

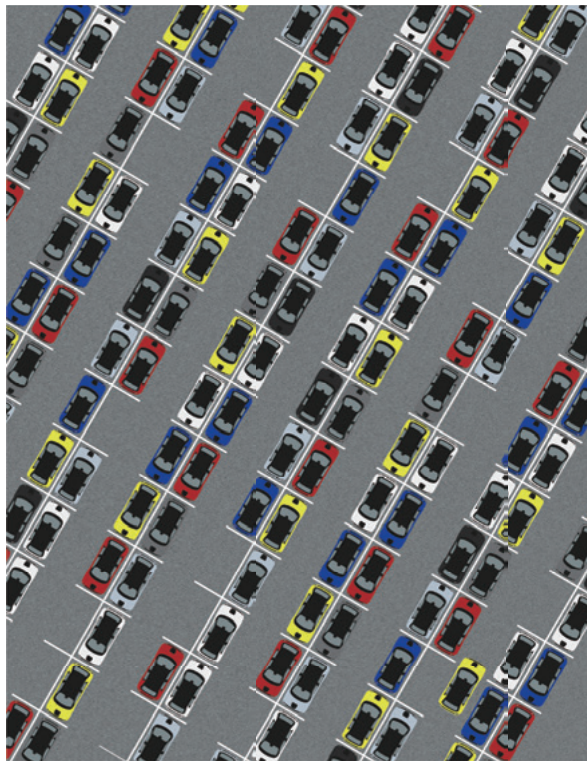


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Comment on the Cover

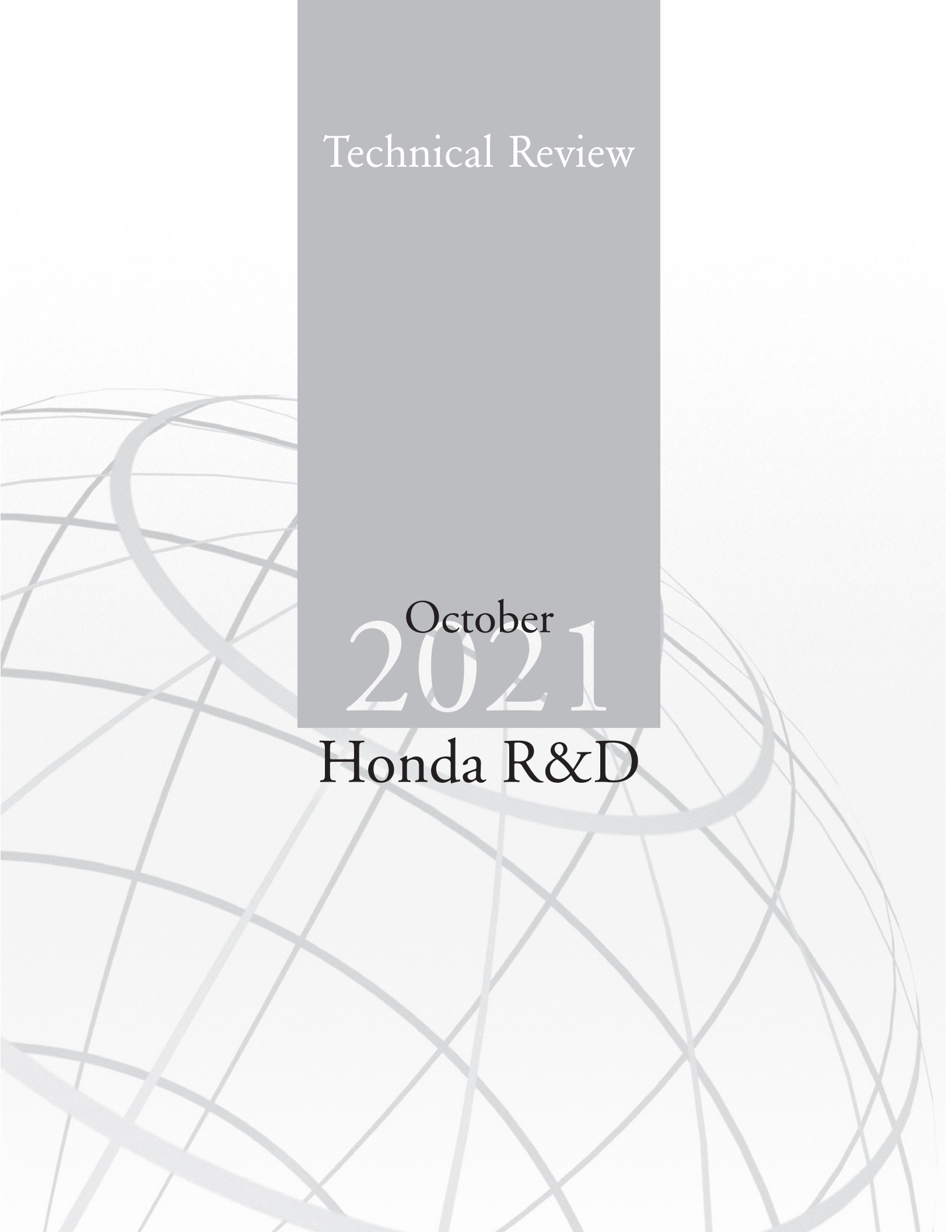
This cover image was created on the theme of an “Unmanned Vehicle Transportation System Using Pair of Thin Robots.”

The image represents the geometrical vision of a scene that comes into being because robots have acted on the driver’s behalf. Here, robots have accomplished the task of everyday automobile use that people are likely to feel is most troublesome for them; that is, parking.

When people hear talk about automation, they may tend to imagine a coldly robotic future. As we see it, however, the theme here is the exploration of ways for robots to coexist with people to create a richer future for us.



Honda Motor Co., Ltd.
Ryohei OYAMA

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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Honda R&D

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Design Development of Honda e - Vehicle Conveying Concepts of Modern Technology and Affinity

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ABSTRACT

The Honda e was developed to be the best compact-size commuter car for in-town mobility, and is Honda's first mass-production electric vehicle. Looking 10 years into the future, the aim was to create a car that would be like a partner that fits closely into the user's everyday life in a world where advanced modern technology seamlessly connects with people.

In giving the design its material form, the expression "Affinity & Modern" served as keywords. The aim for the package was a comprehensive effort to realize the best size for in-town mobility. For the exterior, the design plumbed the depths of simplicity to achieve a stable automotive stance together with distinctive body colors that highlight the styling. The interior expressed the comfort of a cozy living room with a feeling of high quality.

1. Introduction

The Honda e is an electric vehicle (EV) that was developed with the goal of announcing it and putting it on sale in 2020, the year in which European corporate average fuel economy (CAFE) standards were to be strengthened. From the very start of development, this was not envisioned as a means of long-distance mobility, but rather as an in-

town commuter car. Anticipating the impending connected, autonomous, shared, and electric (CASE) era, its base concept was formulated as "Seamless life creator" (Fig. 1). In other words, when the world becomes a place where there is no need to separate people, their residences, and their in-town mobility, then the idea is that even an EV of compact size can become a creator of life that is boundlessly expansive.

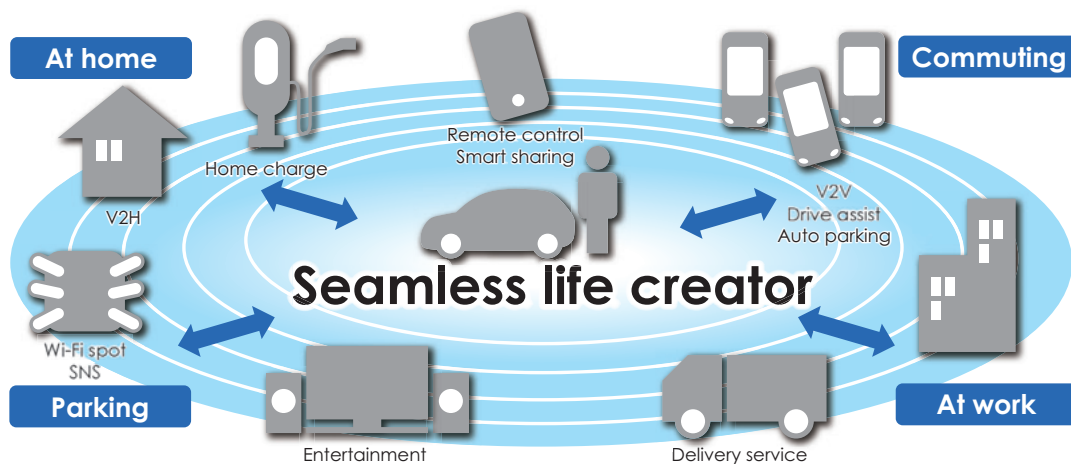


Fig. 1 Base concept

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The further thought this leads to, however, is that in a world with EVs, there is something more than just the visible difference from gasoline-powered vehicles. There should be something more important that is involved.

In order to find that something, the authors set out to pursue research in Northern European countries that are advanced in EVs and that are said to enjoy a high degree of happiness. What they sensed about these countries even before the feeling that they were advanced in EV use was that they felt like places where people can experience time flowing along at a relaxed pace in their prosperous lives and in the midst of nature. They realized, therefore, that the rationale they were looking for was not that this was a new car, or that it was an EV. What became the starting point for design development was the desire to create something that customers would choose because it was closer to the lives they were living. From that realization, the design direction was formulated as “Affinity & Modern” (Fig. 2), and the team set out to develop a car that would put advanced modern technology close to people so they would feel it as a partner in their lives.

2. Package Design Aimed to Make the In-town Best

One thing that was sensed during research in Northern Europe was the attractiveness of cities where nature and modern design are fused together in old cityscapes. In terms of the traffic environment, however, in-town locations faced characteristic issues. Certain things were seen to be important: Given the crowded state of parking on the streets, a compact size; given the consecutive roundabouts, a field of vision that allows good vehicle sense and makes it easier to handle corners; and given the chronic congestion, an interior that provides comfort. Circumstances like these led to the creation of a package that was the best in-town car in terms of being familiar to people and to the city streets. The conclusion arrived at was that even for a new generation EV, what would provide easy in-town handling in Europe was the universal two-box compact size.

