposed model can be used to accurately and efficiently examine various countermeasure methods based on drivetrain and chassis components, such as drive shaft and suspension characteristics, from the initial stages of development.

4. Case of Application

This chapter describes a case of applying a differential gear model constructed using the developed technology to MBD performance design in development of a 2016 model year mass-production vehicle platform. This development planned to change the power unit to a compact T/C in order to enhance fuel efficiency, and there were concerns that the increased drive torque would cause torque steer. Therefore, the developed technology was used to quantitatively simulate the influence of torque steer and formulate countermeasures.

Figure 11 shows the sensitivity of the drivetrain and chassis countermeasure methods to F_{Rack} , compared to the initial specifications for this case. The countermeasure methods assumed changes to the drive shaft stiffness, drive shaft joint angle, and king pin center offset. Each item was varied by up to $\pm 10\%$ of the design value, and the sensitivity was calculated. The horizontal axis expresses the contribution to F_{Rack} due to transient drive torque difference, and the vertical axis expresses the contribution to F_{Rack} due to the drive torque transmission of the axle joint.

Contribution analysis shows that increasing the drive shaft torsional stiffness by approximately 6% is an effective countermeasure method for the development vehicle to

Table 3 Countermeasure list

Weight: 1530 kg, Wheel base: 2.7 m, Center offset: 78 mm

Items	Note
D/S stiffness	Increase D/S stiffness by +6%

achieve the target of a F_{Rack} equivalent to that before the change to a compact T/C.

The developed technology can be used to examine specifications while quantitatively understanding how each countermeasure method contributes to each torque steer mechanism. This makes it an effective method for performing streamlined performance design.

Table 3 shows the calculation condition for the specification with torque steer countermeasures applied to a vehicle equipped with a compact T/C.

Figure 12 shows the F_{Rack} calculation results for the development vehicle before and after changing to a compact T/C and for the proposed specification. This shows that increasing the drive shaft stiffness by 6% as a countermeasure achieves the same F_{Rack} as that before changing to a compact T/C.

These results show that application of a simulation model constructed using the developed technology enables examination of countermeasure methods using drivetrain and chassis components based on quantitative simulation of torque steer in the initial stages of actual platform development, thus demonstrating the usefulness of this technology.

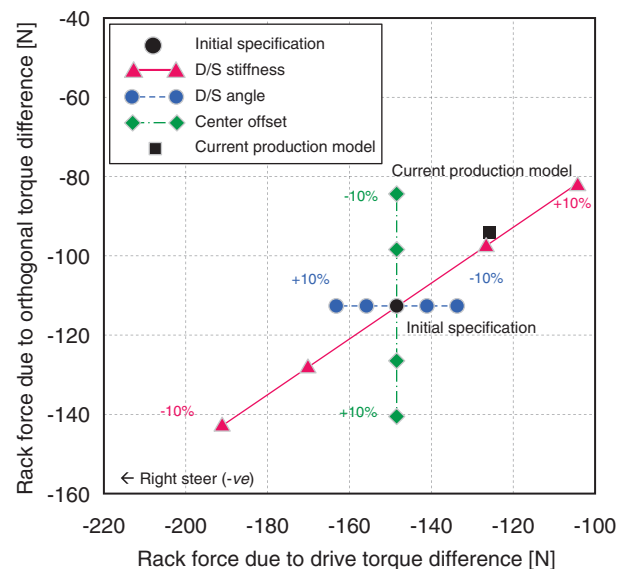


Fig. 11 Sensitivity of countermeasure items

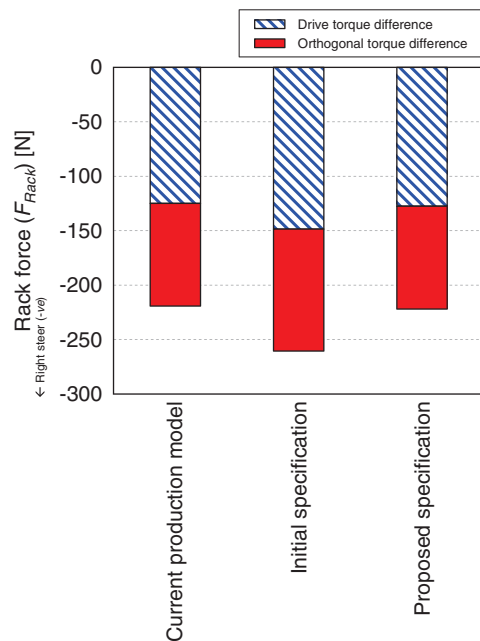


Fig. 12 Difference in F_{Rack} between initial specification and proposed specification

5. Conclusion

A simulation model was proposed that can reproduce the transient left-right torque bias ratio at an accuracy equivalent to that of a more detailed multibody dynamics model.

- (1) The mechanisms that cause the left-right uneven drive torque that is a factor resulting in torque steer were modeled by division into three left-right difference elements.
- (2) A differential gear model was devised that treats *TBR* as variable by the rotational speed difference. This enabled calculation at the same accuracy as that of a detailed model.
- (3) Application of the developed technology to an MBD performance design tool enabled quantitative and efficient examination of countermeasure methods during performance design in the initial stages of development.

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Expansion of Statistical Tire Modeling Method to Tire Rolling Resistance Estimation

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ABSTRACT

The “statistical tire model” method, which is used for performance design in the early stages of vehicle development, was applied in order to expand its function to estimate the rolling resistance of tires just from the information of tire size and its inflation pressure. The influence of tire size on RRC became quantified by using measured rolling resistance of tires that have variation in both its sizes and inflation pressures yet that have the same structure and rubber compound. As a result, a model with good precision was obtained that can estimate the increase/decrease of the rolling resistance with respect to the reference tire if the tire size and its inflation pressure were given. The proposed model made it possible to conduct quantitative parameter studies without carrying out time consuming individual tire measurements.

1. Introduction

Automobiles have been providing us with a method of personal mobility and helped our lives become more convenient and enriched, while the performance of automobiles has been advanced so that vehicle performance such as handling performance, collision safety, roominess, riding comfort, resource saving, etc. is achieved at a high level. In recent years, in order to cope with global warming, technologies for fuel saving by power plant innovation have been advanced. Regarding chassis technology, technology to secure handling performance and braking performance has been evolved while improving fuel consumption efficiency using low rolling resistance tires⁽¹⁾.

On the other hand, when looking at development technologies that support these recent performance evolutions, techniques that understand and model the complicated mechanisms and rationally design and examine them based on quantitative prediction⁽²⁾⁻⁽¹⁰⁾ called performance designs have evolved^{(11),(12)}.

In the early stage of vehicle development, using the performance design method, fundamental design process is conducted so that the target performance would be achieved under limited cost and space layout. In the case of platform design, which commonizes fundamental design of multiple models, it is becoming necessary to grasp the characteristics of each part more quantitatively than ever in order to design comprehensively in

consideration of many derived car models.

When we look at the chassis that supports the vehicle dynamics functions of cars, tires is one of the parts with the largest performance contribution, and tire size affects vehicle basic specifications such as wheel base and tread. Also, its characteristics greatly affect important features such as handling performance, braking ability, riding comfort, noise reduction, fuel economy, and so on.

Also in the case of platform development, considering all the types of vehicles that the platform covers, it is necessary to design the space layout beforehand so that the necessary and sufficient tire size can be installed.

Although it has been an important technical challenge to grasp various characteristics of tires, it has not been very easy to get detailed simulation models of tires in the early stages of vehicle development. So, there have not been many options except asking tire manufacturers for characteristics prediction or conducting time-consuming measurements and analysis on available tires by ourselves. Therefore, a technology has long been desired in this field that can quickly and easily estimate tire characteristics.

In order to solve this issue, we have developed a method called a statistical tire model that predicts statistical average characteristics of arbitrary tire size, and applied the method to the initial chassis design⁽¹³⁾⁻⁽¹⁵⁾.

Since this statistical tire model can predict generalized tire characteristics, it is possible to efficiently search Pareto solutions by examining vehicle performance using tire size

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as one of the parameters. As the tire characteristics can be understood more quantitatively, the initial design quality can be matured. In addition, since performance can be studied without carrying out numerous tire measurements, considerable enhancement can be expected in terms of development efficiency.

This statistical modeling method has been mainly applied to the field of vehicle dynamics performance, and, in this report, it is expanded to the prediction of rolling resistance coefficient (RRC) which is often a tradeoff with vehicle dynamics.

2. Statistical Tire Modeling

Many tire models with various complexity and accuracy have been proposed over the past 50 years. They are roughly classified into four categories: detailed physical models and simple physical models both classified as theoretical models, and interpolation approximation models and characteristic identification models classified as experiment identification models⁽¹⁶⁾.

The proposed statistical tire model is one form of the experimental identification model. Whereas almost all previous models including the Magic Formula tire model try to simulate individual tire characteristics accurately, the statistical tire model tries to identify the general characteristics of tires from the measurement characteristics and meta-information like tire size and inflation pressure from various tires. Therefore, it can be called a generalized tire model (Table 1).

This statistical tire model can provide the estimated tire characteristics only from meta information such as tire size and internal pressure so that it could be an efficient means for determining the tire size at the initial stage of development.

In the previously reported statistical tire model, it was possible to estimate the average characteristics of the tire cornering power C_p , tire vertical stiffness characteristic K_z , the dynamic loaded radius DLR , the tire weight WT , and the contact area SS , only from the provided information such as size, inflation pressure P , and normal load F_z ⁽¹⁵⁾.

In order to determine the size of the tire, in addition to the characteristics related to the vehicle dynamics and ride comfort mentioned above, it is also necessary to consider the RRC characteristic, which is a tradeoff to these characteristics. However, in estimating RRC, it is necessary to model the transformation mechanism of tire deformation and the heat energy, but so far there has been no easy method to investigate RRC, due to high technical challenges.

In this report, the statistical tire modeling method is applied to data obtained by arranging experimental conditions for the modeling. The influence of size and internal pressure on RRC was quantified for the first time and its basic idea, identification method, and application method was reported as following.

Table 1 Major prevailing tire models for vehicle dynamics compared with proposed statistical model

Model type	Model name	Modeling approach	Data for model identification	Tire size parameterization
Experimental model	Statistical model	Fitting tire test data from multiple tires using regression technique	From multiple tires	Single model for various size
	Magic Formula, SWIFT, etc.	Fitting full scale tire test data by regression technique	From individual tire	Individual model for each tire
	Interpolation model, etc.	Distorting, rescaling and combining basic characteristics		
Theoretical model	Fiala model, Brush model, etc.	Using simple mechanical representation		
	FEM tire model, FTire, RMOD-K, etc.	Describing tire in greater detail		

3. RRC Estimation

3.1. Tire RRC Characteristics

Rolling resistance of a tire is the reverse resistance force in the direction of travel which occurs when the tire rolls and is represented by RRC where the resistance value is divided by the ground load.

RRC is about 0.0080-0.0100 for ordinary passenger car tires and about 0.0060 for tires using state-of-the-art low loss rubber compounds.

Since energy loss due to rolling resistance of tires contributes about one third of the energy consumption during fuel consumption mode, reducing RRC is an important technique to improve fuel consumption efficiency of the chassis.

This RRC is due to the fact that the deformation of the rolling tire generates heat by the compound hysteresis. Therefore, RRC has speed dependency as shown in Eq. (1)⁽¹⁷⁾.

Since the RRC is affected by the internal structure of the tire that dominates the deformation of the tire, it could be reduced by lowering the hysteresis of the rubber compound, or by decreasing the total amount of rubber used. Or by reducing the deformation itself with a bigger tire size or with higher inflation pressure (Fig. 1).

$$f_R = f_{R0} + f_{R1} \left(\frac{V}{100} \right) + f_{R4} \left(\frac{V}{100} \right)^4$$

$$\text{where } \begin{cases} f_R : \text{RRC}_{[-]} \\ V : \text{Tire rolling speed [km/h]} \\ f_{R0} : 0.0080 \text{ to } 0.0100_{[-]} \\ f_{R1} : 0.0010 \text{ to } 0.0025_{[h/km]} \\ f_{R4} : 0.0002 \text{ to } 0.0004_{[h^4/km^4]} \end{cases} \quad (1)$$

However, these methods might lower important

functions of the tire such as the grip performance, the ability to absorb the impact, and the durability, or ride comfort, by increased stiffness.

Therefore, the fuel efficiency by low RRC and performances like vehicle dynamics and ride comfort required for the chassis generally form a contradictory issue.

In order to efficiently examine the quantitative relationship between tire size and RRC that we focused on, experimental data from tires with the same compound and structure should be acquired and the influence of size and internal pressure on RRC should be extracted, and then the statistical model should be identified.

3.2. Statistical RRC Modeling

In order to clarify the fundamental properties of tire RRC, sample tires were selected from a certain fuel-efficient tire product line that is popular in the market and also has a lot of size variations. And the model identification was carried out using the precisely measured RRC of these sample tires.

Table 2 shows the statistics of measured tire width (W), flatness (H), rim diameter (D), load index (L), internal pressure (P), load (F_z) and measured RRC.

Measurements were carried out with regulated inflation pressure and load after sufficient warm-up. The tire load was set to 80% of the maximum load, which is determined from the size and inflation pressure of each tire.

The measured RRC, with respect to the rolling speed, are shown in Fig. 2. Although these tires have the same compound and structure, measured RRC varies greatly with different size and internal pressure.

As the speed dependency of RRC can be expressed by Eq. (1), in this paper, the RRC values at 80 [km/h] were selected as the representative RRC value of each tire.

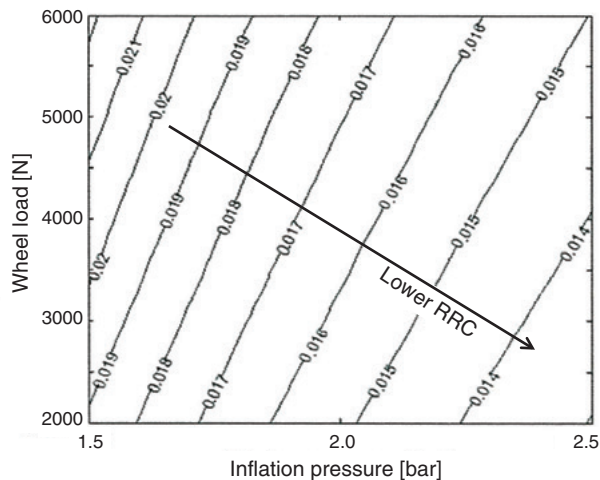


Fig. 1 Example of tire RRC with respect to wheel load and inflation pressure from reference

Table 2 Statistics of tire parameters of 31 cases

	Tread width, W [mm]	Aspect ratio, H [%]	Rim diameter, D [inch]	Load index, L	Inflation pressure, P [kPa]	Normal load, F_z [kN]	RRC at $V=80$, [$\times 10^{-4}$]
Average	202.1	56.3	16.0	89.2	250.6	4.6	69.1
Median	205.0	55.0	16.0	91.0	220.0	4.9	68.4
Std.Dev. σ	17.4	6.2	1.2	5.1	44.9	0.6	7.2
Minimum	155	45	13	73	210	2.89	54.0
Maximum	225	65	18	97	340	5.74	85.8
Max.-Min.	70	20	5	24	130	2.85	31.8
	(4.03 σ)	(3.23 σ)	(4.17 σ)	(4.7 σ)	(2.89 σ)	(4.45 σ)	(4.39 σ)

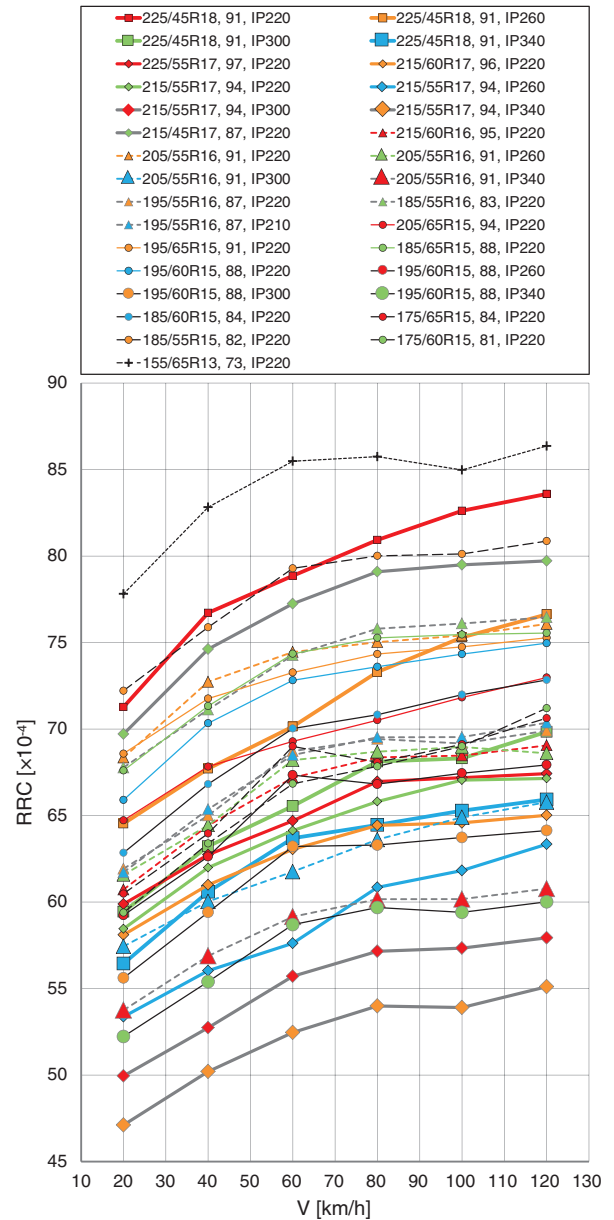


Fig. 2 Measured tire RRC vs rolling speed of 31 cases with normal load F_z equal to 80% of the load index's maximum load and with regulated inflation pressure

In Table 3, the RRC value of each tire at 80 [km/h] is shown as a relative value of No.12 205/55R16 91, $P=220$ [kPa]. The tire size of No. 12, used as the reference, is the median of the tire sizes W , H , D , L , and P of the sample.

Firstly, to analyze correlation between tire size parameters W , H , D , and L , and usage conditions P , F_z , and RRC for the obtained data, a scatter plot was plotted and examined (Fig. 3).

The histogram plotted on the diagonal in Fig. 3 shows the frequency of appearance of each parameter, the scatter plot shows the correlation between each parameter diagonally arranged, and the straight line in the scatter plot represents the linear approximation of correlation.

For example, the plot at the top right of Fig. 3 is a scatter plot with x-axis as RRC and y-axis as tire width W . Since the approximate straight line in the figure goes down to the right, it means that W increases as RRC increases. The bottom left plot is a plot where the x-axis and the y-axis are interchanged.

From the histogram distribution shown in Fig. 3, it can be seen that measured tires have sufficient variations with respect to W , H , and D . If we look at the correlations of W , H , and D , as D becomes larger, W gets larger and H gets smaller. But this is just due to the product line trend on the market that large diameter tires tend to be wider and to have low aspect ratio. It is not a physical causal relationship. Therefore, we adopted W , H , and D as independent input parameters in model identification.

In addition, load index L was used as a parameter of the capacity of the tire, and F_z and P were added to the input parameters that dominate the tire deformation. Since the measured load F_z is set to 80% of the maximum load determined by L in this measurement, the correlation between F_z and L is almost 1, but we regarded there is no causal relationship with this.

There could also be nonlinearity in the correlation between tire size and internal pressure and RRC, so the

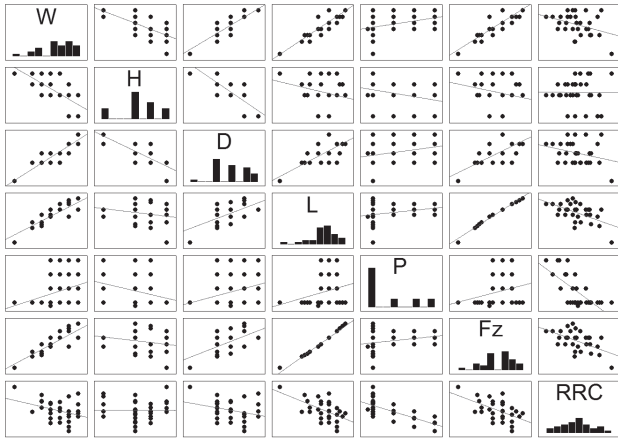


Fig. 3 Correlation overview of sample tire information for “Stat RRC” - W , H , D , L , P , F_z , and RRC

Table 3 Measured RRC relative to No.12* case, with various tire size, load index, inflation pressure, and normal load
* Tire size 205/55R16 of No.12 is a median of sample cases

No.	Tread width, W [mm]	Aspect ratio, H [%]	Rim diameter, D [inch]	Load index, L	Wheel size on measurement	Inflation pressure, P [kPa]	Normal load, F_z [kN]	RRC at $V=80$, [$\times 10^{-1}$]
1	225	45	18	91	18x8J	220	4.85	107.9%
2	225	45	18	91	18x8J	260	4.85	97.7%
3	225	45	18	91	18x8J	300	4.85	90.8%
4	225	45	18	91	18x8J	340	4.85	85.9%
5	215	45	17	87	17x7.5J	220	4.27	105.4%
6	225	55	17	97	17x7.5J	220	5.74	89.3%
7	215	55	17	94	17x7.5J	220	5.25	87.7%
8	215	55	17	94	17x7.5J	260	5.25	81.1%
9	215	55	17	94	17x7.5J	300	5.25	76.2%
10	215	55	17	94	17x7.5J	340	5.25	72.0%
11	215	60	17	96	17x7.5J	220	5.59	85.9%
12*	205	55	16	91	16x6.5J	220	4.85	100.0%
13	205	55	16	91	16x6.5J	260	4.85	91.6%
14	205	55	16	91	16x6.5J	300	4.85	84.8%
15	205	55	16	91	16x6.5J	340	4.85	80.2%
16	195	55	16	87	16x6.5J	220	4.27	92.5%
17	185	55	16	83	16x6J	220	3.82	101.0%
18	215	60	16	95	16x6.5J	220	5.44	91.1%
19	185	55	15	82	15x6J	220	3.73	106.7%
20	195	60	15	88	15x6J	220	4.41	98.1%
21	195	60	15	88	15x6J	260	4.41	89.1%
22	195	60	15	88	15x6J	300	4.41	84.4%
23	195	60	15	88	15x6J	340	4.41	79.6%
24	185	60	15	84	15x5.5J	220	3.92	94.4%
25	175	60	15	81	15x5.5J	220	3.63	90.4%
26	205	65	15	94	15x6J	220	5.25	94.0%
27	195	65	15	91	15x5.5J	220	4.85	99.1%
28	185	65	15	88	15x5.5J	220	4.41	100.3%
29	175	65	15	84	15x5.5J	220	3.92	90.7%
30	155	65	13	73	13x4J	220	2.89	114.3%
31	195	55	16	87	16x6J	210	4.27	92.7%

square terms of these parameters were also taken into account as an input parameter. The validity of the adopted input parameters will be discussed later.

Based on the above assumptions, the statistical RRC model that estimates RRC by the tire size parameters W , H , D , and L , and the usage condition parameters P and F_z , was defined by Eq. (2).

The measurement data of Table 3 was applied to this model definition formula and model coefficients a_1 to a_{12} were identified from the least squares method of estimation error (3).

$$\begin{aligned}
 &RRC(a_1, a_2, \dots, a_{12}/W, H, D, L, P, F_z) \\
 &= a_1 W + a_2 W^2 + a_3 H + a_4 H^2 + a_5 D + a_6 D^2 \\
 &\quad + a_7 L + a_8 L^2 + a_9 P + a_{10} P^2 + a_{11} F_z + a_{12}
 \end{aligned} \tag{2}$$

where

- W : Tread width [mm]
- H : Aspect ratio [%]
- D : Rim diameter [inch]
- L : Load index
- P : Inflation pressure [kPa]
- F_z : Normal load [kN]
- a_i : Coefficients of RRC multi-regression model

Table 4 Identified model parameters for statistical RRC model

Model coefficient	Identified value	Note
a_1	3.62E-2	W
a_2	-1.07E-4	W^2
a_3	-1.06E-1	H
a_4	7.51E-4	H^2
a_5	-8.34E-1	D
a_6	2.38E-2	D^2
a_7	8.61E-2	L
a_8	-9.61E-4	L^2
a_9	-4.09E-3	P
a_{10}	4.55E-6	P^2
a_{11}	7.78E-1	Fz
a_{12}	5.90E+0	y-intercept

$$\frac{\partial J}{\partial a_k} = 0 \rightarrow a_k \left| \frac{\partial J}{\partial a_k} = 0 \right. \quad (k = 1 \text{ to } 12)$$

where

$$J = \sum_{i=1}^n [RRC_i - RRC(a_1, a_2, \dots, a_{12}/W_i, H_i, D_i, L_i, P_i, Fz_i)]^2$$

The coefficients of the statistical RRC model obtained in this procedure are shown in Table 4.

4. Calculation Results

4.1. Estimated RRC

The RRC estimates obtained by applying the tire size, load index, internal pressure and load to the identified statistical RRC model are shown in Table 5. And the correlation between these estimated values and the measured RRC is shown in Fig. 4.

The corrected R^2 , which represents the correlation with the measured value of the statistical RRC model, was 0.913.

Corrected R^2 is a degree-of-freedom adjusted coefficient of determination (also called contribution rate), indicating that the proposed model explains about 90% of variations due to size and internal pressure of RRC. Therefore, when conducting parameter studies on performance, including RRC while changing tire size and its internal pressure at the early stage of development, we think that the statistical RRC model proposed in this paper has sufficient accuracy for the investigation.

However, from Fig. 4, the standard error is still $\sigma = 2.13 \times 10^{-4}$, and the contribution ratio, which cannot be estimated by the prediction equation, remains about 10%. When conducting performance design, we should consider these estimation errors in mind.

The RRC estimated values vs tire width W , aspect ratio H , rim diameter D , load index L , and inflation pressure P are plotted along with measured values and are shown in Fig. 5.

Table 5 Estimated RRC by statistical RRC model

Tire size and IP	Measured RRC at V = 80 in relative form	Estimated RRC at V = 80 in relative form	Error [%]
225/45R18, 91, IP220	107.9%	105.7%	-1.0%
225/45R18, 91, IP260	97.7%	98.0%	0.2%
225/45R18, 91, IP300	90.8%	91.9%	0.5%
225/45R18, 91, IP340	85.9%	87.2%	0.6%
215/45R17, 87, IP220	105.4%	105.4%	0.0%
225/55R17, 97, IP220	89.3%	87.5%	-0.8%
215/55R17, 94, IP220	87.7%	89.3%	0.8%
215/55R17, 94, IP260	81.1%	81.7%	0.3%
215/55R17, 94, IP300	76.2%	75.5%	-0.3%
215/55R17, 94, IP340	72.0%	70.8%	-0.5%
215/60R17, 96, IP220	85.9%	86.7%	0.4%
205/55R16, 91, IP220	100.0%	99.3%	-0.3%
205/55R16, 91, IP260	91.6%	91.6%	0.0%
205/55R16, 91, IP300	84.8%	85.5%	0.3%
205/55R16, 91, IP340	80.2%	80.7%	0.3%
195/55R16, 87, IP220	92.5%	94.6%	0.9%
185/55R16, 83, IP220	101.0%	94.8%	-2.9%
215/60R16, 95, IP220	91.1%	89.7%	-0.6%
185/55R15, 82, IP220	106.6%	104.8%	-0.9%
195/60R15, 88, IP220	98.1%	97.2%	-0.4%
195/60R15, 88, IP260	89.1%	89.6%	0.2%
195/60R15, 88, IP300	84.4%	83.4%	-0.5%
195/60R15, 88, IP340	79.6%	78.7%	-0.4%
185/60R15, 84, IP220	94.4%	95.1%	0.3%
175/60R15, 81, IP220	90.4%	96.4%	2.8%
205/65R15, 94, IP220	94.0%	96.8%	1.3%
195/65R15, 91, IP220	99.1%	99.6%	0.2%
185/65R15, 88, IP220	100.3%	95.5%	-2.3%
175/65R15, 84, IP220	90.7%	91.2%	0.2%
155/65R13, 73, IP220	114.3%	114.0%	-0.1%
195/55R16, 87, IP210	92.7%	96.7%	1.9%