As shown in Fig. 3, that body size was made to provide an extra margin for in-town mobility and parking by giving it a total length of 3895 mm, which is 100 mm shorter

Affinity & Modern

Rich life that begins
with people's feelings



Styling to convey advanced technology
and feelings of affection

Active choice



Fig. 2 Design direction

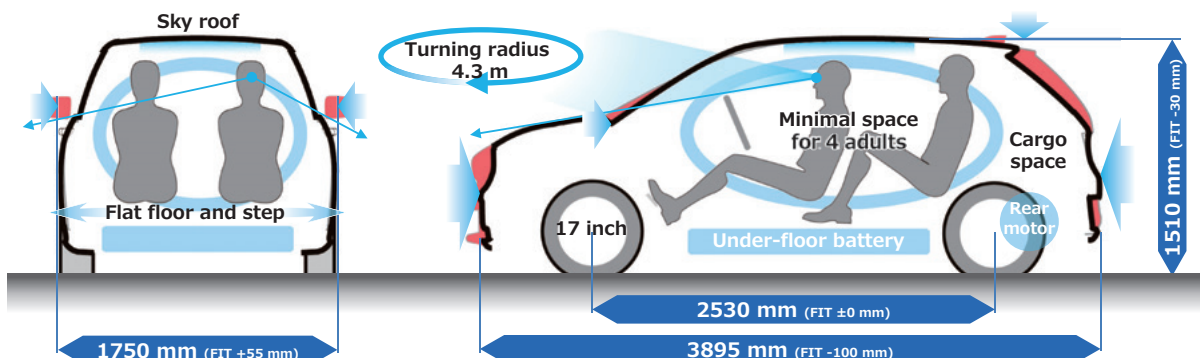


Fig. 3 Package layout (comparison with FIT)

than the FIT, a total width of 1750 mm even including the mirrors because of the camera monitor system (CMS), and a total height that was kept within 1510 mm (there being no roof antenna), which leaves ample room even for ordinary mechanical vertical parking. In addition, the location of the bottom end of the front pillar was moved closer to the driver side, successfully broadening the horizontal angle of visibility to provide easier maneuvering at corners. Steps were also taken to assure good vehicle sense by making a portion of the hood visible from the driver's seat, CMS providing visibility at corners that cannot be obstructed by the door mirrors.

For the interior, the under-floor battery location allows the generous driving posture of a sedan while taking the height of the floor above the ground into consideration, thereby providing a minimal space that can accommodate four adults. A sky roof with a large opening 790 mm wide and 433 mm long comes as standard equipment to effectively produce a comfortable interior even within the compact size.

The floor was also made side-to-side walk-through so that a person who is inside the car alone, for instance, while waiting for it to charge, can easily move over to the passenger seat.

There was concern about the impact that rear motor placement would have on the cargo space. However, making the power control unit (PCU) thinner and other such measures achieved a lower floor (720 mm height above the ground). This gave the cargo space a capacity of 170 L or more, which is the volume of an ordinary supermarket shopping cart. The space is also shaped so that it can hold an ordinary reversible style type A stroller.

This dedicated platform and rear motor placement realize a package (Fig. 3) that is augmented with CMS and other driver assistance equipment of all kinds together with a minimum turning radius of 4.3 m. These and other such features suit this car to be the in-town best for size.

3. Simple Exterior Design Evokes Affectionate Feeling

In order to determine the direction for development, the question of what kind of EV will be truly needed in the times ahead was considered. The result was that although people tend to look for an environmental image or a sense

of being very advanced in an EV, the time is coming when EVs will have become commonplace. Bearing that in mind, it was decided to make a simple and readily understandable design that evokes an affectionate feeling, so that the car fits in easily as a familiar part of people's lives without feeling at all strange or uncomfortable.

3.1. Distinctive EV Proportions and Approachable Silhouette

Thanks to the benefits of rear-wheel drive, the front overhang could be shortened to 700 mm, something not readily achievable in a gasoline-powered front-drive (FF) vehicle of the same class. Since the battery is held under the floor, the wheelbase of 2530 mm is long in relation to the total length of 3895 mm. Compared to gasoline-powered vehicles of the same class, both vehicle weight and torque are greater, and the tires are also slightly larger as a result. For these reasons, within its compact total length the car successfully realizes the proportions of a short overhang, a long wheelbase, and large-diameter tires. In order to take full advantage of these highly favorable proportions while also expressing a friendly, approachable quality, the universal two-box silhouette was chosen (Fig. 4).

3.2. Styling to Make the Most of Simplicity

Styling faced the challenge of how to handle the growing complexity of functional components resulting from the presence of radar, sensors, cameras, and so on in a way that would highlight simplicity. Automobiles generally have an exterior appearance that includes numerous parts such as door mirrors, door handles, and so on that are functionally necessary, and further styling efforts are made in order to give them some individuality. The result in the finished product is often the addition of numerous parts, unintended cut lines, protrusions, and so on that did not exist at the sketch stage. In the design development of the Honda e, therefore, the door mirrors were replaced by cameras, the door handles, radar, and sensors were set flush to the surface, and other such measures were taken to make the car's original functionality – meaning the body, the cabin, the tires and wheels, and the lights – stand out as a presence. The aim here was an exterior appearance that is simple, friendly, and approachable even if it is complex and multi-functional.

For the cabin, sashless doors were adopted. Then, combining large pillar garnishes with a glass roof created



Fig. 4 Exterior sketch

the exterior appearance of a blacked-out glass canopy with few differences in surface level.

For the edge of the hood, a link-type hinge was adopted to make it possible to raise the hood wide open along the side. That edge was extended all the way to the door panel so that it would be linked visually with the shoulder line, making the hood edge blend into the overall design.

The front grille design of an EV generally has few constraints due to cooling performance requirements. What was done here with the camera and radar, therefore, which are crucial items of safety equipment for recent automobiles, was to design them to be blacked out so they could be inconspicuously positioned. Since the surface curvature and angle of the covers on cameras and radar are generally restricted by their function, the grille design is ordinarily given priority with the covers then positioned by adding another level or a separate component. For the grille of the Honda e, however, the surface was positively designed to suit the angle and curvature for the camera and radar, achieving a balance between their advanced

safety function and a flush surface. The same approach was followed in the rear design to provide a unified impression of simplicity (Fig. 5).

Steps were taken so that the line between the lower part of the doors and the side sills would be inconspicuous. Automobiles generally have the side sill farther to the outside of the lower edge of the door for protection from stone chipping. This part can reflect the light, however, so that the difference in level becomes conspicuous. For the Honda e, a protector was added to the lower edge of the door so that the upper edge of the side sill would be farther to the inside of the door. This suppresses the reflection of light and achieves a design that keeps that line inconspicuous (Fig. 6).

3.3. Headlights and Rear Combination Lights Provide Communication with People and Cars

As the eyes of a car, the lights play a very important part in forming the car's facial expression. For the Honda e, the light interior was made a perfectly circular shape

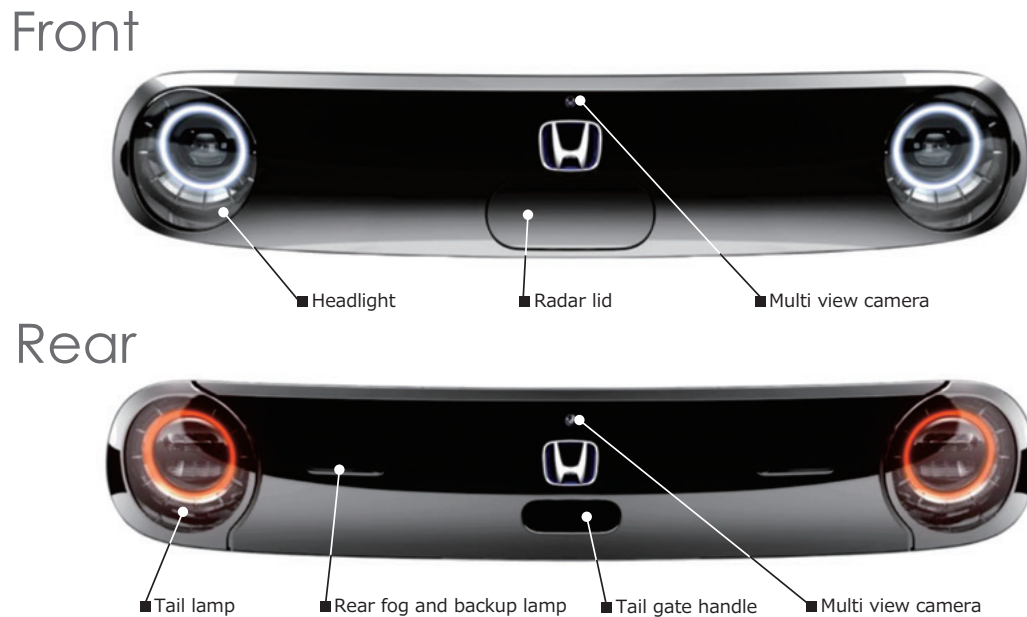


Fig. 5 Consolidation of functions

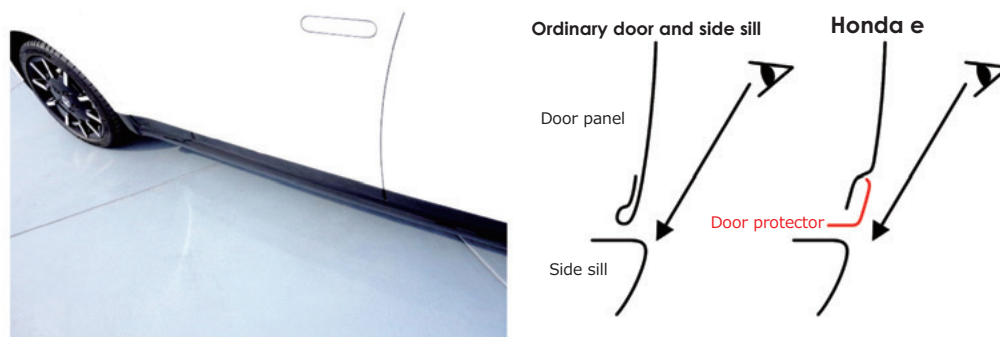


Fig. 6 Styling that highlights simplicity

that faces forward, and then the housing and outer lens were designed on that basis. The perfect circular shape was adopted to create an approachable expression and it was also considered an effective means for producing a greater impression of completion as a product embodying design simplicity. There are severe constraints on the outer shape of the headlights, however, and matching this motif with the overall form of the car also presented a challenge.

The aim for the exterior appearance of the lights was to produce abundant expressiveness and beautiful illumination when turned on. When they are turned off, however, the design makes them look totally black so their presence will not be sensed. Since an EV has no engine operating sound, the car was made so that the only way to tell whether the ignition is on or off from the outside is by the illumination from the lights.

Specifically, edge lights were adopted for the daytime running lights (DRL), the tail lamps, and the front and rear turn signals. These lights all have separate inside and outside edge lights, and they distribute their light using only

a clear lens without a reflector, which means that if their housing is black, then the light units can be made to appear black when they are turned off.

The only reflector used is in the rear stop lamps. This reflector's angle is adjusted so that it will not reflect the bright lights in the external world, even during the daytime. The design was also made so that the only thing reflected would be the LED board, which is colored black.

Adopting a round motif enables the same internal mechanism to be used on both left and right. This contributes also to a reduction in the number of parts (Fig. 7).

3.4. Charge Lid Produces a Fully Satisfying Charge Experience

Compared to the refueling of gasoline-powered vehicles of the same size, the Honda e will have a higher frequency of energy charging, meaning recharging. There was a desire to produce a special experience even during recharging by giving the charge lid a feeling of high quality as well as usability, and by the use of lights and movement. The design

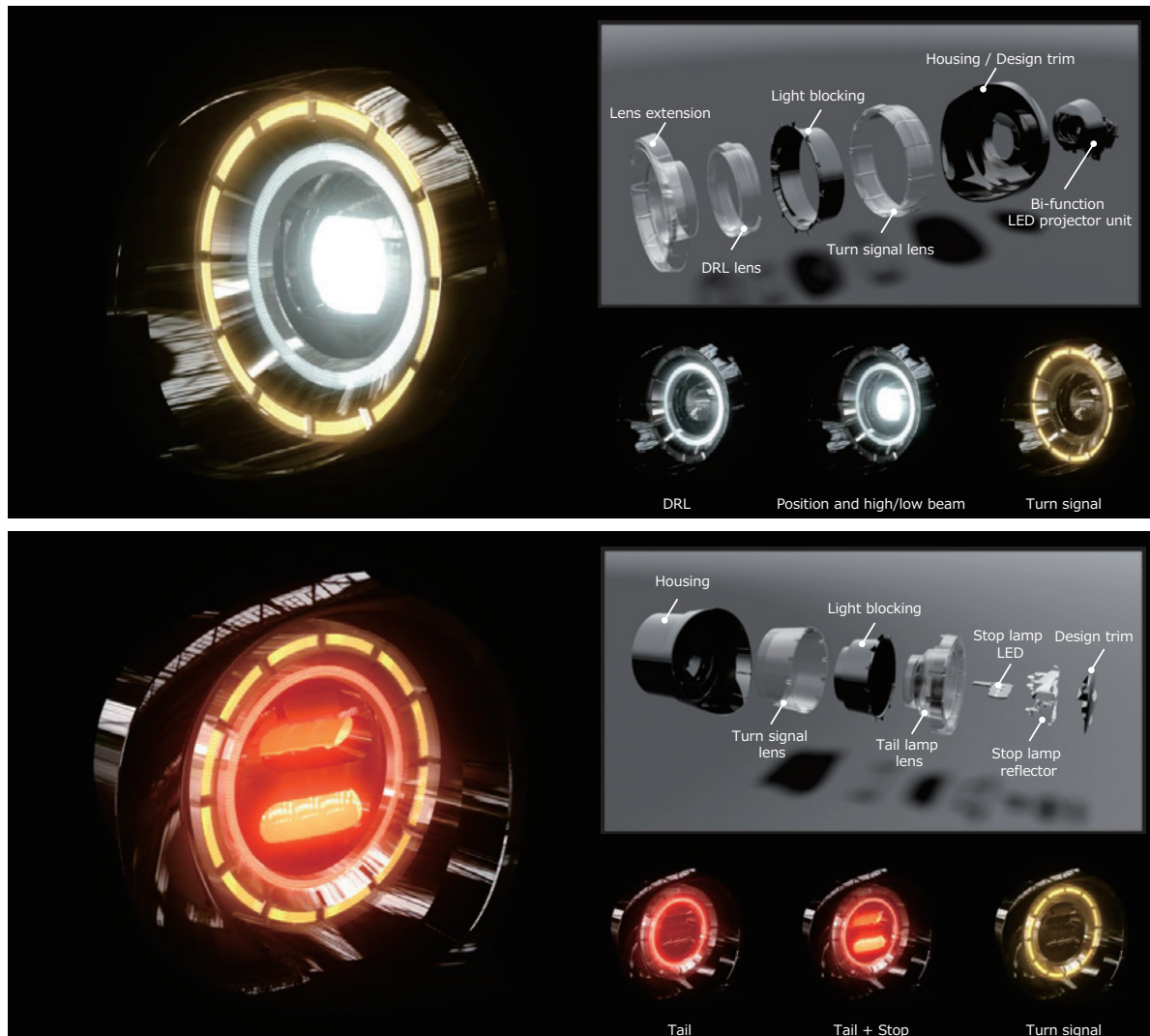


Fig. 7 Headlight and tail lamp

was carried out, therefore, with a conceptual approach that calls for special handling and treatment of those components and functions that will be special to the user.

The lid location is centered at the front of the hood. Glass was chosen for the lid material to provide a feeling of quality to the touch. The mechanism for opening it causes the lid to rotate and slide into the open portion. In order to make the movement smoother, the same opening and closing mechanism was adopted for the cabin interior console lid. The inside under the charge lid was carefully shaped for ease in making a connection even when holding a heavy charging gun. There is also an indicator above the charging inlet that lights up evenly with a blue light to show charged status. The system is further designed so that when the car key is brought close to the lid, a white light will be visible even when the lid is closed to also serve as a welcome lamp that makes it easy to find the charge lid even in dark conditions (Fig. 8).

As on conventional vehicles, the lid is an impact energy absorbing structure that is also compliant with pedestrian safety regulations. The glass lid is also coated with a film to help prevent shattering.

3.5. Side Camera Mirrors with People-friendly Design

This is the first time for Honda to adopt the CMS, and everything from the internal mechanisms to the locations were designed from the ground up. In addition to this effort, the Honda e design development was pursued with the conceptual approach described earlier of “people-friendly design” with simplicity that also makes for ease of use.

First of all, in order to maintain an expansive field of

vision, consideration was extended to shaping the visor around the CMS camera lens so that raindrops would not adhere to the lens (Fig. 9, right), allowing for clear visibility even on rainy days. Good visibility directly from the driver’s seat was also taken into consideration, and by contrast with ordinary door mirrors, the side camera mirrors are placed on the door skin at a height that will not interfere with the direct field of vision from the driver’s seat.

Next, aerodynamic performance was considered in light of its impact on cruising range, with every effort made to reduce the frontal projected area. Thus, the CMS camera, multi-view camera, and side turn signal are placed side by side in the longitudinal direction, and the housing was positioned to make its vertical dimension slimmer (Fig. 9, center). A simple model was also fabricated and subjected to wind tunnel testing in the search for a low-resistance shape. As a result, the coefficient of drag (Cd) value was successfully reduced by 10 or more relative to ordinary door mirrors.

Finally, steps were taken with regard to the “people-friendly design” that is a distinctive feature of this car. The housing was held within the total width of the car, and it was given a rounded shape without protrusions or sharp corners. This design was intended to give people a sense of security even if passing close by (Fig. 9, left).

3.6. Flush Outer Handles Contribute to Simple Exterior Appearance

Since people touch a door handle every time they get in the car, it is an exterior component that is a very close presence to them. For the Honda e, therefore, the simple,



Fig. 8 Charge lid



Fig. 9 Side camera mirror

clean design that is the conceptual approach to the car as a whole was augmented by comprehensive care in order to make the outer handles something that people would want to touch every day.

The front outer handles were given a simple, low-noise design. This was achieved by adopting a flush-type handle, without differences in level, that pops up automatically when the key is brought close to it. While in conventional cars the key cylinder is an exposed part of the exterior appearance, here it is concealed internally to give a cleaner impression. The lock sensor is located on the top surface of the outer handle. This makes it easy to press when using it, and conceals it when closed, which contributes to making the exterior appearance less noisy. In addition, the rear side of the top surface was cut away so that users can easily put their fingers in the handle from behind as well as from below. To make the location of the sensor easier to find even under dark conditions, an LED light was also built into the door so that a light source there would be able to illuminate the sensor (Fig. 10, left).

Like the front outer handles, the rear outer handles were designed for simplicity and less noise. The handle functions were consolidated within a black area in a method that does away with differences in level and lines demarcating it from the body. This was accomplished by fitting the rear outer handles inside the side window, making the body less noisy in appearance. In order to give it a cleaner look, a flush, manually operated flap-type handle without a surface concavity for inserting the hand was adopted. Although this made for a clean appearance, not knowing how to open the door presented an issue. An indentation was thus designed into the part that users need to press, making it intuitively obvious how to make the flap open (Fig. 10, right).

3.7. Functional Beauty and Originality Highlighted by 16 Inch and 17 Inch Wheels

First of all, the 16 inch wheels were designed with electricity consumption in mind. Ordinary gasoline-powered vehicles have the effect of engine braking, so that fewer wheel openings are needed for brake cooling. When an EV is fully charged, however, it cannot use regenerative braking, which corresponds to engine braking in a gasoline-powered vehicle. On continuous, long downhill roads or other such circumstances, EVs need more brake cooling than gasoline-powered vehicles, and wheel design also

demands a larger area of openings. These wheels have less space open around the brake disks, in particular, so it was necessary to arrange the 10 spokes efficiently to help assure both cooling performance and rigidity.

A distinctive feature of this design is that it has a large-diameter central cap that conceals the wheel nuts. This is effective in two ways: the first is that the aluminum around the wheel nuts can be carved away to contribute to weight reduction; and the second is that concealing the wheel nuts yields a simple exterior appearance. The result is that the need for cooling performance is satisfied while achieving lighter weight and high rigidity in a design with a simple exterior appearance.

Next, for the 17 inch wheels, the design sought a creative modern quality not found in previous wheels.