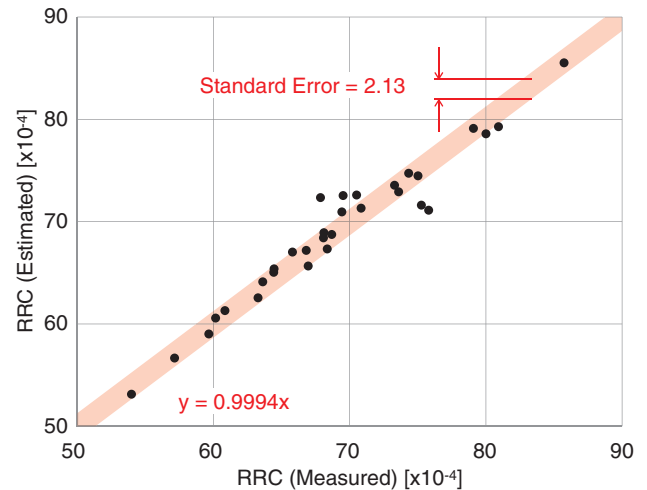


Fig. 4 Correlation between measured RRC and estimated RRC from statistical RRC model with W , H , D , L , P , and Fz given

Table 6 Multiple regression model - Stepwise verification using forward selection method

Model ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Independent parameters	W	W,H	W,H,D	W,H,D,L	W,H,D,L,P	W,H,D,L,P,Fz	W,H,D,L,P,Fz,W ²	W,H,D,L,P,Fz,H ²	W,H,D,L,P,Fz,D ²	W,H,D,L,P,Fz,L ²	W,H,D,L,P,Fz,P ²	W,H,D,L,P,Fz,Fz ²	W,H,D,L,P,Fz,W ² H ²	W,H,D,L,P,Fz,W ² H ² D ²	W,H,D,L,P,Fz,W ² H ² D ² L ²	W,H,D,L,P,Fz,W ² H ² D ² L ² P ²	W,H,D,L,P,Fz,W ² H ² D ² L ² P ² Fz ²
Statistics																	
R	0.367	0.516	0.554	0.639	0.906	0.907	0.912	0.957	0.935	0.926	0.908	0.947	0.960	0.968	0.968	0.972	0.973
R ²	0.135	0.266	0.307	0.408	0.821	0.823	0.831	0.916	0.875	0.857	0.824	0.897	0.922	0.937	0.937	0.945	0.946
Adjusted R ²	0.105	0.213	0.230	0.317	0.785	0.779	0.780	0.891	0.836	0.814	0.771	0.865	0.894	0.910	0.906	0.913	0.910
Standard error	6.832	6.404	6.336	5.967	3.345	3.395	3.385	2.384	2.920	3.117	3.455	2.650	2.349	2.169	2.260	2.132	2.163
Coefficients																	
y-Intercept	1.33E+0	2.16E+0	2.78E+0	1.80E+0	2.66E+0	3.19E+0	4.79E+0	8.36E+0	9.14E+0	-5.89E+0	3.39E+0	6.83E+0	7.56E+0	9.65E+0	4.88E+0	5.90E+0	2.37E+0
W	-2.04E-3	-3.97E-3	-1.73E-3	9.64E-3	8.12E-3	7.21E-3	-2.42E-2	-5.69E-3	-3.18E-3	8.74E-3	7.21E-3	8.15E-3	2.34E-2	4.51E-2	3.08E-2	3.62E-2	4.18E-2
H		-7.82E-3	-1.20E-2	8.07E-3	-1.46E-3	-3.21E-3	-9.33E-3	-1.33E-1	-1.91E-2	1.11E-3	-3.40E-3	2.88E-3	-1.47E-1	-1.31E-1	-1.08E-1	-1.06E-1	-1.19E-1
D			-5.24E-2	-2.36E-2	-5.75E-2	-5.98E-2	-8.15E-2	-9.39E-2	-9.75E-1	-5.24E-2	-6.08E-2	-3.67E-2	-7.77E-2	-7.24E-1	-7.33E-1	-8.34E-1	-1.08E+0
L				-3.26E-2	-2.25E-2	-2.81E-2	1.11E-2	-1.32E-2	3.57E-2	1.97E-1	-2.80E-2	-1.77E-1	-4.97E-2	-3.93E-2	9.68E-2	8.61E-2	2.40E-1
P					-1.50E-3	-1.49E-3	-1.54E-3	-1.46E-3	-1.71E-3	-1.51E-3	-2.94E-3	-1.68E-3	-1.41E-3	-1.54E-3	-1.54E-3	-4.09E-3	-3.81E-3
Fz						6.53E-2	-1.46E-1	2.46E-1	-1.76E-1	1.04E+0	6.54E-2	2.80E+0	4.82E-1	4.57E-1	7.62E-1	7.78E-1	6.06E-2
W ²							7.12E-5						-7.03E-5	-1.32E-4	-9.25E-5	-1.07E-4	-1.27E-4
H ²								9.77E-4					1.13E-3	9.56E-4	7.78E-4	7.51E-4	8.25E-4
D ²									2.78E-2					2.04E-2	2.05E-2	2.38E-2	3.11E-2
L ²										-2.03E-3					-1.02E-3	-9.61E-4	-1.75E-3
P ²											2.63E-6					4.55E-6	4.09E-6
Fz ²												-1.79E-1					7.24E-2

It is confirmed that the RRC estimated value for each size parameter has a good accuracy and is distributed within approximately ± 2.13 of the measured value.

4.2. Model Verification

In order to verify the identified statistical RRC model, using the stepwise variable increasing method of multiple regression analysis, the accuracy of several models with various input parameter combinations were obtained and compared with the proposed model. The results are shown in Table 6 and the proposed model is Model 16. The

coefficient of determination and standard error of each model are shown in Fig. 6 and Fig. 7, respectively.

From Table 6, increasing the number of variables generally increases the coefficient of determination, enhancing the correlation, and reduces the standard error, therefore enhancing the accuracy of the model.

For example, Model 1 has only input parameter W and its coefficient of determination (contribution rate) is 0.105, and Model 2, which has two input parameters, W and H , exhibits 0.213 of coefficient of determination. So the contribution rate of parameter W and H to RRC can be

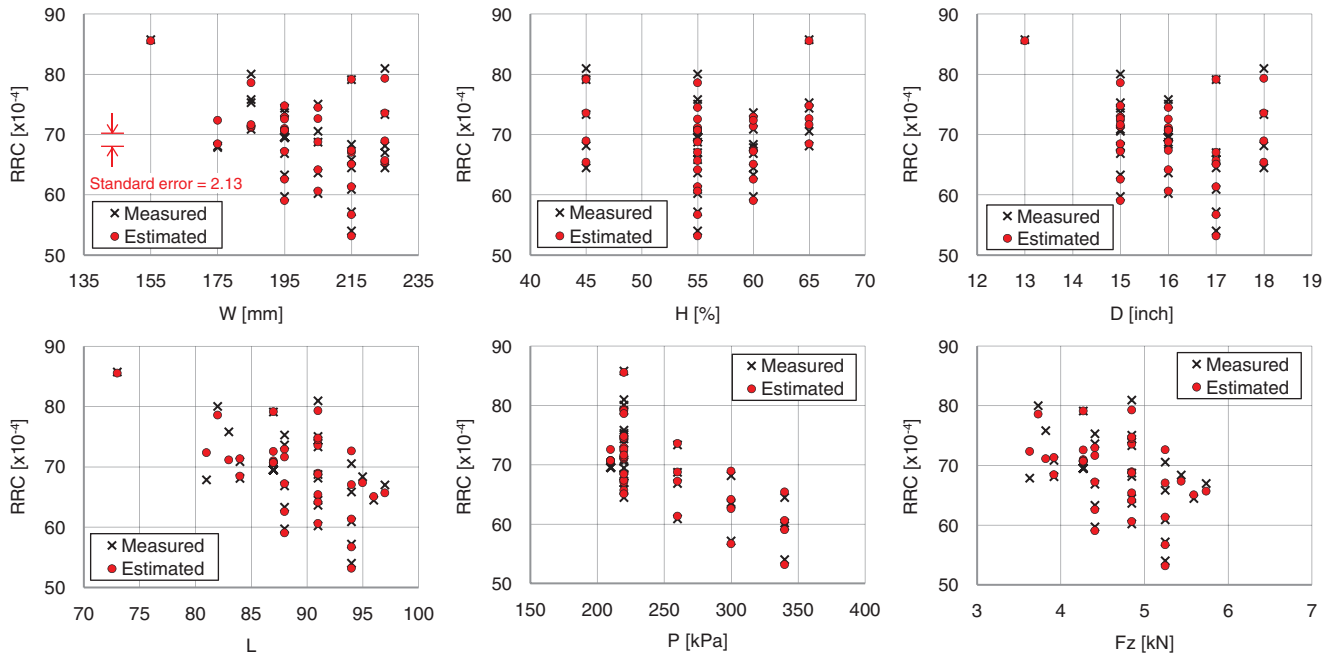


Fig. 5 Comparisons between measured RRC and estimated RRC with respect to W , H , D , L , P , and Fz

analyzed as about 10% each.

Focusing on differences in Models 4 to 5 and Models 7 to 8, when the internal pressure P and the square of the aspect ratio H^2 are added as variables, respectively; the

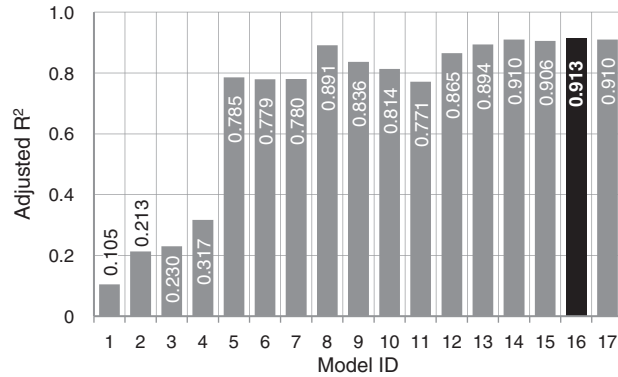


Fig. 6 Adjusted R² of multiple regression models

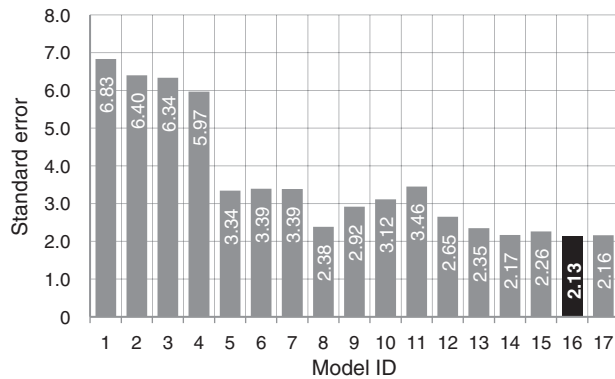


Fig. 7 Standard error of multiple regression models

coefficient of determinations are greatly increased from 0.317 to 0.785 and 0.780 to 0.891, respectively. It can be understood that the internal pressure P of the input parameter and the square of aspect ratio H^2 contribute about 47% and 11%, respectively.

However, in Model 17 where the square of load Fz^2 is added to the proposed Model 16, the coefficient of determination decreases and the standard error increases. For RRC, it can be safely said that the linear approximation of the load Fz is more appropriate.

Through the above verification work, it was confirmed that the proposed Model 16 is a highly correlated model that can predict the contribution of size factors and internal pressure to RRC with good accuracy. Note that Model 8 is simpler, but the coefficient of determination is 0.891 and its prediction accuracy is relatively good, so we will consider it from the viewpoint of robustness of the estimation in the next chapter.

5. Application Examples and Discussions

5.1. Discussion on Model Robustness

Figure 8 compares the estimated RRC from both the proposed Model 16 and the simpler Model 8 with the measured values for various tire sizes.

Model 8 is a simpler model with only W , H , D , L , Fz , and H^2 as variables, but its estimate is close enough to the measured value, and its standard error is also about $\sigma = 2.38$, which is just 11% larger than the error of Model 16.

Figure 9 shows the RRC estimate obtained by varying only the tire width W from 145 to 235, with respect to reference tire 205/55R16 91, IP=220.

The RRC estimate has an upwardly convex shape in the case of Model 16 and it estimates extremely low RRC values in the ranges of $W < 155$ and $W > 225$. On the other

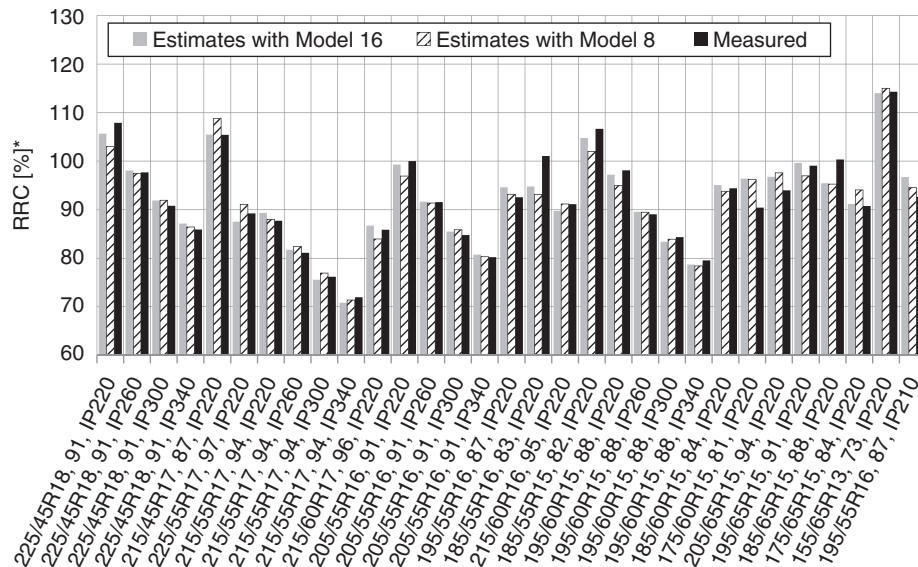


Fig. 8 Comparison of estimates of RRC from Model 16 and Model 8 with measured RRC (relative to 205/55R16's)

hand, RRC is linearly predicted to be decreased with respect to W in the simpler case of Model 8.

Considering the relation between the tire width and RRC, when the tire width gets narrower under a constant load condition, the contact length of the tire becomes longer and the bending deformation of the tire contact patch occurs, which causes hysteresis to increase. Therefore, prediction of Model 16 that the RRC will decrease in the extrapolated area of $W < 155$ does not agree with this general trend. On the other hand, the simple Model 8 approximates the relationship between the tire width W and the RRC in a linear fashion, so the trend agrees with this qualitative consideration and seems rational.