Distinctive elements in this design include the elongated oval motifs that are used repeatedly throughout the Honda e body as a whole. These are arrayed in the wheel like the dial markings on a clock and joined to the large-diameter disk in the center. This arrangement sets this design apart from the conventional spoke-centric wheel design, giving it a modern exterior appearance. The disk portion in the center has approximately the same diameter as the brake rotor, and it is intended to conceal the soiled brake disk from the outside view.

This creative design presented two very challenging issues.

The first was securing the rigidity of the joints between the spokes and the disk. The designers also made proposals regarding the shape of the inside surface as they proceeded with adjustment of the amount of spoke overlap on the disk. Analysis of the data was carried out repeatedly as the design was maintained while securing the rigidity of the joints.

The other issue was securing cooling performance. The issues involved with openings in EV wheels for cooling are as described earlier. The design here, however, does not succeed if the openings become too large. The usual way of addressing such an issue is by aerodynamic simulation of the side view alone, but here, measurement of the cooling area in the depth direction was included in the calculation. Computational fluid dynamics (CFD) was used to analyze the flow of air, and even what appeared to be a small area in the side view turned out to secure highly efficient cooling performance (Fig. 11).

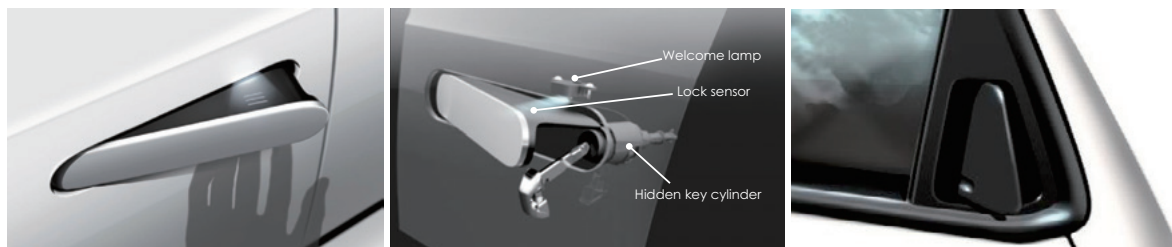


Fig. 10 Front and rear flush outer door handles

3.8. Body Colors that Highlight the Styling

A lineup of seven colors was prepared for the exterior body color (Fig. 12). The white, silver, steel metallic, and black produce a basic beauty, while the blue and red produce a fine-quality beauty.

The new color of charge yellow provides a simple yet solid feeling of quality in a highly saturated yellow. This color was created to highlight brisk driving and an exhilarating feeling. The bright, lively color also adds visual contrast to the iconic grille, the charge lid, and the

black-out cabin.

These two highly contrasting color tones further enhance the production of the simple and modern Honda e character. In order to convey a feeling of quality that highlights the simple, non-noisy exterior design, the color was made to have a solid-like texture. Seen from a distance, the color gives the quality feel of solidity and presents a clean, uncluttered surface. Seen close up, the slightly metallic admixture produces a sensation of hardness (Fig. 13).

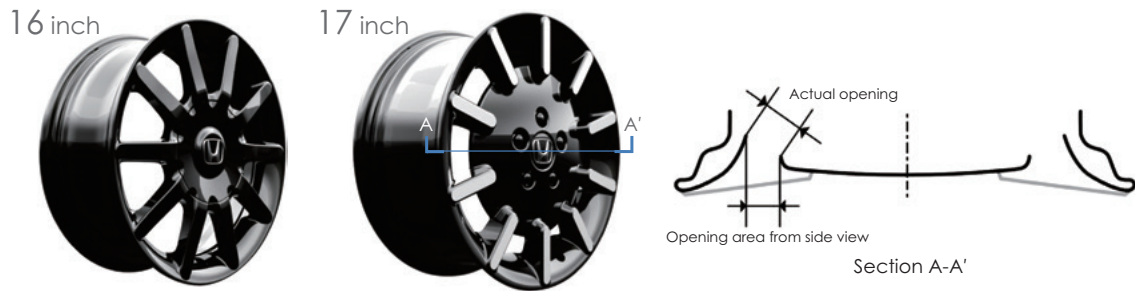


Fig. 11 Wheel design



Fig. 12 Exterior color lineup

Iconic color

Solid texture

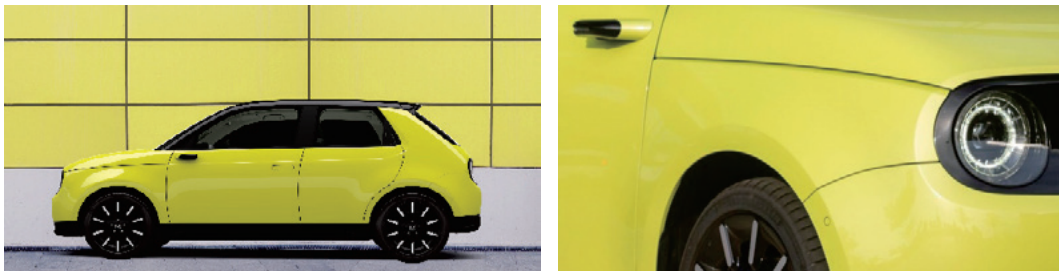


Fig. 13 New charge yellow

4. Interior Design with Cozy Comfort

4.1. Approachable Image of Mobility Also Informs the Interior

Work on the Honda e interior design was begun with a ground-up review that was not swayed by existing car values. This approach embodies the desire to expand the value of this car beyond just a mere unit of mobility.

The question of how the conceptual approach of this design, formulated as “Affinity & Modern,” should be expressed in the car interior was thus carefully considered before specific styling measures were begun.

This began by examining an era in which mobility and people’s lives are connected together seamlessly, a connection that brings prosperity to everyday life. Attention was focused on the value of such a mobile space when it becomes a living space that is rooted in daily life. From that emerged the desire to have the interior express a modern quality that conveys the feeling of a new lifestyle that is people-friendly and tranquil. This examination produced the notion that the value embodied in people’s living rooms would fit precisely and comfortably in this vehicle.

This is the concept that a living room with a good-quality sofa and table and a large TV monitor (Fig. 14) extends outward. In this case, it seems that it could be possible to provide an experiential value that feels like a seamless expansion of the living space. The value of the living room is itself often expressed in terms of styling motifs and the use of materials with good texture, but in the design here, the reference expands to include actual usability.

Another consideration is that EV recharging facilities in private homes have not become widespread. For this

and other reasons, it was thought likely that there would be more opportunities for recharging at destinations away from home. Where refueling with gasoline takes about five minutes, recharging generally differs in that it takes a minimum of about 30 minutes. It was envisioned, therefore, that the user would sometimes wait in the car until recharging was complete. For this reason, it was reasoned that for situations when users stop the car and wait inside while recharging, it would be desirable to create a space in which they could relax comfortably. This may become even more necessary in the near future as automated driving becomes more widespread. It is hoped that this kind of conceptual approach may lay the groundwork for the next generation of value.

4.2. Interior Space Conveys the Feeling of a Cozy, Comfortable Living Room

The Honda e is equipped with numerous advanced devices such as the Honda CONNECT widescreen display, which is long enough from side to side that it can be easily viewed and operated from both the driver’s and passenger’s seat. There is also the side camera mirror system, which displays the images from the side mirrors at either side of the instrument panel where they are readily visible. The aim was to build these into a simple, tranquil, living room-like space, and every effort was made to that end. The result is considered to be a design that successfully achieves the coexistence of a highly advanced quality with simplicity and modernity (Fig. 15).

The upper parts of both front and rear doors as well as the armrests are covered with fabric in the same way as the seats. This is a heavy fabric that does not stretch much at all, and this imposed limits on how it could round corners and



Fig. 14 Conceptual image sketch

be handled at end-points. The shapes that were produced after examining such considerations, however, present an atmosphere and other qualities in their curved surfaces that seem even more natural than otherwise. The shapes turned out to be people-friendly and pleasant to the touch.

For the contours of the seats, steps were taken in where and how they were covered according to the shape and the fabric, so that they help to create an atmosphere unlike those in regular Honda vehicles. The rear seats, in particular, were arranged in a form like a two-seat sofa. The same fabric was also used on the side bolsters and rear door armrests to create a space that, while compact in size, is seamlessly unified as a whole. The aim was also to produce the visual effect of a space that appears to be expansive (Fig. 16).

4.3. Instrument Panel with Horizontal Arrangement of Five Displays

The aim of creating a highly advanced and usable interior space of a kind never experienced in a car was accomplished with an 8.8 inch meter display and a pair of 12.3 inch displays in the middle, then two 6 inch CMS displays, one at either end. These make up the world's first instrument panel with a total of five displays arranged horizontally. The displays do more than just provide new enjoyment and comfort, as they were designed with the goal of forming new links between people and the car by means

of a diversity of connectivity.

In the course of realizing this set of displays, the issue arose of how to settle them into the space so that they would fit comfortably without jarring. This was because, although this kind of horizontally extended display is commonly seen in concept cars and other such contexts, the attempt here was the first not only in a Honda car, but in a mass-production vehicle. Since the horizontally extended panel holding the displays was flat and linear, the approach taken was to use that to advantage and make the horizontal straight lines a motif for unifying the whole and completing it with the keynote of simplicity. As it turned out, this made for a well-balanced styling that contributed to the achievement of a modern living-room space.

As a secondary effect, this approach left the upper surface of the instrument panel clean and uncluttered. The result is believed to lighten the influence of the displays on the driver's field of vision.

The wood-grained panel that forms a horizontal motif can appear to be similar to a living room table and here again, this is not just a distinctive decoration meant to produce a visual effect. The panel was also intentionally shaped to provide a place where people can rest the palm of their hand, making operation of the touch panel display easier when the car is moving and so helping to prevent mistaken operation (Fig. 17).



Fig. 15 Interior sketch



Fig. 16 Front and rear interior designs

In this way, the interior design of the Honda e is shaped and carefully arranged as a cozy, comfortable space, and no effort was spared to connect these qualities closely to usability and functionality.

4.4. Equipped for Comfort with Advantageous Use of Materials

The previous section touched on some ways in which attention was given to creating shapes and equipment was arranged advantageously for usability. Two instances of this will be explained here.