From the above discussion, with regard to at least the tire width, it can be seen that Model 16 shows high reproducibility in the range of the given sample, but its prediction accuracy may decrease if the estimation range is out of sample's range. When using the statistical RRC model, it is important to consider carefully whether to emphasize on the precision within the range given, or to examine under general trends, and to select an appropriate model according to the purpose.

5.2. Sensitivity Analysis

In the early stages of vehicle development, tire size determination, including size for derived models, is performed not only in terms of fuel consumption performance but also in consideration of load capacity and handling stability. In that case, it is necessary to measure all the RRC characteristics and cornering characteristics of the candidate tire with the conventional method⁽¹⁸⁾, and a new method to reduce the time and cost has been needed. Combining the proposed statistical RRC model with the

previously reported statistical C_p model makes it possible to search for initial specifications with good fuel economy and good handling performance in various derived models.

The predicted sensitivity of C_p and RRC by statistical model is calculated and shown in Fig. 10. The tire parameters W , H , D , P were varied with respect to 205/55R16, $L = 91$, $P = 220$ [kPa] respectively.

Plot D +1 is a case where the rim diameter D is raised from 16 inch to 17 inch. It is predicted that C_p will increase by 4% and RRC will also be reduced by 5%. Therefore, although the outer diameter of the tire increases, it can be seen that increasing the rim diameter can achieve both handling stability and fuel economy.

Likewise, if tire width W is increased by +10, the C_p increases by 4%, the RRC also reduced by 8%, and similar compatibility can be expected.

On the other hand, even if the inflation pressure P is increased by +20, the enhancement is only 1% for C_p and 4% for RRC. Therefore, the effect of the countermeasure for the handling performance by the tire inflation pressure will be limited if compared with the size change. Also, the decreasing aspect ratio H by -5 increases C_p by just 5% while it increases RRC by 13%. So handling performance and fuel economy becomes a tradeoff with this size change case.

For example, when trying to make an SUV with weight increase as a derivative model from a basic platform, and good fuel consumption should be realized while securing handling performance that can compensate for weight increase, it is suggested that a space layout, which allows both a larger rim diameter and wider tire, should be prepared in advance.

Next, in the case of size 225/45R18, the same sensitivity

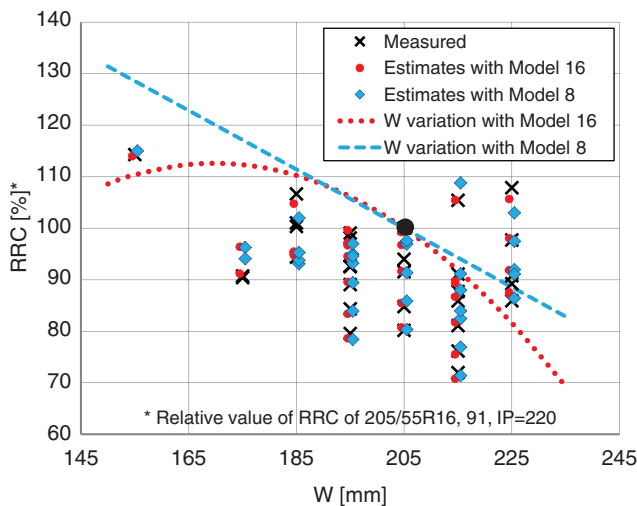


Fig. 9 Comparison of estimates of RRC from Model 16 and Model 8 with measured RRC with regard to tread width W

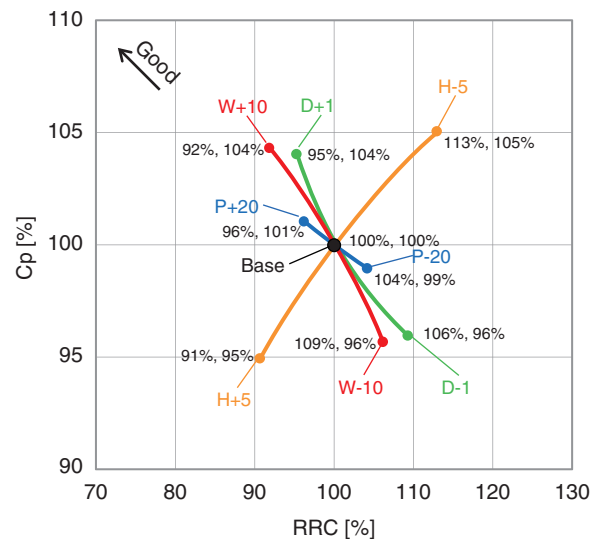


Fig. 10 Sensitivities of tire parameters W , H , D , and P of 205/55R16 tire on both cornering stiffness and RRC

is shown in Fig. 11. It is the case of the outermost size of the sample tire.

The sensitivity tendency of the size parameters W , H , and P is almost the same as 205/55R16, but the C_p sensitivity is slightly lower and the RRC sensitivity is slightly higher. In addition, the sensitivity of D to RRC is considerably low, and for the $D+1$ plot case, even if the rim diameter is increased, RRC increases and it is a prediction result that is highly unlikely to occur in reality.

In this example, the sensitivity analysis is performed on the size having W , H , and D , which are outermost in the sample statistics shown in Table 2. When the size parameter is extrapolated from the data sample used for modeling, it can be seen that the correlation cannot be guaranteed in this model.

In order to circumvent this, it is necessary to increase the number of samples with more variations, and/or to separate the data for model identification and the data for verification, and perform the verification. Also, when applying this method to development studies, it is necessary to accumulate know-how to select models appropriately depending on the application cases.

Regarding the prediction of tire RRC, correction method considering tire temperature, etc. is also being proposed⁽¹⁹⁾. As the fuel economy of automobiles advances, technologies for predicting RRC with higher precision are increasingly required.

By expanding this statistical tire modeling method, it is possible to conduct an initial examination utilizing existing tire measurement data, and it is possible to greatly support efficiency improvement of conventional chassis development.

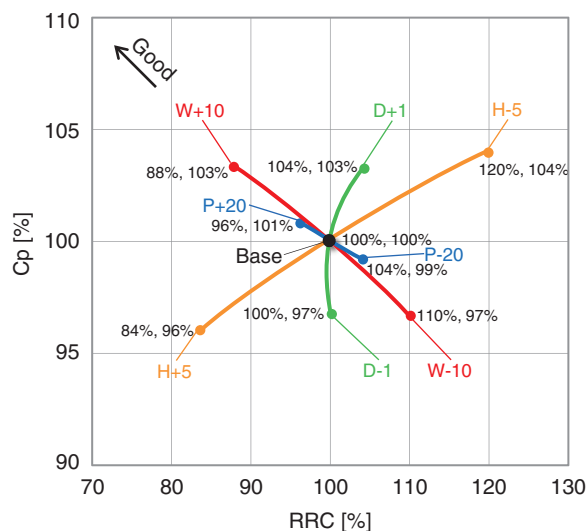


Fig. 11 Sensitivities of tire parameters W , H , D , and P of 225/45R18 tire on both cornering stiffness and RRC

6. Summary

In this paper, we extend the method of statistical tire models, which can decide the characteristics and size of tire rationally and efficiently at the initial development stage, to the prediction of rolling resistance coefficient of tire and obtained the following knowledge:

- (1) From the RRC measurement data that made the compound and structure of the tire the same brand, it turned out that the tire size and internal pressure are important factors affecting RRC.
- (2) Under certain compound and tire structures, it is possible to construct a model that estimates RRC based only on tire size and internal pressure, and the proposed model can explain about 90% of actually measured RRC fluctuation.
- (3) When the statistical RRC model is combined with the statistical C_p model, it became possible to study the tire size that can achieve both handling performance and fuel efficiency without conducting tire measurement.

The statistical RRC model reported in this paper would be able to be further expanded by incorporating measurement data of tire such as hysteresis characteristics of compound, tire weight, contact area of tire and contact length in the future.

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Elucidation of Hydrocarbon Purification Mechanism of Catalyst for Lean Burn Engine Using Surface Analysis and Ab-initio Calculation with Large-scale Cluster Model

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ABSTRACT

When a platinum supported acidic support catalyst is used as a hydrocarbon purification catalyst for lean burn engines, it shows a high level of purification performance. In order to elucidate the causal factors, the surface state of the platinum particles was analyzed by an X-ray absorption near-edge structure analysis and ab-initio calculations, with a density functional theory using a large-scale cluster model and slab model, were carried out. The results showed that platinum particles retain a metallic state when acidic support is used. It was also found that there is a distribution of charge in the platinum particles, and when platinum atoms in proximity to the support are positively charged, they are in a state that tends to resist the adsorption of oxygen. It was found from these results that the high level of purification performance of acidic supported platinum is due to the electronic activity of the acidic support, which helps to prevent oxygen adsorption on the surface of platinum in proximity to the support so that the catalyst yields high activity with respect to paraffin.

1. Introduction

The reduction of CO₂, which is said to be a greenhouse gas, is an urgent issue for humankind. In order to reduce the CO₂ emitted from automobiles, it is important to raise the thermal efficiency of the engine. Attention is being focused on lean burn engines for this purpose. Honda has reported research on homogeneous lean charge spark ignition (HLSI) as one solution^{(1),(2)}.

In the lean exhaust gas atmosphere that accompanies lean burn, however, the three-way catalyst that is normally used in a stoichiometric atmosphere faced the issue of reduced efficiency in purification not only of nitrogen oxides (NO_x), but also of hydrocarbons (HC). Figure 1 shows the HC concentration and HC composition of stoichiometric and lean exhaust gas^{(3),(4)}. It is apparent that the lean exhaust gas has a higher HC concentration, with a particularly high proportion of paraffin. Figure 2 shows the temperature characteristics of HC oxidation reactions. The purification of paraffin occurs at a higher temperature than olefin and aromatics, indicating that purification does not occur readily. These factors are thought to cause a reduction in purification efficiency in a lean atmosphere.

The authors have determined that a platinum supported acidic support catalyst is effective for paraffin oxidation reactions^{(3),(4)}. Figure 3 shows a conceptual image of the reaction in a platinum supported acidic support catalyst. Among the precious metals, platinum is known to yield high activity in paraffin oxidation reactions. In this scheme, paraffin and oxygen are adsorbed onto the surface of the platinum particles, where they react with CO₂ and H₂O and are desorbed. In a lean atmosphere there is an excess

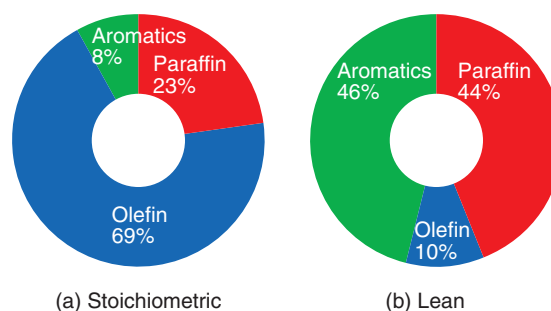


Fig. 1 HC composition in exhaust gas (HLSI, Ne: 1500 rpm, BMEP: 450 kPa)

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of oxygen relative to a stoichiometric atmosphere, so that oxygen is adsorbed onto the platinum surface, as shown in Fig. 3(a), and by covering the surface, it blocks the adsorption of paraffin and the reactivity is reduced. It was found, however, that when a high acidity material is used as a support for the platinum, it yields a higher level of paraffin oxidation activity. It has been inferred that when an acidic support is used, the electron-withdrawing effect of the acidic support causes the platinum particles to become electron deficient as shown in Fig. 3(b) so that the strength of the bond between the platinum surface and oxygen is reduced. This limits coverage of the platinum surface by oxygen and allows the paraffin and oxygen on the platinum surface to react more readily. However, the electron-withdrawing effect on the platinum caused by the acidic support and the limiting effect on oxygen adsorption by the platinum surface did not have sufficient detailed analysis or theoretical research. The present study is therefore founded on a research concept that combines an experimental approach in the form of surface analysis and so on together

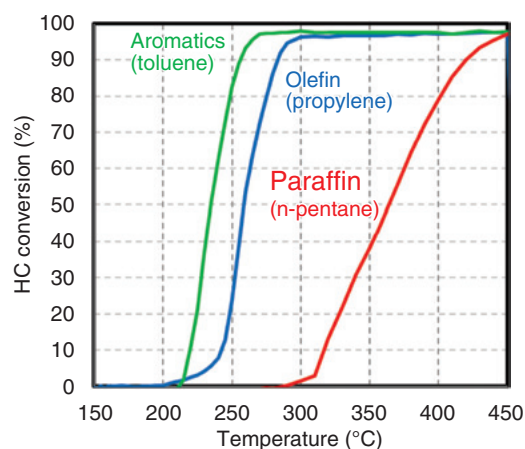


Fig. 2 Oxidation characteristic of HC (Catalyst: Three way catalyst, Aging: 750°C, Evaluation: O₂ 7%, HC 1200 ppm, CO 3000 ppm, NO_x 70 ppm, CO₂ 8%, H₂O 7%)

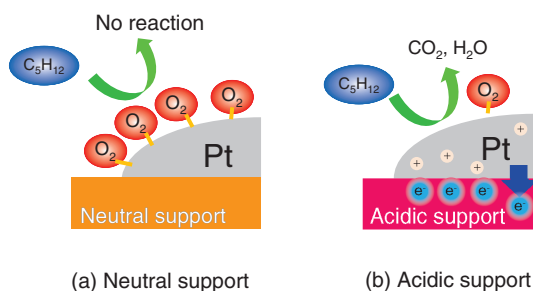


Fig. 3 HC purification mechanism of Pt supported catalyst

with a theoretical approach using ab-initio calculation for the purpose of substantiating the mechanism of high activity in a platinum supported acidic support catalyst that efficiently purifies paraffin.

2. Research Concept

The research conducted for this paper applied the following concept to the mechanism of high activity in a platinum supported acidic support catalyst that efficiently purifies the paraffin in lean burn exhaust gas.

Figure 4 shows a conceptual image of the configuration of a platinum supported acidic support catalyst. The catalyst material has an acidic oxide support, the surface of which supports platinum particles. This catalyst material is coated on a honeycomb surface and is used as a lean burn exhaust gas purification catalyst.

In order to obtain corroboration for the inferred scheme of reaction to the platinum supported acidic support catalyst, as shown in Fig. 3, three types of support material with different acidity were used as model materials. These three were SiO₂, Al₂O₃, and MgO. These were then used in the methods given as (1) to (3) below, and that evaluation of activity, analysis of material properties, and theoretical computation were conducted in a comprehensive examination of the matter.

(1) Evaluation of platinum supported catalyst activity

The activity is measured by using the reaction rate obtained for each catalyst through paraffin oxidation reaction tests, together with the platinum surface area obtained by CO adsorption amount measurement, to calculate the reaction rate per platinum atom.

(2) Clarification of the mechanism of high activity by analysis of material properties

The acidity of each support is determined by using ammonia temperature-programmed desorption (NH₃-TPD) to calculate the surface acid score of each support material. For the platinum supported catalyst, the amount of oxygen adsorption on the platinum surface is measured

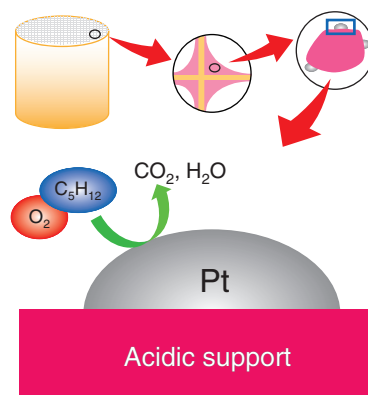


Fig. 4 Pt supported catalyst configuration

using O₂-TPD. Next X-ray absorption near edge structure (XANES) analysis is used to examine the electron state of the platinum particles. These are taken together to infer the causal factors for the activity difference measured in (1) from the influence that support acidity has on the platinum particles and platinum surface state.

(3) Corroboration of inference by theoretical computation

Calculations are made of the electron state of the oxygen adsorption characteristics using a large-scale platinum cluster model for each material and a platinum slab model that has the electron state altered deliberately. In this way, theoretical corroboration is obtained for the influence that the support acidity found in (1) and (2) has on activity and material properties.

For this research, the measures to calculate electron states using the large-scale platinum cluster model in (3) are of particular interest. The electron density of metals can be calculated by ab-initio calculation, and this method has been commonly used with automobile catalysts⁽⁵⁾,⁽⁶⁾. It does involve a computation cost, however, so there are limits on the number of atoms and calculations for structures combining multiple elements presented challenges. Consequently, there were few examples of investigation into calculations of support models with metal particles of a diameter, making them the same size as an actual catalyst⁽⁷⁾,⁽⁸⁾. For this paper, by contrast, the use of more efficient modeling techniques and the expansion of computer capabilities have made it possible to calculate the model for a structure of several hundred atoms supporting a large-scale platinum cluster. Therefore, it was decided to engage in calculations with cluster sizes more closely approximating reality.

On the other hand, ab-initio calculation of the oxygen adsorption state on a platinum surface was carried out without using a large-scale cluster model, which involves significant computation cost. The calculation was carried out instead using a platinum slab model to simulate the charge state on the platinum cluster surface. In this case, the slab model refers to a plate-shaped model with a specific index surface for the outermost surface and having a periodic boundary. Oxygen molecule adsorption is a phenomenon that occurs locally on the platinum metal surface. Therefore, an attempt was made to obtain calculation results more efficiently and in a shorter time by having the slab model represent only the atoms in those places considered likely to have a particularly large influence on adsorption.

The above research concept was used to elucidate the mechanism of high activity in a platinum supported acidic support catalyst used as an HC purification catalyst in a lean burn engine.

3. Experimental and Computational Methods

3.1. Samples

The platinum was supported by support material of different acidity and used as a platinum supported catalyst.

Table 1 Oxide materials

Type	Support material
Acidic oxide	SiO ₂
Neutral oxide	Al ₂ O ₃
Basic oxide	MgO

Table 2 Model gas composition

	Concentration
CO (ppm)	3000
HC (ppmC)	1200 (n-C ₅ H ₁₂)
NO (ppm)	70
O ₂ (%)	7
CO ₂ (%)	8
H ₂ O (%)	7

For the acidic support material, SiO₂ was used; for the neutral support material, Al₂O₃ was used; and for the basic support material, MgO was used (Table 1). Each support material was impregnated with platinum nitric acid solution, evaporated to dryness, and dried in an atmosphere at 150°C for 15 hours. It was then calcined in an atmosphere at 500°C for two hours and used as catalyst material. For analysis, support material powder and catalyst powder were used. For reaction testing, the catalyst material coated on cordierite honeycomb was used. The honeycomb had 900 cells, a thickness of 2.5 mils, a diameter of one inch, and a length of 30 mm.

3.2. Reaction Test Method

The purification performance evaluation of the catalyst was carried out using a model gas reactor. The composition of the model gas is shown in Table 2. It has a space velocity of 100000 h⁻¹. While the catalyst was exposed to the model gas flow, it was heated from room temperature to 400°C. The catalyst exit gas was analyzed and the purification rate before and after the catalyst was calculated. The catalyst was used after hydrothermal aging at 750°C for 20 hours.

3.3. Analysis Method

3.3.1. Measurement of number of atoms on platinum surface

The number of atoms on the platinum surface was measured by the CO adsorption amount. Pretreatment consisted of heating to 400°C in a flow of helium gas, followed by keeping at a constant 400°C in an H₂ atmosphere for 15 minutes. The temperature was then lowered to an ambient temperature in a flow of helium gas, after which a CO pulse of 200 mm³ was injected three time or more until the exit CO concentration was stable. The adsorption amount was then measured.

3.3.2. Acidity measurement

The evaluation of acidity was carried out using NH_3 -TPD. This method evaluates acidity according to the characteristic whereby a larger adsorption amount of NH_3 , which is a base, indicates higher acidity. The NH_3 desorption amount was measured after first heating the sample to 500°C in a helium atmosphere for 60 minutes and then exposing it to a flow of 0.5% NH_3 at 100°C for 60 minutes, following which it was heated from 100°C to 600°C in a flow of helium. After this pretreatment, the NH_3 desorption was measured using a quadruple mass spectrometer.

3.3.3. Oxygen adsorption amount measurement

Measurement of the oxygen adsorption amount was carried out using O_2 -TPD. Pretreatment consisted of holding the sample at 500°C in an oxidizing atmosphere for 60 minutes. It was then exposed to a flow of helium and heated from ambient temperature to 900°C , after which the oxygen desorption amount was measured using a quadruple mass spectrometer.

3.3.4. Electron state analysis

XANES measurement was carried out to examine the electron state of the platinum particles. The analyzing device was the BL-11 line at the Kyushu Synchrotron Light Research Center (case number 1606044G). An Si(111)2 crystal spectrometer and an ion chamber detector were used. Measurement was carried out in vacuum by the transmission method to obtain Pt-III Edge spectra for analysis.

3.4. Ab-initio Calculation Method

3.4.1. Creation of large-scale cluster model

Theoretical calculation of the electron state necessitates modeling of the platinum support state on the support. It is conceivable that, in creating a large-scale cluster model, the atomic arrangement and electron state of the stable structure that is finally obtained through ab-initio calculation may end up in a state that depends on the initial atomic arrangement. Therefore, the initial atomic arrangement, as shown in Fig. 5(a) and (b), does not have the platinum atoms arranged manually. The procedure used here to create the model instead set up the atomic arrangement in a broad

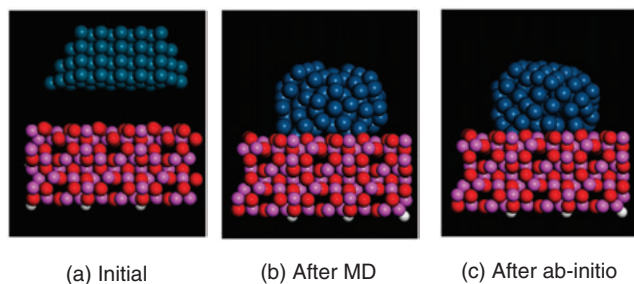


Fig. 5 Cluster model of Pt supported catalyst

Table 3 MD calculation conditions

Item	Detail
Software	LAMMPS
Potential	Lennard-Jones
Simulation time, Time step	500.0 ps, 1.0 fs
Ensemble condition	NVT

Table 4 Ab-initio calculation conditions

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

manner using classical molecular dynamics (MD) so that the energy field between the atoms could be considered on a macro scale. After that, the stable structure was calculated in detail from the ab-initio calculation, which takes quantum mechanics into consideration. Then the model was completed as shown in Fig. 5(c).

The above method combining MD calculation and ab-initio calculation was employed because it was reasoned that this would enable more efficient modeling of a platinum support state that is closer to reality. Specifically, in order to simulate the state of platinum particles approximately 1 nm in diameter, supported on an oxide support, a model was created in which there is a platinum cluster consisting of approximately 100 atoms on an oxide support with about five layers.

3.4.2. Molecular dynamics calculation

The calculation was carried out with the atoms of the oxide support in a fixed state and an initial velocity given only to the platinum atoms supported. Table 3 shows details of the calculation conditions.

3.4.3. Ab-initio calculation

For this paper, the electron state of the platinum was analyzed using ab-initio calculation based on density functional theory. For this purpose, a platinum support cluster model was used to analyze the electron state of the supported platinum, and a platinum slab model was used to analyze oxygen adsorption on the platinum. For calculation of the platinum support cluster model, structure optimization calculation was carried out with that half of the platinum on the side not supported by the oxide support in a fixed state. For the platinum slab model, a model of 32 atoms in eight layers was adopted. The oxygen molecules and the three layers of platinum atoms from the outermost surface down were subjected to structure optimization calculations. All of the calculations were carried out under the conditions shown in Table 4⁽⁹⁾⁻⁽¹¹⁾.

4. Results of Experiment and Calculation

4.1. Evaluation of Activity of Platinum Supported Oxide Catalyst

Testing was performed of the paraffin purification performance of platinum oxide catalyst with platinum supported on oxides of differing acidity, and the amount of platinum on the surface was calculated from measurements of the CO adsorption amount. Turn over frequency (TOF) was used as an index for purification activity. As shown in Eq. (1) below, the TOF is a figure that indicates the number of reactions per unit of time per atom of active metal. It is commonly used as an index of activity.

$$\text{TOF(/sec)} = \frac{\text{Reaction rate (mol/sec)}}{\text{Amount of active metal on surface (mol)}} \quad (1)$$

The reaction rate at 300°C and the surface platinum amount in the purification performance evaluation results were used in Eq. (1) to determine the TOF. Those results are shown in Table 5. It was observed from these results that the catalyst using an acidic support, which was Pt/SiO₂, had the highest TOF. Considering also that the Pt/SiO₂ catalyst had a surface amount of platinum that was one order of magnitude smaller than the other two catalysts, it could be inferred that progressive aggregation of the platinum particles is taking place. Despite that, however, it was found that the platinum atoms on the surface maintained a high level of activity.

4.2. Inference of Causal Factors of High Activity According to Analysis of Material Properties

4.2.1. Examination of oxide support acidity

The acidity of each oxide was evaluated using measurements of the NH₃ adsorption amount and the results are shown in Table 6. As anticipated, these results confirmed that the NH₃ adsorption amount is greater in descending order of SiO₂, Al₂O₃, and MgO, and that the acidity is greater in this order.

4.2.2. Characteristics of oxygen adsorption on the platinum surface

It was inferred that the reason for the higher paraffin purification performance of acidic support, as shown in Fig. 3, was that oxygen adsorption on the platinum surface was inhibited. The oxygen adsorption amount was therefore measured by O₂-TPD in order to ascertain the characteristics of oxygen adsorption by the platinum oxide catalyst. The results are shown in Table 7. The oxygen adsorption amount was greater in descending order in Pt/MgO, Pt/Al₂O₃, and Pt/SiO₂. In other words, this suggests that the catalyst using SiO₂ with its higher acidity as a support has the effect of reducing oxygen adsorption on the platinum. According to this effect, support material with higher acidity would have a correspondingly smaller amount of adsorbed oxygen on the platinum surface. It was inferred

Table 5 Calculation of TOF in Pt supported catalyst

Catalyst	Conversion (%)	Pt amount (μmol)	TOF (/sec)
Pt/SiO ₂	48.0	2.4	0.44
Pt/Al ₂ O ₃	70.0	29.0	0.04
Pt/MgO	30.0	28.0	0.02

Table 6 Amount of NH₃ adsorption in NH₃-TPD

Material	NH ₃ ads. (μmol/g)
SiO ₂	63
Al ₂ O ₃	23
MgO	2

Table 7 O₂ adsorption amount on Pt in O₂-TPD

Catalyst	O ₂ ads. (μmol/g)
Pt/SiO ₂	4
Pt/Al ₂ O ₃	12
Pt/MgO	50

that this would allow paraffin to be more readily adsorbed on the platinum surface, advancing the oxidation reaction so that the TOF was higher.

4.2.3. Platinum electron state analysis

It was inferred that oxygen adsorption on the platinum was inhibited due to the different electron state of the platinum particles on the various oxides. XANES measurement was therefore carried out. At this time, measurements were also made of platinum foil for the purpose of comparison of the metal state and measurements of a piece of PtO₂ for the purpose of comparison of the oxidation state. The results are shown in Fig. 6. It was apparent from these results that the peak representing the platinum on SiO₂ is closest to the peak for platinum foil. The peak location shifts increasingly in the direction of the PtO₂ piece with Al₂O₃ and MgO, in that order. In other words, this indicated that platinum on the SiO₂ is closest to

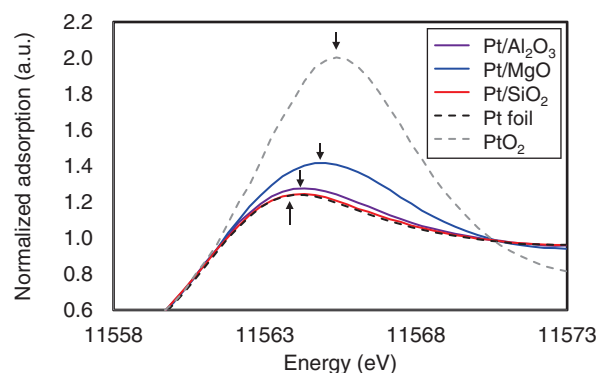


Fig. 6 XANES spectrum of Pt supported catalyst

the metallic state. This further confirmed that the Pt/SiO₂ catalyst inhibits oxygen adsorption on the platinum surface.

4.3. Corroboration of Inferences Based on Theoretical Computation

4.3.1. Ab-initio calculation based on cluster model

An analysis of material properties suggested that the electron state of platinum particles influence the enhanced performance of oxide catalysts. In order to clarify the kind of electronic influence the support has on platinum particles, therefore, calculations were made of the electron state of a cluster model with a platinum cluster arranged on an oxide support. Figure 7 shows the cluster models for each oxide. In every case, the platinum cluster was a globular form in a stabilized state supported on the oxide support. Due to the differences in support material, however, the platinum clusters ended up taking different shapes. It is inferred that this is due to the different ways in which the support materials and platinum clusters interact.