First, there is the cup holder for use from the driver's seat. The front seats in this car are arranged so that people can walk through from one side to the other. This made it necessary to leave enough space between the instrument panel and center console to allow people's legs to pass through. For this reason, a cup holder that slides in and out drawer-like from the console was adopted. If the handle on that holder were a typical resin part, however, people could be expected to hit their legs against it when walking through, which would make it a jarring element in that environment. A soft synthetic leather strap was therefore used for the handle. Similar care was put into the color.

It was made brown with stitching not only for visibility when people are seated, but also for the appearance of high quality to the eye as well as for a better feel to the hand when pulling out the holder (Fig. 18).

The other example is the central lower pocket under the instrument panel.

Here, similarly, every effort had to be made to create a workable pocket while having to take every possible measure to keep the pocket from projecting outward. Thus, the same fabric used for the seats was adopted for the pocket.

This makes it possible to put away a smartphone or other such device while keeping it connected and charging. In addition, this also helps limit rattling and damage to such devices while the car is in motion. A smartphone that is connected can be operated using Android Auto, Apple CarPlay or similar apps (Android Auto is a trademark of Google LLC; Apple CarPlay is a trademark of Apple Inc.).

Cables for connecting devices often present challenges on how to route them and where to store them. Here, the pocket makes it possible to keep them with the device, and when they are not in use, to bundle them up neatly and put them away (Fig. 19).

These two equipment examples illustrate how the design



Fig. 17 Instrument panel



Fig. 18 Cup holder

created through this kind of repeated examination with careful consideration given to details of function was also successful in increasing the friendly, approachable quality in the car's attractive overall appearance.

4.5. Warmth and Natural Texture Sought in Wood-grained Panel

In order to achieve a high-quality texture that elicits the warm feeling of a living room table, development of the wood-grained panel was designed to make it seem like the real thing.

Walnut is often used for ordinary furniture, and that is the wood-grain pattern adopted here to recreate the living room as a living space. Multiple colors were also overlapped to recreate the complex coloration of natural wood grain. Although the decoration here is a film, it produces the three-dimensional effect of wood grain's irregular surface, which is formed by capillaries, and so can also convey the warm feeling of real wood in terms of tactile sensation. The angle of the panel was determined through examination of the ease of touch operation of the display and the reflection

of the wood grain in the display image (Fig. 20).

4.6. Fabric Evoking the Modern Living Room

As noted above, what was sought for the interior was a design that has a friendly, approachable quality and that would remain interesting. For the material covering the seats and doors, therefore, a melange-toned fabric that imparts a feeling of friendly familiarity was used. This thick, high-quality woven textile combines varying shades of grey to produce a modern living room space.

For the seatbelts and the tags on the side airbags in the front seats, a brown was selected to harmonize with the wood grain color. Seatbelts, tags, and other such functional parts are not ordinarily considered as decorative elements, but here they were deliberately colored to play a role as interior accents. Brown accents go well with grey upholstery and they produced an added note of opulence in the space conceptualized as simple.

Some parts of the doors and seats have zigzag stitching, creating points of attention that are pleasing to the eye and elicit an affectionate feeling (Fig. 21).



Fig. 19 Central lower pocket



Fig. 20 Wood grain tone panel

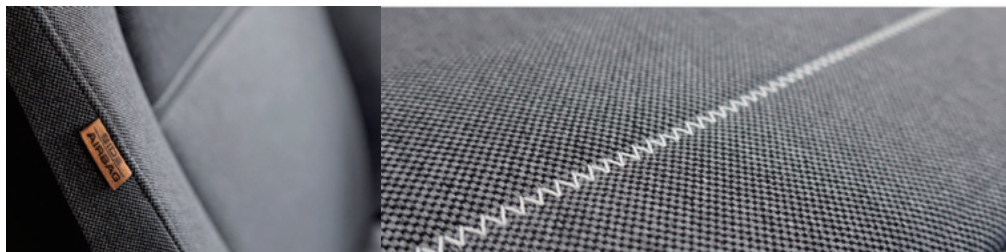


Fig. 21 Expression of living room

5. Responses from the Market

Although the Honda e was only put on sale in two markets, Europe and Japan, it received notable recognition in the form of numerous awards that are highly regarded around the world. Some of these were awards that were being won for the first time by a Japanese car, and some were awards specifically for design (Fig. 22).

6. Conclusion

Development of the Honda e began only after other companies had already brought out mass-production EVs, and it goes without saying that Honda members had the shared, distinctively Honda feeling that they would never make a car that is like another company's product. This also served as one of Honda's specific responses to the



Prize	Country	Awarded in
AUTOBEST 2021 Awards – ECOBEST title	Europe	2020
German Car of the Year 2021 – overall winner, 'New Energy' category *	Germany	2020
Red Dot Design Awards – Red Dot: 'Best of the Best Car Design' & 'Smart Product' **	Europe	2020
News International Motor Awards 2020 – 'City / Small Car of the Year'	UK	2020
Autocar Best Car Awards – 'Best Car Tech'	UK	2020
AutoGids Best Car Awards – 'Small Electric'	Belgium	2020
EuroCarBody Awards 2020 – Winner, Volume Segment	Germany	2020
The Les Numériques Digital Star 2020-2021 for 'Connected Car'	France	2020
Axel Springer Motor Awards – 'Best Design' **	Spain	2020
Denmark Car of the Year 2021 Awards – The Innovation Award, The Car-Joy Award	Denmark	2020
The Best of Moto Awards – Alternative Drive, Design	Poland	2020
Automobile Awards by Motul – Design **	France	2020
2020 TopGear.com Awards – City Car of the Year	UK	2020
'Most Exciting Novelty/New Car' from Vezess.hu	Hungary	2020
JIDA Design Museum Selection Vol. 22 – Gold Selection **	Japan	2020
Japan Automotive Hall of Fame – 2020-2021 Car Technology of the Year	Japan	2020
2021 Women's World Car of the Year – Best EV	World	2021
UK COTY (Car of the Year) Awards 2021 – City Car of the Year	UK	2021
World Car Awards – 2021 World Urban Car	World	2021

* First award to a Japanese car ** Design award

Fig. 22 Awards given as of April 2021

future carbon-free society that began with the European strengthening of CAFE standards from 2020 on.

Issues like these were viewed positively by the team, as they did not conceive of this car as the EV that would supplant the generation of gasoline-powered vehicles. They consolidated their response as such, within the compact size of an EV that would be the ideal for an in-town car. To further enhance this car's appeal as a product, despite its compact size, they unstintingly adopted rear-wheel drive powered by a high-output electric motor, a platform intended exclusively for use with an under-floor battery, large-format displays, and other advanced technology that were firsts for Honda.

Meanwhile, the design development team conducted research in Northern Europe that yielded their direction, formulated as "Affinity & Modern." Working from this, the team went on to give concrete form to "a car that would be like a partner bringing advanced modern technology into a relationship of affinity with people."

Honda exhibited it for the first time at Milano Design Week 2019. This was an opportunity for a special exhibit centered on the prototype, but reports indicate that the exhibit received strong support from furniture, fashion, and other non-automotive designers as well as from the mass media.

"Honda" was used in the car's name in part to heighten the brand's presence in Europe. The numerous, highly regarded awards received suggest that this purpose has been achieved.

Measures to counter the COVID-19 crisis have had an unfortunate impact on new car announcements and news coverage in Japan, which have taken place in a remote environment. Even in this context, however, there have been many video reports posted by customers themselves who have used EveryGo (Honda's car rental and car-sharing service) to take test rides. The magnitude of the response has been astonishing.

The hope even in times like these is that Honda can pursue its mission and continue to provide a vision of cars in a bright future.

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Development of Ropot, Traffic Safety Advice Robot

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ABSTRACT

In Japan, seven-year-olds experience an exceptionally high number of pedestrian accidents. To address this, the authors developed a traffic safety advice robot, Ropot, to assist the teaching of traffic safety to children in the lower grades of elementary school.

Ropot has educational functions and receptive functions. In particular, three of the educational functions, known as “check point remind,” “backward check remind,” and “check point result review function,” have not been found in any other device up to now.

To develop these functions, the authors used a global navigation satellite system with high-precision positioning and millimeter wave radar with good environmental robustness. These functions are contained within a partner design that is appealing to children, which enhances the receptive functions.

At an educational trade fair and proving tests, children, their guardians, and school personnel responded positively to the educational and receptive functions, and the effectiveness of Ropot was confirmed.

1. Introduction

The number of traffic accidents has fallen in recent years thanks to the spread of preventive safety technology, establishment of laws, and stricter observance of the rules by drivers and pedestrians. However, an exceptionally high number of seven-year-olds suffer casualties from pedestrian traffic accidents in Japan, a phenomenon sometimes called “the devil’s seven” (Fig. 1)⁽¹⁾. This is the age when children are still mentally and physically immature but are starting to commute to and from school without a guardian. In fact, accidents while commuting to and from school are the most common type (Fig. 2)⁽²⁾.

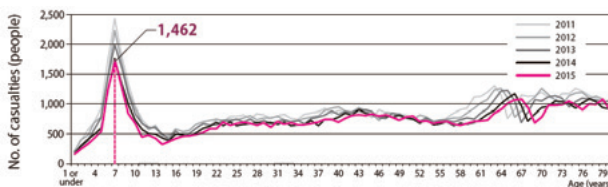


Fig. 1 No. of casualties from pedestrian traffic accidents (2011-2015)

Honda’s 2030 Vision Statement says that we “will strive to become a company that leads efforts to realize a...collision-free mobile society”⁽³⁾. Specifically, “to realize a collision-free society...Honda is pursuing safety in view of three components of safety-human ability, mobility performance, and the traffic ecosystem”⁽⁴⁾ (Fig. 3)⁽⁵⁾.

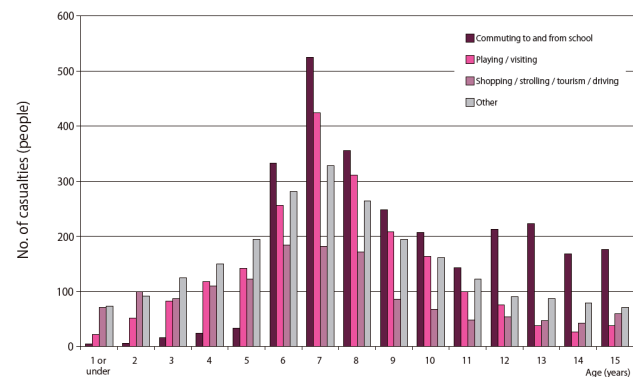


Fig. 2 No. of casualties from pedestrian traffic accidents by trip purpose (2015)

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The reference point for traffic safety is humans. In order to increase human ability, Honda too is providing a variety of traffic safety education before and after the age when children start attending school. However, because of their behavioral characteristics, children of that age are easily distracted by things other than traffic safety. Instead of paying attention to cars, for example, they run after friends who are close by and talk with them. The authors of this paper focused on this point. They decided to develop a traffic safety advice robot (below, “Ropot”) as a system to supplement traffic safety education by reminding children on the spot to take safety check actions, which they otherwise tend to forget. Ropot consists of the main device (“Ropot device”), the cloud, and a smartphone application.