In order to ascertain the electron state of the platinum clusters in these platinum cluster models, the clusters as a whole were subjected to Hirshfeld charge analysis. The results are shown in Table 8. It was found from these results that the positive charge amount is higher in SiO₂, Al₂O₃, and MgO, in decreasing order. In other words, this can be interpreted to mean that when the support has higher acidity, the platinum cluster will have an electron deficiency. The cause of this could be that the acidic oxide support has greater electron-withdrawing force than other oxides.

Further calculation was also made of the electron state of each individual atom making up the platinum cluster and the charge distribution within the platinum cluster was examined. Figure 8(a) to (c) shows the charge distribution in the platinum clusters. The vicinity of the XY plane in the figures is the point of contact with the support oxide. The charges of all the atoms within the platinum cluster in the model were color coded and plotted on their coordinates. In every figure from (a) to (c), the charge distribution within the platinum cluster is uneven. The positive charges were concentrated in the vicinity of the point of contact with the support while the negative charges were concentrated in the upper part of the cluster. The positive charges were localized in a particularly conspicuous manner in the vicinity of the

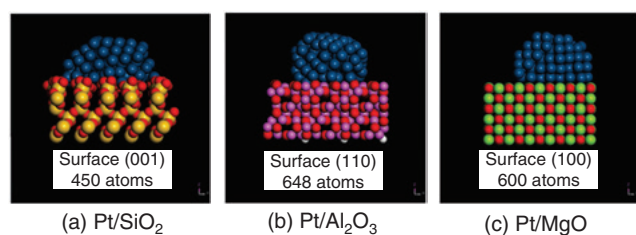


Fig. 7 Cluster models of Pt supported catalyst

Table 8 Charge of Pt cluster

	Pt/SiO ₂	Pt/Al ₂ O ₃	Pt/MgO
Total charge of Pt cluster	5.93	3.1	0.19
Maximum + charge	0.32	0.31	0.06
Maximum - charge	-0.02	-0.04	-0.05

point of contact with the support in the charge distribution for the platinum cluster on Pt/SiO₂ shown in Fig. 8(a). It can be inferred that this occurs because the SiO₂ is an acidic support with an electron-withdrawing effect that results in electrons travelling from the platinum to the support in the vicinity of the point of contact with the support, so that the lower part of the platinum cluster instead becomes positively charged.

It was found from the above that ab-initio calculation based on the cluster model showed the support with higher

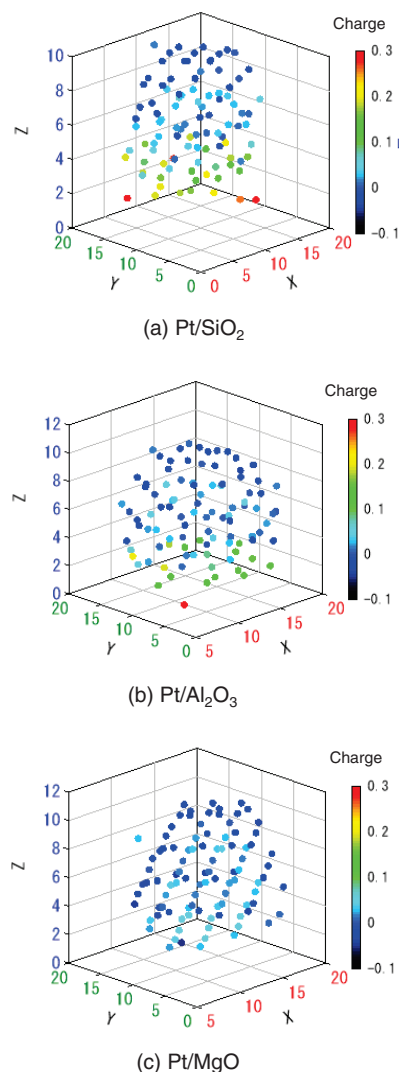


Fig. 8 Charge distribution of Pt cluster

acidity had correspondingly greater electron-withdrawing effect. This caused the platinum particles as a whole to have a greater positive charge, and the positive charge was concentrated in the vicinity of the interface.

4.3.2. Oxygen molecule adsorption on platinum according to the slab model

It can be seen from Fig. 8 that the state of the surface charge on the platinum cluster differs in the acidic support and basic support. With the acidic support, in particular, the upper part of the platinum cluster is negatively charged while the part close to the support is positively charged. It was inferred, therefore, that this difference in the charged state could be having an influence on oxygen adsorption characteristics. A platinum slab model was therefore created to recreate the upper part of the platinum cluster and the portion close to the support and the oxygen adsorption energy was compared in order to investigate the kind of influence that the surface charge state of the platinum cluster has on oxygen adsorption characteristics. A slab model with Pt₃₂ atoms as shown in Fig. 9(a) was created for this purpose.

Next, in order to control the charges state of the platinum surface in the slab model, additional charges were applied to the slab model to give it different levels from -3 to +3, as shown in Fig. 9(a). The ab-initio calculation was carried out using this model. The result, as shown in Table 9, was that the applied charges succeeded in changing the surface charge of the platinum slab model within a range from -0.240 to +0.212. In addition, it was confirmed that the charge states of the platinum atoms in the three platinum cluster models shown in Table 8, which ranged from -0.05 to +0.32, were generally reproduced. This suggests that the surface states of the upper part of the platinum cluster and of the portion close to the support were simulated successfully.

4.3.3. Calculation of characteristics of oxygen adsorption on platinum in the slab model

The next step was to ascertain the influence that the electron state on the platinum surface has on oxygen

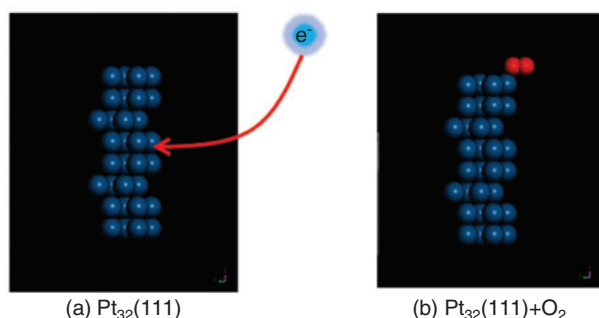


Fig. 9 Pt slab model and Pt+O₂ slab model

Table 9 Charge level of Pt surface

Total charge amount	-3	-1	0	1	3
Charge level of surface Pt atom	-0.240	-0.093	-0.017	+0.060	+0.212

adsorption characteristics. For this purpose, a model was created that has O₂ molecules adsorbed on the surface of the slab model shown in Fig. 9(a). Figure 9(b) shows a schematic illustration of this model. Ab-initio calculation of this model was carried out and Eq. (2) was then used to calculate the O₂ adsorption energy from the calculated energy before and after adsorption.



The results are shown in Fig. 10. The greater the charge applied, the larger ΔE_{ads} becomes. Where the charge was +3, the oxygen ends up being desorbed from the platinum surface following the stabilization calculation. In other words, this indicates that the greater the extent to which the platinum surface becomes positively charged, the more unstable the oxygen adsorption state will become, entering a state that tends to resist adsorption. From this it can be inferred that although a positive charge was concentrated on the platinum surface on the part of the platinum cluster close to the support in Fig. 8(a), the platinum surface of the part close to the support was in a state that tends to resist oxygen adsorption. This suggests, therefore, that the platinum surface close to the support on the platinum supported acidic support becomes a highly active site and promotes reaction.

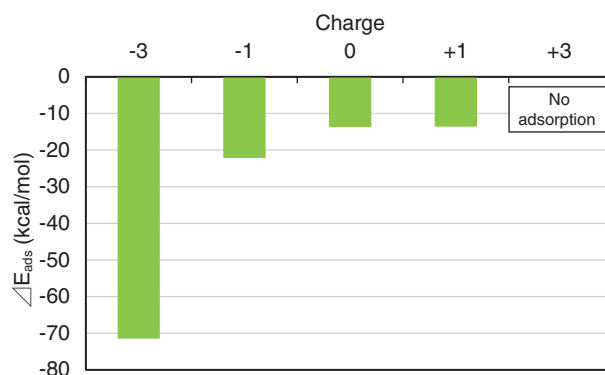


Fig. 10 Oxygen adsorption energy on Pt surface

5. Discussion

When the results to this point are consolidated, they show, first of all, that the paraffin oxidation reaction of platinum supported catalyst using the SiO₂, Al₂O₃, and

MgO that were selected as model materials present the highest TOF and so the highest level of activity with the SiO₂. This confirms that the use of an acidic support yields higher paraffin oxidation performance. The analysis of material properties also shows that when the acidity of the support is higher, the electron state of the platinum particles will be in a metallic state. This shows that since oxygen adsorption is successfully inhibited, the use of an acidic support maintains the platinum in a state that tends to inhibit oxidation. It is further shown by ab-initio calculation that acidic support causes the platinum surface close to the support to become positively charged, and the oxygen adsorption state becomes unstable. This provides theoretical corroboration for the inhibition of oxygen adsorption.

Based on these results, the mechanism that promotes paraffin oxidation performance by means of the acidic support is as shown in Fig. 11. Since the acidic support withdraws electrons from the platinum particles, the platinum particles become electron deficient. This electron-withdrawing effect acts with particular effect on platinum atoms that are close to the acidic support, causing them to become positively charged, and the adsorption of oxygen consequently tends to be inhibited. The result of this is that the adsorption of paraffin is not blocked and paraffin oxidation reactions tend to proceed more readily. Therefore, the reaction mechanism that was inferred initially has been successfully corroborated by a combination of evaluation of activity, analysis of material properties, and theoretical computation.

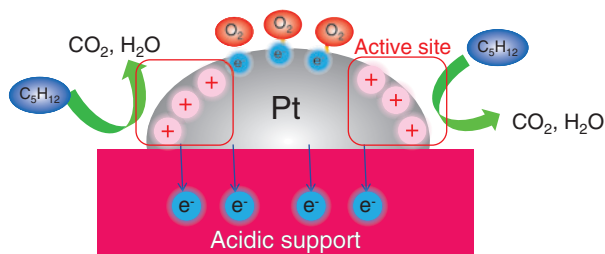


Fig. 11 Schematic image of HC oxidation on Pt supported catalyst

6. Conclusion

Platinum supported acidic support catalyst yields high performance as an HC purification catalyst for lean burn engines. The mechanism that causes that performance was elucidated by selecting SiO₂, Al₂O₃, and MgO as acidic, neutral, and basic model materials and subjecting them to evaluation of activity, analysis of material properties, and ab-initio calculation. The following was learned as a result:

- (1) The evaluation of activity showed that higher acidity in

the support results in correspondingly higher paraffin purification performance.

- (2) The analysis of material properties showed that when platinum particles are on an acidic support, they more readily retain a metallic state and oxygen adsorption on the platinum surface is inhibited.
- (3) The ab-initio calculation showed that platinum particles on an acidic support are positively charged and that the positive charge is particularly concentrated on the surface of platinum particles that are close to the support. It was also found that when the surface of a platinum particle is positively charged, it tends to resist the adsorption of oxygen.

These observations successfully corroborated that the cause of the high level of purification performance shown by platinum supported acidic support catalyst is the electron activity of the acidic support, which inhibits oxygen adsorption on the surface of platinum that is close to the support, and that this produces the high level of activity.

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Development of Calendar Aging Model for Lithium Ion Rechargeable Batteries

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ABSTRACT

A new life prediction model was developed on the basis of lithium ion rechargeable battery analysis results. This makes it possible to predict an accurate battery capacity fading status that is dependent on storage time and to shorten the time for acquisition of experimental data required for prediction. For this model, attention was focused on the fact that the various causes of aging are electrochemical reactions that occur within the battery, and model equations that have terms for temperature and energy were adopted for this model. The variables that are required in the established equations were determined by curve fitting with the results from accelerated calendar aging tests conducted at three temperature conditions and three state of charge conditions, for a total of nine conditions. The variables obtained from the accelerated calendar aging test conducted at 65°C and state of charge of 80% yielded prediction results that matched the experiment values. Since this model can also be applied to predict the charge and discharge curves of a battery that has aged, it is anticipated that the model can be further applied to estimate the state of charge from the battery terminal voltage.

1. Introduction

As lithium ion rechargeable batteries enter widespread use, there are growing needs for prediction of remaining life and for analysis of aging state, regardless of whether it is for aging caused by repeated cycles of charge and discharge (cycle aging) or for aging caused by storage (calendar aging). In some cases, spare batteries used as service parts need to be available for long-term supply, for as many as 10 years or more after production has finished, as long as there is demand for them. This means that life prediction technology is needed for defining the needed conditions for long-term storage. When batteries are used for emergency power supply, their performance in a long-term stand-by state needs to be guaranteed, and life prediction by calendar aging is therefore a crucial technology. At present, life predictions for 10 years or more are being made from limited data for about two years of testing⁽¹⁾⁻⁽⁶⁾ due to the need to shorten development time. In such cases, the method used is to carry out accelerated calendar aging tests at a higher temperature than the temperature during actual use or at a higher state of charge (SOC), and then to predict aging in the envisioned temperature range of use

by means of the Arrhenius equation. Working from the results for capacity fading due to calendar aging, Su et al.⁽⁴⁾ derived an equation that is similar to the Arrhenius equation to express the aging rate as a function of temperature and SOC. However, battery aging is not something that occurs due to just a single factor⁽⁷⁾⁻⁽¹⁰⁾, so issues are likely to remain regarding the accuracy of aging rate values obtained using just a single equation. There is also the work of Ouyang et al.⁽⁵⁾, which divides the cause of cycle aging between the loss of cyclable lithium, in other words the capture of active lithium by solid electrolyte interphase (SEI) between the electrodes so that there is less active lithium flowing between the electrodes, and single-electrode capacity fading. The respective aging rates were expressed using the Arrhenius equation, incorporating elements from empirical equations when representing the C-rate effect. These approaches all include empirical equations that are not based on the aging mechanism^{(4), (5)}, so issues are likely to remain regarding the accuracy of values obtained by long-term life prediction using limited data from short-term testing.