This report narrows the focus to commuting to and from school, which is the setting with the most accident factors. It describes how the authors developed Ropot, how they determined the educational functions and receptive functions, how they implemented them (including the design) in Ropot, and how they confirmed the actual effectiveness.



Fig. 3 Enhancing joy that comes with freedom of mobility while pursuing zero collisions

2. Functions Required of Ropot

2.1. Educational Point of View: Assistance to Confirm Traffic Safety

The authors considered which functions are necessary to assist traffic safety education targeting seven-year-old children.

They began by studying children’s biological cognitive abilities. Dr. Stina C. Sandels found that, compared to adults, children are less able to see the movement of things with their peripheral vision⁽⁶⁾. Moreover, six-year-old children (who are nearly the age of those studied here) have an average horizontal visual field of about 90° and average vertical visual field of about 70°, both of which are more limited than those of adults (150° and 120°, respectively)⁽⁷⁾. Children of this age are also rather short, so their line of vision is low. In addition, compared to adults, children have less perceptual ability to determine where a sound comes from (sound localization), according to Sugita et al.⁽⁸⁾, and are less likely to notice approaching vehicles that are outside their visual field.

The authors next surveyed the behavioral tendencies of children in a traffic environment. According to Renge et al., there are a number of issues to be addressed. For example, children tend to run forward and running makes it more challenging for them to check to their right and left, so even if a car comes, it is hard for a child to stop in time and drivers, even if they do notice the child, find it a challenge to respond⁽⁹⁾. Therefore, it is important for children to come to a full stop and to move their heads to view the scene with a wider visual field.

Next, the authors studied the characteristics of traffic accidents involving seven-year-olds. According to the Institute for Traffic Accident Research and Data Analysis, in fiscal year 2015, commuting to and from school was the purpose of the trip in 38% of cases of casualties to elementary school first-graders (seven-year-olds), the cause of the accident was rushing into the road or crossing the road at other than a pedestrian crossing in about 40% of cases, and the accident happened at or close to an intersection in about 58% of cases⁽¹⁰⁾.

Based on these facts, the authors decided it would be useful to have a function that encourages children to stop temporarily to confirm traffic safety, particularly when they approach locations that require a safety check, such as intersections when children are commuting to and from school (“check points”), and when a car approaches from behind, which tends to be outside a child’s visual field.

2.2. Educational Point of View: Assistance to Repeated Education

The authors believed that to help children establish a habit of stopping to confirm traffic safety, it would be useful to have not only a function that encourages them to stop but also a function that assists in the establishment of the habit of stopping. For that reason, the authors considered methods for developing the habit of stopping in children.

According to Renge et al., police officers and traffic guides often directly provide traffic education in Japan, but by the nature of children, it is important for those already close to them, namely their guardians and teachers, to teach the children themselves⁽¹¹⁾. Also, according to the Institute for Traffic Accident Research and Data Analysis, to change

children's behavior, it is necessary to instruct children repeatedly over some period of time. Another effective way to teach children is for guardians and children to walk the school commuting route together so the guardian can assess the child's development while teaching specific lessons⁽¹⁰⁾. Based on these, the authors concluded that repeated instruction by a guardian as the child grows would be an effective way to establish a habit in the child of stopping to confirm traffic safety.

Realistically, however, it would be challenging for guardians to walk the school route with their children every day. The authors therefore concluded that children could be repeatedly educated as they grow if a guardian provides the child's first traffic safety education and further traffic safety education as the child grows, while a device provides repeated reminders during the child's daily commute to help the child recall what they learned from their guardian and keeps a record of the child's stopping to confirm traffic safety.

To enable the device to play this role, it was decided to design its basic structure so that it could be worn on the child's body. Each day, the child would wear the device, which would give reminders and keep records. The function that repeatedly encourages the child to stop at check points is called check point remind, while the function that repeatedly encourages the child to stop for vehicles approaching from behind is called backward check remind. The function that records the child's behavior and provides a safety confirmation track record to the guardian and child is called the check point result review function.

2.3. Receptive Point of View: A Partner That Teaches and Watches over the Child

Children, guardians, and schools need to be receptive to the Ropot device if children are to wear it during their daily commutes to and from school.

First, if the child is to wear it, the device has to be compact and lightweight enough so it is not a burden to the child during the commute. So to make sure the child would want to wear the device every day, the authors considered the kind of character that the hero of an animated program might carry on its shoulder. There are many animated works that have a character like this. Such a character acts together with the hero. It is like a partner who stays with the hero, constantly watching over them. The authors considered these things as they aimed to create a small partner that would sit on the child's shoulder (Fig. 4). This became the partner design.

Next, to encourage children's guardians to be receptive to Ropot, the authors conducted a web-based survey of guardians across Japan who have children in elementary school. The survey revealed that guardians want to be able to check on their commuting children (learn their current location, be notified when they arrive or depart, etc.) in real time. The authors decided that to do this, guardians would need an application on their smartphone or other

device. The application would have functions capable of confirming the child's current location and departure and arrival. The survey also showed that guardians want to take some responsibility for their children's education and that entrusting traffic safety education to guardians responds to the guardians' eagerness to participate in education.

Finally, elementary schools would need to be receptive to their students bringing the Ropot devices to school so that the children could use them every day on their commutes. This would require a function that partially limits the functions of the Ropot device while at school, so that the children would not use it as a toy during classes and the like. This is called the silent function.

2.4. Required Functions

Following is a description of the basic user experiences and necessary functions as based on the above considerations.

- (1) On the actual school commuting route, the guardian teaches the child the check points and how to confirm traffic safety at them and how to confirm traffic safety in respect to approaching vehicles.
- (2) Using the application, the guardian registers check points to the cloud.
- (3) For the daily commute, the child puts the Ropot device, their "commuting partner," on their body (partner design) and leaves home. The guardian's smartphone receives a departure notification from the cloud (departure notification function).
- (4) As the child approaches a check point, the Ropot device reminds the child to pay attention (check point remind function). The child remembers their guardian's lessons about confirming traffic safety and confirms it.
- (5) When a vehicle approaches from behind, the Ropot device reminds the child to pay attention (backward check remind function). The child remembers their



Fig. 4 Concept of Ropot device in first grade of elementary school

guardian's lessons about confirming traffic safety and confirms it.

- (6) The guardian confirms the child's current location, etc. through the application (current location confirmation function).
- (7) The child arrives at school. The guardian's smartphone receives an arrival notification from the cloud (arrival notification function).
- (8) At school, the Ropot device's functions are automatically limited (silent function).
- (9) The child leaves school, in a process similar to (3) to (7) above.
- (10) After the child returns home, the guardian and child look at the record of stopping to confirm traffic safety while reviewing the child's traffic safety (check point result review function).
- (11) As steps (3) to (10) are repeated, the child develops a habit of taking safety check actions.

Table 1 lists the relationship between points of view and functions required of Ropot as determined by the examination in this chapter. The next chapters introduce Ropot based on the points of view and functions listed in Table 1.

Table 1 Relationship between points of view and functions of Ropot

Point of view	Functions
Educational	Check point remind Backward check remind Check point result review
Social receptivity	Partner design Departure/arrival notification Current location confirmation Silent mode

3. Implementation in Ropot

3.1. Ropot System

3.1.1. Ropot system configuration

Ropot consists of the Ropot device, the cloud, and a smartphone application. Through the application, the school's location and check points are registered to the cloud. The Ropot device obtains that information and activates the check point remind function (Fig. 5).

3.1.2. Ropot device

To use the Ropot device, children in the lower grades of elementary school wear it on their school backpacks (randoseru). The device has a remind function to encourage traffic safety and a function that uploads to the cloud location information and a route history of every stop the child made to confirm traffic safety at check points. Figure 6 shows the hardware configuration and Table 2 the major specifications.

Table 2 Specification of Ropot device

Item	Specification
Size (L × W × H) ^{*1} (mm)	81 × 53 × 59
Mass ^{*1} (g)	170
Continuous operation time (h)	3.5
GNSS receivable signals	GPS QZSS L1C/A, L1S
Data communication system	LTE Cat-M1
Millimeter wave radar frequency band (GHz)	76-77
Charging connector	USB Type-C
Dust-proof/drip-proof performance	Equivalent to IP44

^{*1} Except for attachment part

The Ropot device uses a lithium-ion battery as its power supply. It consists of a CPU, global navigation satellite system (GNSS), millimeter wave radar, acceleration/angular velocity sensor, data communications module (LTE), and vibrating motor.

The size and weight of the Ropot device are such that it is used mounted on the randoseru of a child in the lower grades of elementary school. In consideration of the battery capacity, the authors conducted a web-based survey on

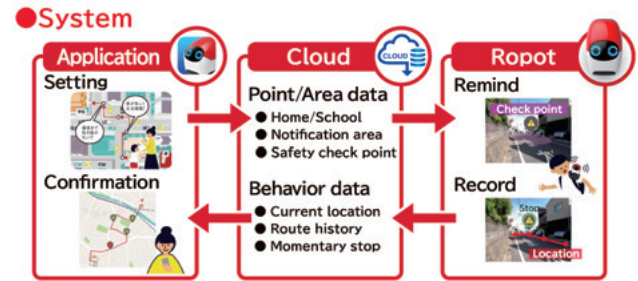
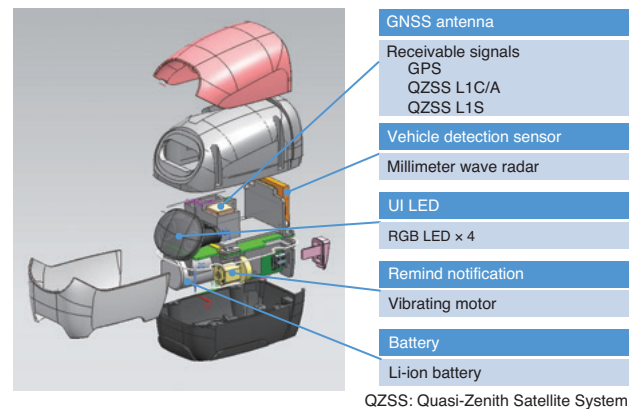


Fig. 5 System configuration



QZSS: Quasi-Zenith Satellite System

Fig. 6 Device configuration

how much time it takes for elementary school students to commute to school. The results showed that the one-way school commuting time for elementary school students throughout Japan was roughly within 50 minutes. Therefore, daily operating time was set as 100 minutes, the combined time for commuting to school and returning home. Considering that users may forget to charge the battery for a day, the authors set 210 minutes as the continuous operation time so the battery would not lose its charge over two days of commuting. The Ropot device also has an acceleration/angular velocity sensor that detects a state of repose when the device is allowed to sit still. It has a function that automatically activates sleep mode to save power at those times.

To communicate with the cloud, it uses an LTE Cat-M1, since a slow speed of a few kB/s is sufficient.

It uses a USB Type-C charge connector so the user does not have to think about which side is the front and which is the back when connecting.

The authors gave the Ropot device dust-proof/drip-proof performance equivalent to IP44 to protect against raindrops during the commute and sand and pebbles on the playground.

3.1.3. Application

An application was created that works on the Android OS (Android is a trademark of Google LLC).

The application enables the guardian to set the home, school, and check point locations. It has a graphical user interface (GUI) designed to let the guardian work with the child to raise the child's awareness of traffic safety.

Users can see the Ropot device's current location as well as check point, school, and home locations from the main screen (Fig. 7). They can use the menu (Fig. 8) to navigate to the check point result review function and notification history, which are described later.

3.2. Educational Functions

Ropot has three educational functions. This part explains the check point remind, backward check remind, and check point result review functions.

3.2.1. Check point remind

The check point remind function reminds the child to check for traffic safety at places where many vehicles are passing, such as pedestrian crossings, intersections, and parking lots (Fig. 9). In the application, the guardian registers check points in advance. Referring to the registered check point information and latitude and longitude information obtained by GNSS, the Ropot device activates the vibrating motor to remind the child to confirm traffic safety when they approach a check point. Signals that can be received by GNSS include both GPS signals and sub-meter level augmentation signals (LIS) from the Quasi-Zenith Satellite System (QZSS). This is to enable the remind function to operate more accurately at a specified

location, such as right in front of a pedestrian crossing.

The acceleration/angular velocity sensor determines whether the child stopped close to the check point. If it detects that the child did stop, the vibration notification stops and a signal is sent to the cloud indicating that the child stopped. If the child passes the check point area without stopping, however, it stops the vibration notification



Fig. 7 Application main view



Fig. 8 Application menu view

and a signal is sent to the cloud indicating that the child did not stop.

There are also situations where the child may take a different route going to school than when leaving, or the stopping locations for pedestrian crossings are different for the two trips. For that reason, the device allows the guardian to register separate check points for the commute to school and the commute from school.

3.2.2. Backward check remind

The backward check remind function reminds the child to pay attention to vehicles approaching from behind when walking on public roads (Fig. 10). When the Ropot device detects an approaching vehicle, it causes a vibration notification that encourages the child to confirm traffic safety behind them. The timing of the vibration notification takes account of the time it takes for the child to confirm traffic safety after the vibration notification occurs.

The Ropot device also uses millimeter wave radar as a vehicle detection sensor.

Using millimeter wave radar waves allows accurate detection of approaching vehicles even if the Ropot device is covered by an umbrella, scarf, parka hood, etc. Also, in general, the higher the frequency of millimeter wave radar, the smaller the antenna surface area. The frequency band of the millimeter wave radar on the Ropot device was set to 76 GHz to provide adequate approaching vehicle detection range while enabling the device to be smaller.



Fig. 9 Check point remind function

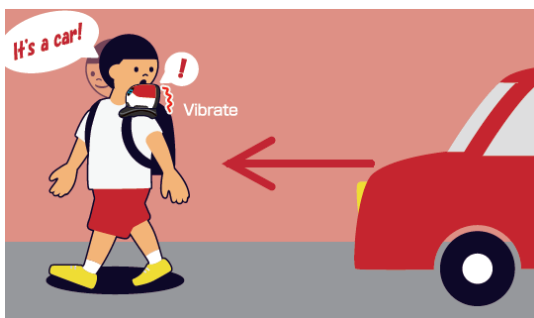


Fig. 10 Backward check remind function

3.2.3. Check point result review function

The check point result review function is intended to help the guardian and child become more aware of traffic safety while communicating with each other. Using the application, the guardian and child can view the child's location information history and a behavior history showing whether the child stopped at check points. They can see the child's actual commuting route since the location information history can show position information at 10-second intervals (Fig. 11).

Long-term changes in the child's awareness of traffic safety can be checked because the route history can show data for the past four weeks.

3.3. Receptive Functions

This part describes the receptive functions, the purpose of which is to make children, guardians, and schools comfortable with the Ropot device so it will get used.

3.3.1. Design/UX concept

When considering the Ropot device's design, the authors tried to create a form that children would feel an attachment to and would present an image of a "partner that rides on the shoulder." In addition, the following points were considered elements that children and guardians have loved for a long time.

- A size small enough to sit on the shoulder
- A form that inspires an affectionate attachment
- An expression that gives a sense of being alive

Based on the above, the design concept was defined as "Minimum & Friendly."



Fig. 11 Report view on application

The Ropot device has a rounded and warm form. It resembles a four-legged living organism. The part of the device surface that is black is used effectively to impart contrast that makes the device look even smaller.

In addition, the Ropot device has four full-color LEDs in front (upper right, upper left, lower right, and lower left) that give a sense of the device being alive. The viewer can see what state the device is in: charging, startup, or normal (Fig. 12). It also has three facial expressions: normal, smile, and sleepy. This design is intended to make the user feel more of an attachment to the device (Fig. 13).

The UX concept was defined as “the guardian working with the child to raise the child’s awareness of traffic safety.” The following elements were provided to encourage communication between guardian and child.

- Graphics that children find interesting
Ropot was designed so children themselves would find it interesting, not something that their guardians make them carry.
- GUI that makes children’s safety actions and changes in them easy to understand
The child’s safety actions and changes in them are expressed visually on the application so that the guardian can easily confirm the child’s record of stopping and give feedback to the child.
- Picture book-like user’s guide so guardian and child can read together (Fig. 14)
Pages are provided so that the guardian can show illustrations to the child to easily teach them traffic safety actions and Ropot’s functions.

The Ropot device, application, and user’s guide were designed with an integrated world view.

3.3.2. Departure/Arrival notification

Departure/arrival notifications is a function that sends push notifications to a smartphone to notify the guardian when the child has arrived at or departed from home or school.

Aside from the departure/arrival notifications, there is a function that sends push notifications to remind the user to recharge the Ropot device’s battery when it is low (Fig. 15).

To make it easier for the guardian to check the child’s location, the application shows a history of push notifications, with specific times of departure and arrival.

3.3.3. Current location confirmation

Current location confirmation is a function that forwards the Ropot device’s current location information via the cloud and displays it on the application.



Fig. 14 Traffic safety guide



Fig. 12 Status expression by LEDs



Fig. 13 Facial expression by LEDs



Fig. 15 Notification history list in application

The Ropot device uploads detected current location information to the cloud every 100 seconds, so the guardian can view the device's location within the last 100 seconds on the application. The display uses a Ropot icon to indicate the current location, and the update time is shown close by, so the user can view the Ropot device's current location and update time. Moreover, if the Ropot device's location data has not been updated for five minutes, the Ropot icon indicating current location is grayed out, so the user knows the current location is not updating (Fig. 16).

3.3.4. Silent function

The silent function keeps the Ropot device from operating inadvertently, at school for example.

Using the application, the Ropot device can be set to stop operating in places such as the school grounds where the operation of the LEDs and vibrating motor are not wanted. If the Ropot device detects that the location obtained by GNSS is at a facility where it is set to be silent, the started-up LEDs and vibrating motor will stop operating. Also, if the sensor detects continuous acceleration beyond a set level, such as a walking action, the LEDs light up and the vibrating motor operates, activating the remind function and switching the Ropot device over to normal operation. This arrangement helps prevent the LEDs from suddenly lighting up during school. Then, when walking begins, the LEDs light up so the child can see the Ropot device's operating status.

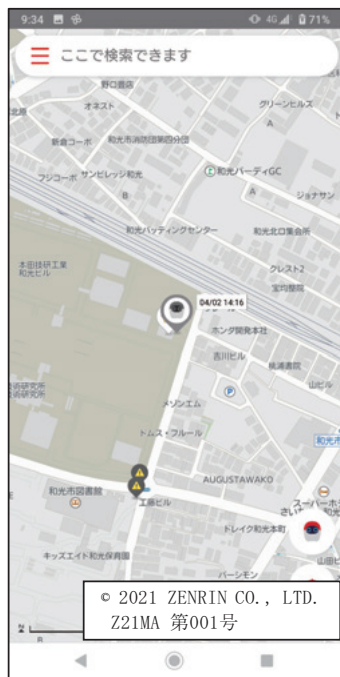


Fig. 16 Ropot current location

4. Verifying Educational Effect and Receptivity

4.1. Social Receptivity Verification: Education Expo Japan

A prototype Ropot was exhibited at the 2020 Education Expo Japan (EDIX) to verify the receptivity of school personnel to the Ropot concept and design. Visitors answered a questionnaire to evaluate the Ropot concept.

Honda set up a display booth to resemble a city intersection. School personnel who visited the booth learned that Ropot was intended to assist traffic safety education along school commuting routes and that it has a child-oriented design, functions that live up to the wishes of guardians, and a silent function so it does not become a distraction at school. The exhibit provided hands-on experience of the check point remind function and backward check remind function so school personnel could better understand Ropot (Fig. 17).

The hands-on exhibit helped school personnel to recognize that Ropot is a device intended to provide traffic safety education. It furthermore confirmed the strong possibility that school personnel would be receptive to children bringing the device to school, based on its design and the low possibility of it being a distraction at school. Overall, 97% of visitors had a favorable impression of the Ropot concept (Fig. 18).