In a previous report⁽⁷⁾, the authors elucidated the mechanism of calendar aging in high-power lithium ion

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rechargeable batteries and clarified that the principal causes are the loss of active lithium and cathode capacity fading. (These two causes will be referred to hereafter as the aging mechanism.) The purpose of the present research, therefore, has been to create a predictive equation that is based on this aging mechanism and that accords with physical law, and in this way to establish a method for predicting the capacity fading of a cell more accurately from data obtained through short-term testing.

2. Creation of the Prediction Model

2.1. Issues in Conventional Model Equations

As stated above, methods of conducting accelerated tests and employing the Arrhenius equation to predict the aging that will occur in the envisioned temperature range of use were widely proposed⁽¹⁾⁻⁽⁶⁾ for the purpose of shortening the storage test period. However, there are two general types of enhancement that would be desirable for these methods. The first is the need to apply equations that divide battery capacity fading between the cathode and the anode, and the second is to apply the relationship between aging and SOC to the prediction equation.

The former, as has already been reported⁽⁷⁾, arises from the fact that battery aging is not caused by a single chemical reaction, and battery capacity fading therefore cannot be accurately expressed in a single equation⁽⁸⁾⁻⁽¹⁰⁾. The latter arises from the fact that the Arrhenius equation does not clearly express the relationship with SOC. Actually, as shown in Figs. 1 and 2, both cathode and anode display aging behavior that is dependent on SOC (potential), but unless the prediction equation is dependent on SOC, tests will need to be conducted under various SOC conditions so as to determine the dependence on SOC. A prediction equation that includes the relationship between aging and SOC will also be needed in order to cut back on test conditions.

2.2. Extending the Arrhenius Equation to Include Dependence on SOC

The battery aging mechanism can be understood as a change in the form of matter that occurs in conjunction with electrochemical reactions. In the batteries described in this paper, the active lithium amount loss was caused by SEI formation while cathode active material capacity fading was caused by a crystalline structure transformation. This kind of change of state can be expressed by the Arrhenius equation, as shown in Fig. 3(a). The chemical reaction rate k in the process of transition from State A to State B (the chemical reaction process) is expressed using the activation energy E_0 and the temperature T during the process of state transition. In order to provide for dependence on the electrode potential, or in other words the SOC, the energy on the State A side is raised by the external potential V , as shown in Fig. 3(b). As a result, the activation energy that was initially E_0 is reduced by the amount αV . Here α

is a transfer coefficient that is assigned a value of about 0.5. As a result, the reaction rate, which is dependent on the external potential V , can be expected to increase. The model equations were formulated according to this conceptual approach. The conceptual approach for this SOC dependence is the same as for the overpotential dependence in the Butler-Volmer equation⁽¹¹⁾, so the Arrhenius equation extended to include SOC is hereafter referred to as the Butler-Volmer equation.

2.3. Derivation of Model Equations for Active Lithium Loss

As reported in the previous paper⁽⁷⁾, SEI is an accumulation on the anode surface of products of the decomposition of the electrolyte components, including

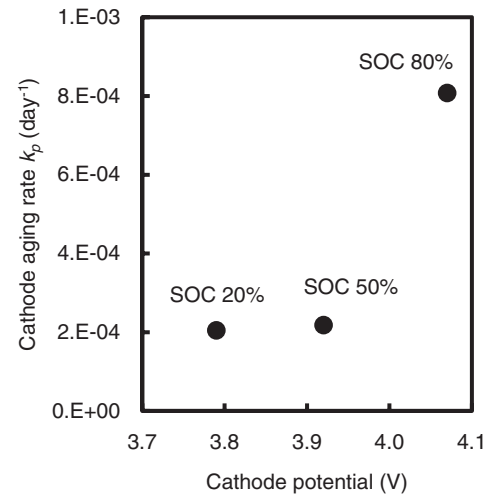


Fig. 1 Cathode aging rate. $Q_{cathode}(t) = (1 - k_p t) Q_{cathode-initial}$ (aging condition: 65°C)

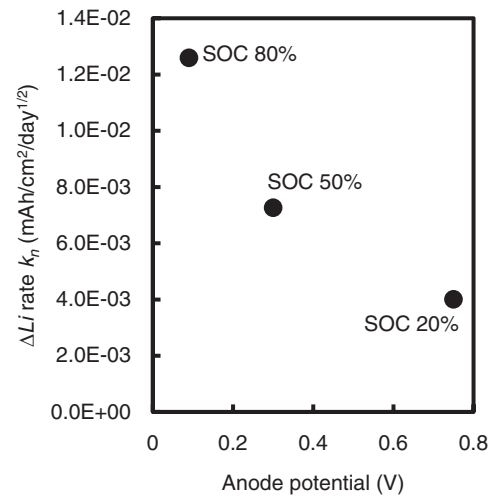


Fig. 2 Anode ΔLi increasing rate. $\Delta Li(t) = k_n \sqrt{t}$, $\Delta Li = Q_{shift} + Q_{cathode}$ (aging condition: 65°C for 100 days)

cyclable lithium, or in other words, active lithium flowing between the electrodes, and this accumulation results in the loss of active lithium. Since this decomposition occurs by an electrochemical reduction reaction^{(7), (12)-(19)}, the Butler-Volmer equation determines the rate of that reaction by the electrode potential at the anode, the reaction temperature, and the concentration of the reactant. The reactant exists in large amounts in the electrolyte, and it is assumed that changes in its concentration over the battery lifetime can be ignored. Therefore the reactant concentration can be treated as a constant. Taking the electrical conductivity of the SEI into consideration, a correction was made to the electrode potential at the anode according to the following rationale.

An ideal SEI is an electrical insulator, and as a solid electrolyte membrane, it can only conduct lithium ions. However, the SEI in an actual battery is said to have slight

electrical conductivity due to the doping effect of electrolyte components⁽¹⁵⁾⁻⁽¹⁷⁾. The gradual SEI growth in lithium ion rechargeable batteries occurs because of this slight electrical conductivity. In such cases, the value of the activation energy of SEI growth will be the difference between the reaction equilibrium potential of the electrolyte components and the electrode potential from which the reduction in potential due to the electroconductive resistance of the SEI is further subtracted. When the term for activation energy in the reaction equilibrium potential is $E_{0,n}$ and the anode overpotential is V_n , the activation energy, as shown in Fig. 3(b), will be reduced by $\alpha_n V_n$ so that it will be $(E_0 - \alpha_n V_n)$. When the SEI thickness is x while the electrical conductivity and electrical resistance of SEI are σ_{SEI} and ρ_{SEI} , respectively, then the term for activation energy will be $\left[E_{0,n} - \alpha_n \left(V_n - \frac{F}{\sigma_{SEI}} x \right) \right]$. Here F is the Faraday constant.

Therefore the SEI growth rate $\frac{dx}{dt}$ can be expressed by Eq. (1) using the Butler-Volmer equation^{(11), (15)}.

$$\nu_{Li} = \frac{dx}{dt} = \frac{N_s - \Delta Li}{N_s} \frac{M_{SEI}}{F \rho_{SEI}} A_n \exp\left(-\frac{E_{0,n}}{RT}\right) \exp\left(\frac{\alpha_n V_n}{RT}\right) \exp\left(-\frac{\alpha_n F}{RT} \frac{1}{\sigma_{SEI}} x\right) \quad (1)$$

Here t is time, N_s is the number of moles of active lithium in the anode, ΔLi is the number of moles of active lithium loss, M_{SEI} is the molecular weight of SEI components, A_n is the frequency factor in the Arrhenius equation, R is the gas constant, T is the absolute temperature, and α_n is the transfer coefficient.

Here k_{s1} and k_{s2} are inserted to form the following:

$$k_{s1} = A_n \exp\left(-\frac{E_{0,n}}{RT}\right) \exp\left(\frac{\alpha_n V_n}{RT}\right) \quad (2)$$

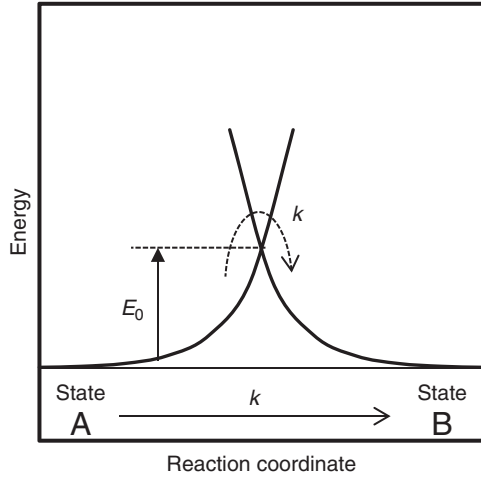
$$k_{s2} = -\frac{\alpha_n F}{R} \frac{1}{\sigma_{SEI}} \quad (3)$$

Equation (1) can therefore be expressed as Eq. (4):

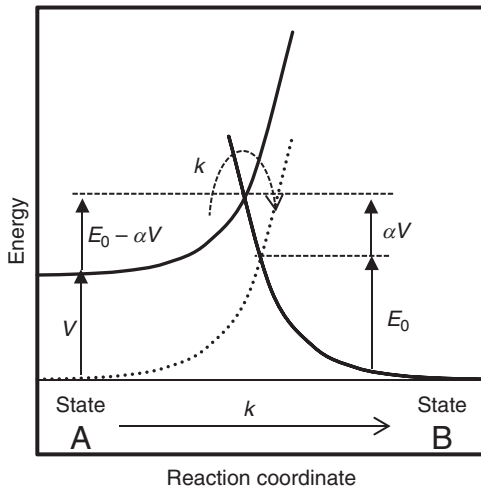
$$\nu_{Li} = \frac{dx}{dt} = \frac{N_s - \Delta Li}{N_s} \frac{M_{SEI}}{F \rho_{SEI}} k_{s1} \exp\left(-\frac{k_{s2}}{T} x\right) \quad (4)$$

The term for k_{s2} expresses the electrical conductivity of SEI, and this is considered to be similar to the mechanism of electrical conductivity in semiconductors⁽¹⁵⁾. In a semiconductor, electrical conductivity occurs due to scattered carriers, and so it is known to be proportional to the temperature raised to the power of 3/2. Therefore k_{s2} can be expressed as shown in Eq. (5), as a function of $T^{3/2}$.

$$k_{s2} = k_{2a} T^{\frac{3}{2}} + k_{2b} \quad (5)$$



(a) Activation energy in transition from State A to State B



(b) Changes in activation energy in case of application of electric potential

Fig. 3 Potential expansion of Arrhenius law in state transition of chemical reaction

In Eqs. (1)-(5) above, V_n , T , and time t are set according to the test conditions, while the variables A_n , $E_{0,n}$, α_n , k_{2a} , and k_{2b} can be determined by fitting the active lithium loss amount derived from electrochemical measurement. Specific usage data groups are given at the beginning of Section 3.1.

2.4. Derivation of Model Equations for Cathode Active Material Capacity Fading

Cathode capacity fading occurs as a result of partial crystalline structure transformation of cathode active material^{(7), (20), (21)}. Its rate v_p is governed by the reaction temperature and cathode potential. As with the anode, v_p can be expressed as Eqs. (6) and (7) using the Butler-Volmer equation⁽¹¹⁾.

$$v_p = k_p \quad (6)$$

$$k_p = A_p \exp\left(-\frac{E_{0,p}}{RT}\right) \exp\left(\frac{\alpha_p V_p}{RT}\right) \quad (7)$$

Here k_p is the rate of crystalline structure transformation of cathode active material determined by testing, A_p is the Arrhenius equation frequency factor, $E_{0,p}$ is the reaction equilibrium potential, α_p is the transfer coefficient, and V_p is the cathode potential. As with the anode, V_p , T , and time t are set according to the test conditions, k_p is determined from testing, and A_p , $E_{0,p}$, and α_p can be derived by curve fitting using Eqs. (6) and (7). Since V_n and V_p are determined by approximation from the battery SOC-Open Circuit Voltage (OCV) curve (Fig. 4), the values defined as test conditions are SOC and retention temperature T .

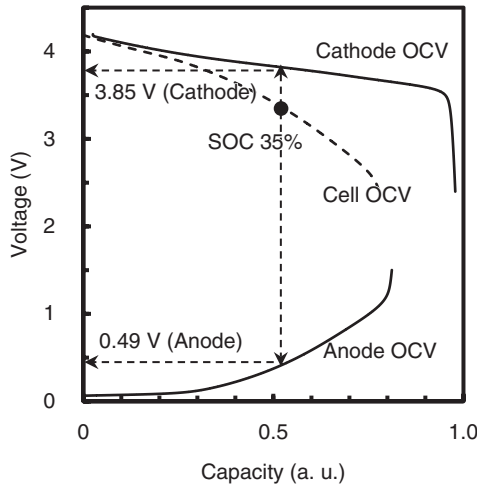


Fig. 4 Calculation of electrode potential from SOC-OCV curve

3. Analysis Results and Discussion

3.1. Computed Prediction of Active Lithium Loss Amount

The results of electrochemical measurement given in the previous report⁽⁷⁾ and Eqs. (8) and (9) were used to calculate the loss amount of active lithium ΔLi . The battery storage periods were defined up to 180 days, and SOC of 80%, 50%, and 20%, together with temperatures of 65°C, 55°C, and 45°C were used for the respective conditions.

$$\Delta Li = Q_{shift} + \Delta Q_{cathode} \quad (8)$$

$$Q_{shift} = Q_{R, cathode} - Q_{R, anode} \quad (9)$$

Here Q_{shift} is the amount of shift, while $Q_{R, cathode}$ and $Q_{R, anode}$ are the remaining discharge capacity of the respective electrodes and $\Delta Q_{cathode}$ is the cathode capacity fading value.

The variables A_n , $E_{0,n}$, α_n , k_{2a} , and k_{2b} were successfully determined from the active lithium loss amount determined by Eq. (8) together with fitting using model equations Eqs. (2)-(5). These values were then plugged back into the model equations again and the active lithium loss amount was predicted (Fig. 5) for validation. The various symbols in the figure represent actual measurements and the lines indicate predicted values. The active lithium loss amount predicted to occur after 180 days or more matched with the actual measurement. This result indicates that the active lithium loss amount can also be predicted over a long term, extending beyond the test period.

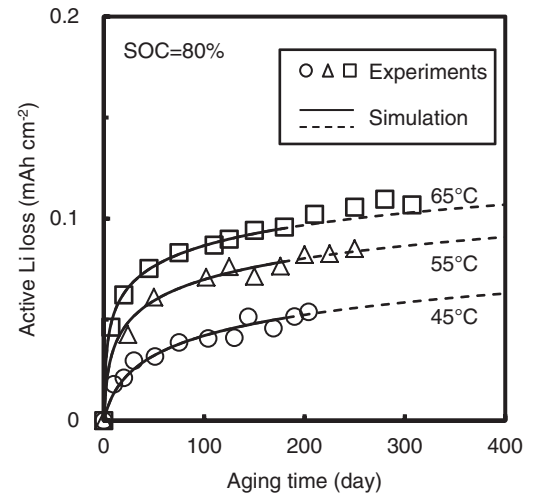


Fig. 5 Parameter fitting for active Li loss by SEI growing

3.2. Computed Prediction of Cathode Active Material Capacity Fading

As reported in the previous paper, the cathode capacity fading value $\Delta Q_{cathode}$ can be measured directly, and its change over time is shown in Fig. 6. These values were used for curve fitting in accordance with Eqs. (6) and (7) to derive the variables A_p , $E_{0,p}$, and α_p .

3.3. Computed Prediction of Battery Capacity Retention

The variables derived in Sections 3.1. and 3.2. were plugged in to the model equations and the results were used to determine the charge and discharge curves for the

electrodes after the passage of a certain amount of time together with the shift amount Q_{shift} . The concept illustrated in Fig. 7 was then followed to rebuild the full cell charge and discharge curves. As a result, it was possible to predict the battery's charging and discharging characteristics and capacity at a certain SOC and a certain temperature and after a certain amount of time. This made it possible to predict battery life below the low limit value set for capacity (Fig. 8). The parameters used were derived from data for up to 180 days at the retention temperature of 65°C shown in Fig. 8, and they matched with test results for up to 610 days, including the distinctive turnoff points in the changes of capacity retention that appear after 180 days (arrowhead

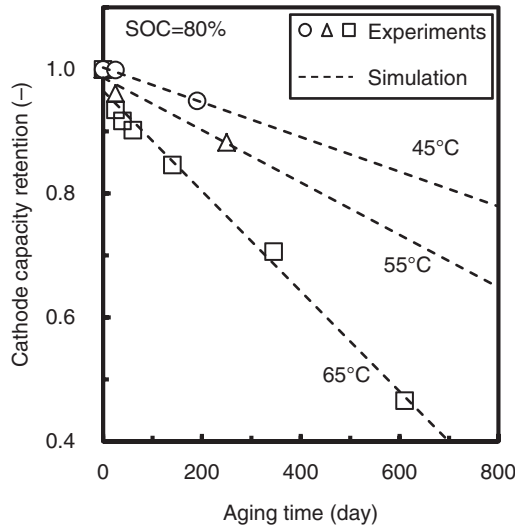


Fig. 6 Parameter fitting for cathode capacity fading

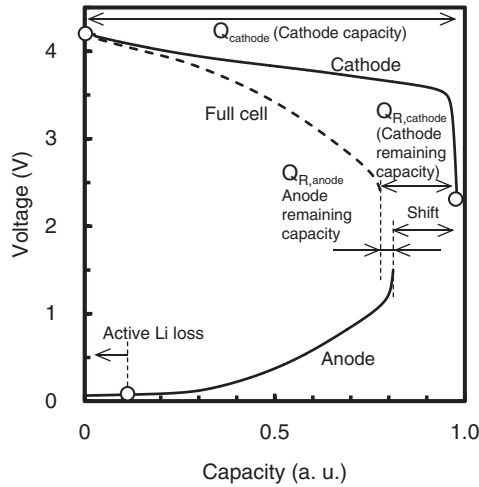
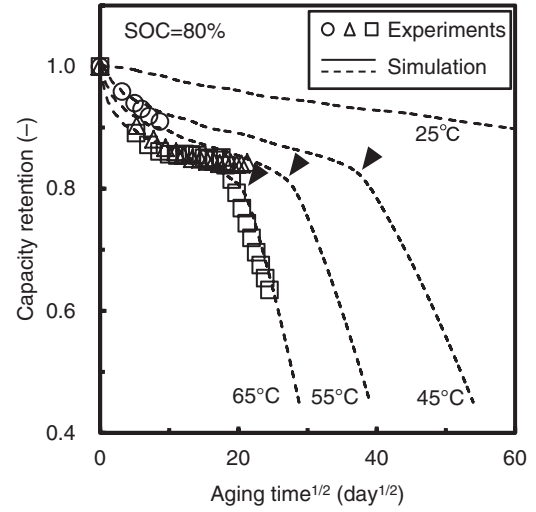
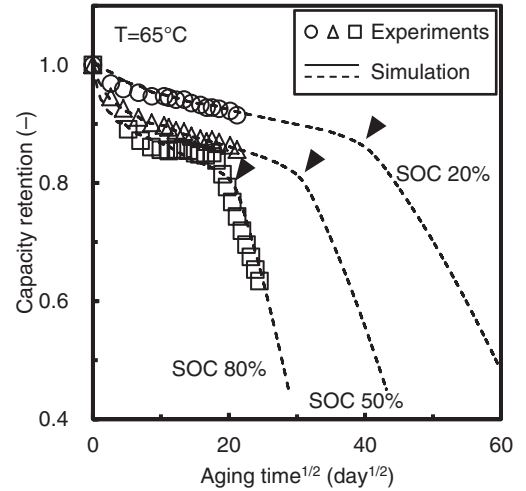


Fig. 7 Schematic drawings about cathode capacity, capacity shift between anode and cathode, and full cell capacity



(a) Temperature variable (aging condition: SOC=80%)



(b) SOC variable (aging condition: T=55°C)

Fig. 8 Results of capacity retention prediction by using the model developed in this work

symbols in Fig. 8), so that prediction was successful. It was apparent from the test results shown in Figs. 5 and 6 that even under conditions of different temperature (55°C and 45°C) and different SOC (50% and 20%), the causes of aging were the same as at 65°C and SOC 80%. Therefore the application of this model is valid. Testing was not carried out to the range where capacity attenuation increases under these conditions, but that timing was successfully predicted [Figs. 8(a) and 8(b)]. As shown by the prediction results at a temperature of 25°C [Fig. 8(a)], it is also possible to predict conditions that have not been tested.

Figure 9(b) shows the discharge curve that was rebuilt at the specific numbers of 453 days and 1220 days at SOC 80% and 55°C. It was predicted that battery aging would be accompanied by changes in the discharge curve. By using this discharge curve and the voltage between the electrodes, it also becomes possible to estimate the SOC so as to be consistent with actual conditions, and the application of this to estimate the remaining capacity in batteries on-board a vehicle can be anticipated.

Since this method can also be used for life prediction over the long term, it also enables the investigation of

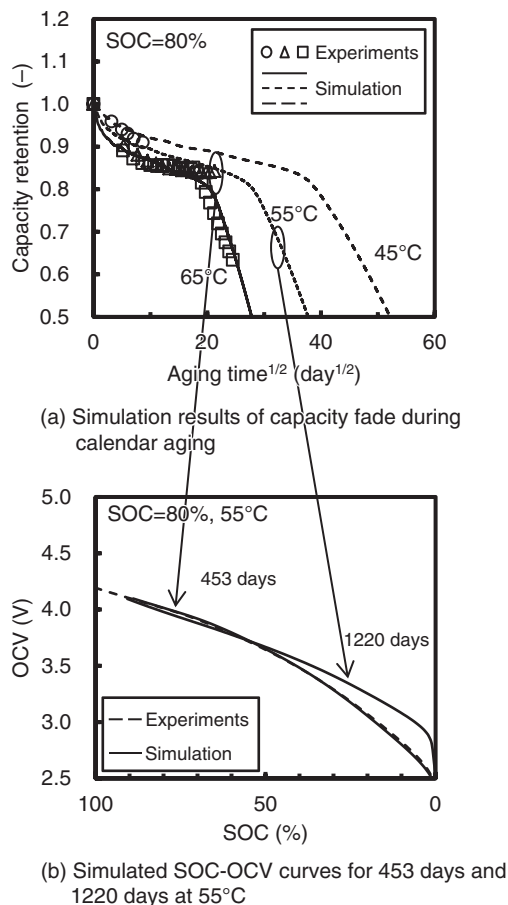


Fig. 9 Simulation results of capacity fade and SOC-OCV curves

constraint conditions on the storage environment for batteries as service parts. For example, the constraining temperature and SOC to realize capacity retention of 80% or more were sought for a storage period of 15 years (5475 days) (Fig. 10). By this approach, it will be possible to determine an appropriate storage SOC even if the storage location is not air conditioned, as long as the temperature at that location can be anticipated.

As this indicates, this model has been created as a physical model. Therefore it can be used for long-term life prediction from a brief storage period of about a half year together with testing at three temperature conditions and

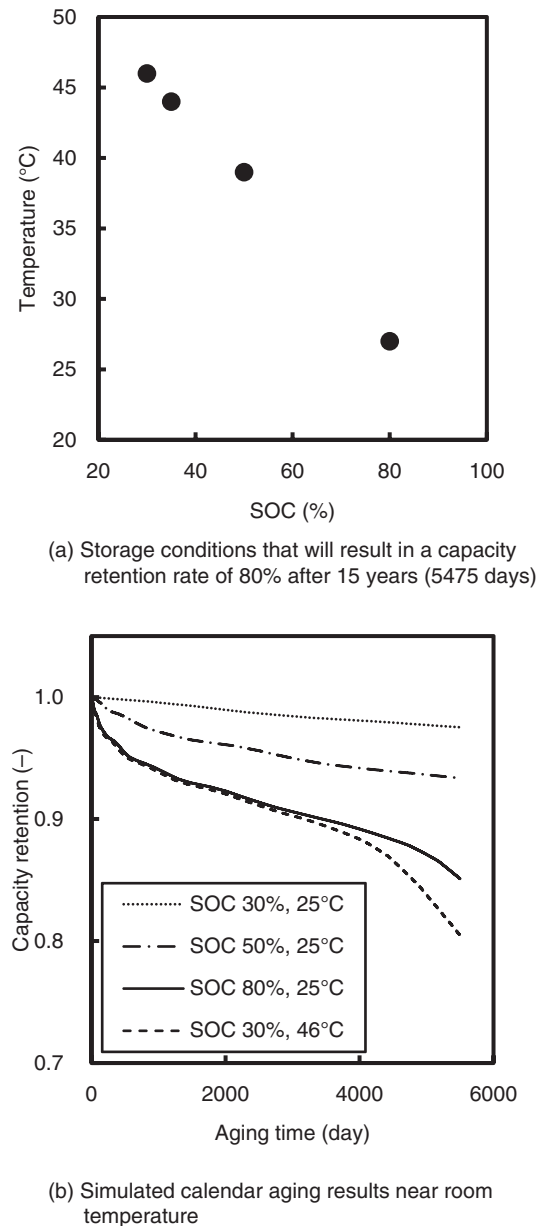


Fig. 10 Simulation results of temperature and SOC constraint conditions for long term storage

three SOC conditions, for a total of nine conditions, which takes less time and effort for testing.

3.4. Discussion of Modeling

As indicated up to this point, inserting the temperature and SOC as input to the model equations that were created allows prediction of battery capacity and discharge curve for the desired time. It is possible that this will be able to reduce the number of tests required to create aging maps by one-half or more.

If it is within the scope of applicability of the previously reported⁽⁷⁾ aging mechanism, it will also be possible to apply this approach not only to the high-power batteries already reported on, but also to high-capacity type batteries and cycle aging.

At the same time, this model derives the variables it uses by curve fitting based on test results. This means that measurement errors and individual differences in the batteries used for testing need to be taken into account, and the occurrence of error in the prediction results also needs to be taken into account. Under the accelerated aging conditions of 65°C temperature and 80% SOC, there was also a slight discrepancy between the active lithium loss amount measured in electrochemical testing and the predicted amount. It may be that this is caused by an oxidation reaction that occurs in the electrolyte at the cathode and cancels out the active lithium loss amount^{(8), (22), (23)}. In this model, this oxidation reaction is included in the cathode capacity fading and processed together with it. However, it is conceivable that this oxidation reaction may no longer be negligible in a temperature range and under SOC conditions that produce a faster oxidation reaction rate. As an issue for the future, a term for the oxidation reaction will probably need to be inserted into the model equation in order to further enhance prediction accuracy.

4. Conclusion

A new life prediction model was created on the basis of the battery aging mechanism elucidated by analysis results. The focus of this paper was on the fact that the aging mechanism arises from electrochemical reactions. Taking the Arrhenius equation as the point of departure, a prediction model that takes in SOC (potential) was newly created. The model's variables were derived by curve fitting based on test results. The charge and discharge curves of a battery after aging were successfully predicted from the variables that were obtained. Battery capacity was calculated from those charge and discharge curves, and the time taken to reach the previously decided lower limit for capacity, or in other words the battery life, was successfully predicted. Since this model was created to be a physical model, the short period of about one-half year that is the period of the accelerated calendar aging test, together with the limited test results, consisting of the three lowest conditions of temperature and the three lowest conditions

of SOC, for a total of nine conditions, were used to derive variables by which long-term life prediction has been made possible. As a result, it became possible to use this model to predict capacity retention behavior where the slope of the curve changes, which conventional methods are unable to predict. It is anticipated that this approach will be applied in defining the constraint conditions for the environment in which batteries are stored as service parts and other such matters. The use of predicted charge and discharge curves and the voltage between the electrodes will make it possible to estimate the SOC so as to be consistent with actual conditions. It is also anticipated that this approach will be applied to estimate the remaining capacity in batteries on-board a vehicle.

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Editorial Afterword

It is now 30 years since Honda R&D Technical Review Volume 1 was published in 1989. Naturally enough, terms that are commonplace today (automated driving, AI, hybrid, electrification, fuel cell, etc.) will not be found in those first editions of the Technical Review. It feels like a different era. I am sure that no automakers or engineers of the time could have predicted today's social environment. Perhaps this is an era of such diversity that it could not have been accurately predicted. But how will society change in the next 10 to 30 years? We can identify key phrases such as movement away from dependence on petroleum, low-carbon, and diversification, but it is challenging to declare that one has the "right answer." I have the feeling that we cannot find the "right answer" without the benefit of hindsight. But looking at the urgent issues that face us—global warming, population increase, food shortages—it seems beyond a doubt that the next 30 years will be harsher than the previous 30.

Having said this, I consider the publication of the Technical Review, which allows us to communicate the role of Honda R&D Co., Ltd. to the world and continue to accumulate technological achievements, to be important as a means of discovering the "right answer." Having been a reader of the TR, I certainly never imagined that I would one day become an editor. And with that, I bring you Vol. 31, No. 1.

Hiroaki Nishida

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