Fig. 17 Hands-on exhibition of Ropot

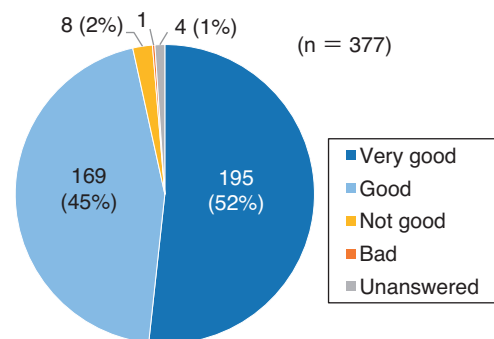


Fig. 18 Evaluation of Ropot concept

Additionally, many media outlets reported on Ropot as a device intended for traffic safety education. Some of the users participating in actual demonstration experiments at elementary schools in Wako City, Saitama Prefecture and Fukuoka City, Fukuoka Prefecture had been motivated to do so because of the media reporting. This fact confirmed that Ropot is gradually becoming widely recognized by society as a device for assisting traffic safety education.

4.2. Educational Effect and User Receptivity Testing: Demonstration Experiments

4.2.1. Experiment overview

To verify the educational effect and receptivity to the service in daily life, demonstration experiments of commuting with Ropot were conducted with families that actually had elementary school students.

The authors recruited families with children in grades 1 to 4 at two elementary schools, one in Wako City and one in Fukuoka City. Over about two weeks, 27 families participated in Fukuoka City and 25 in Wako City (Fig. 19).

4.2.2. Experimental method

Participating elementary school students used the Ropot device for 12 days while commuting to and from school. Three of them were observed for behavior while commuting to and from school. Based on questionnaires that guardians filled out before and after use and on group interviews, the authors confirmed the educational effect and user receptivity (Fig. 20). The authors confirmed school receptivity by having the principals of the two elementary schools where the experiment was conducted fill out a questionnaire on whether any trouble had occurred in the school as a result of the experiment.

Behavioral observation took place at points where traffic safety actions were considered necessary along the school commuting route (e.g. a pedestrian crossing with no signal). Observers recorded whether children actually commuting to and from school took safety check actions or not. The experiment conditions included three time periods: before wearing the Ropot device; 10 days during which the

child wore the Ropot device and the remind functions were in effect; and the final two days, when the child wore the Ropot device but the remind functions were not in effect.

Prior to conducting the experiment, the method underwent advance assessment by an bioethics committee within Honda R&D Co., Ltd. Families participated in the experiment by their own free will. The persons responsible for the experiment fully explained the purpose and content of the research and the participants' rights to the children and guardians in advance, both verbally and in writing, and received their written consent to participate.

4.2.3. Experiment results

The experiment results relating to the educational functions are discussed first. Behavioral observation confirmed that the execution of safety check actions such as stopping increased while the children were wearing the Ropot device and its remind function was in effect, as compared to the time period before wearing it (Fig. 21). Even during the final two days of the experiment, when the remind function was not in effect, the increase in execution of safety check actions as compared to the time period before wearing it was maintained (Fig. 21).

Moreover, according to a questionnaire survey of guardians one month after the completion of the experiment, 77% of guardians answered that their child's awareness of safety actions remained, even one month after use (Fig. 22).

A questionnaire survey taken immediately after the completion of the experiment asked guardians about the

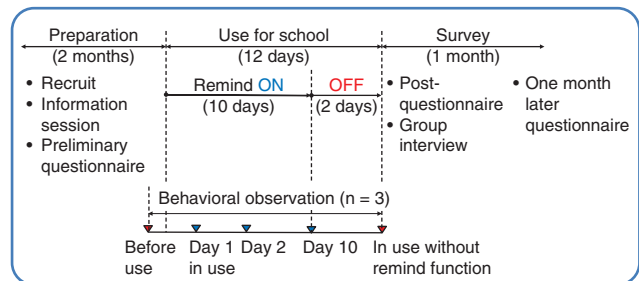


Fig. 20 Outline of experiment



Fig. 19 Demonstration experiment by elementary school students

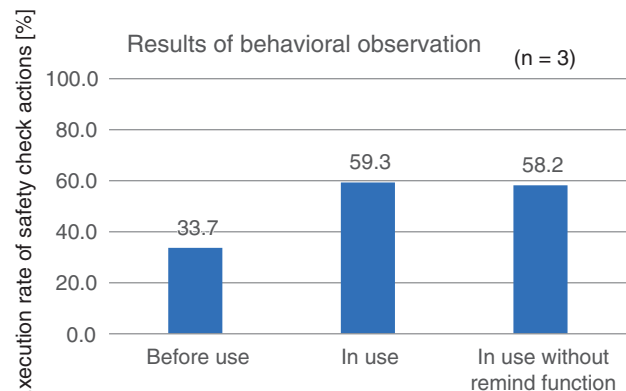


Fig. 21 Results of behavioral observation

three effects of the educational functions. It found that 80% to 90% of guardians felt those effects (Fig. 23). That same questionnaire and interviews conducted at the same time yielded specific comments with positive evaluations. Both children and guardians confirmed the effect of the functions. One person said, “I saw children stop at a pedestrian crossing where they did not previously stop.” Another said, “Feeling the vibration caused a remarkable change in awareness of what is behind (backward check).” Still another commented, “Because there was a report, I did not need to interrogate my child as I would have if I didn’t have any means to check. So we were able to talk.”

The experiment results relating to the receptive functions are discussed next. When the same questionnaire survey asked about children’s receptiveness to Ropot, 98% answered they had an attachment to it (Fig. 24). Specific comments heard during group interviews immediately after the experiment was completed included “My son was even more enthusiastic than us, his parents, and he kept saying he wanted to wear it. It really seemed like a partner for him.” Another said, “My child loved it so much, petting it and talking to it.” Another: “My child really seemed to like how the Ropot device’s eyes changed.” Still another: “Starting about the third day, it became a habit to wear it. My child just put it on without being told to do so.” Comments like these confirmed that the children were largely receptive to the partner design and “Minimum & Friendly” concept.

The questionnaire survey taken immediately after the completion of the experiment asked about the guardians’ receptivity. It found that 70% to 80% of guardians felt the effect of the receptive functions “departure/arrival

notifications” and “current location confirmation,” indicating a high level of receptivity among guardians as well (Fig. 25).

Concerning schools’ receptivity, results of the questionnaire for principals of the two elementary schools where the experiment was conducted indicated no reports of trouble at either school. There were no cases where bringing the Ropot device into school caused any disruption there.

To assess guardians’ evaluation of the service overall in light of these educational functions and receptive functions, a questionnaire survey taken one month after the completion of the experiment asked about guardians’ inclination to have their children use Ropot in future. It found that 92% said they would like to do so (Fig. 26). They were also asked about what type of usage scenario they would like to see. Many indicated they would like to have their children use Ropot on outings other than commuting to and from school. For example, one said, “It would be nice if there were some kind of platform that would allow Ropot to sit somewhere besides on a randoseru, like on a backpack or the shoulder strap of a bag.” Another commented, “It would be great if a child could use it not just when commuting to and from school, but also on their days off or when going to lessons.”

4.2.4. Discussion

In terms of the educational functions, the fact that the increase in actions to confirm traffic safety and the awareness of traffic safety remained even after the experiment was completed indicates that there is an

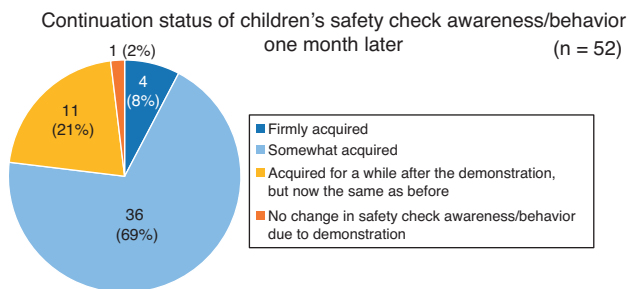


Fig. 22 Continuation of child safety confirmation awareness one month later

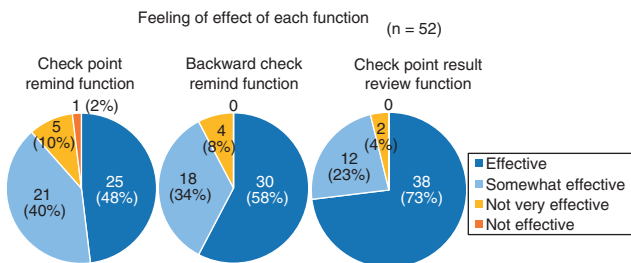


Fig. 23 Feeling of effect of each educational function

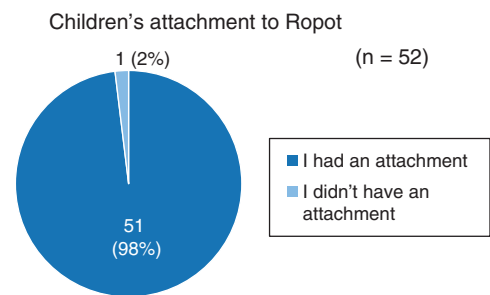


Fig. 24 Feeling of attachment

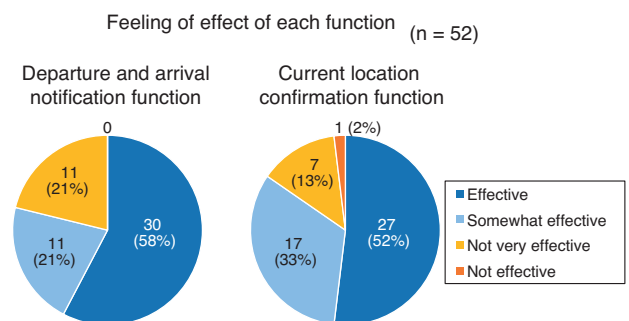


Fig. 25 Feeling of effect of each function to increase receptivity

educational effect. Moreover, the fact that there was a strong feeling of the effectiveness of these functions indicates that the positioning function provided by GNSS and the vehicle detection function provided by millimeter wave radar offered sufficient performance.

Concerning the receptive functions, the fact that both children and guardians evaluated Ropot so highly indicates that both children and guardians would be receptive to it as a product. On the other hand, the fact that so many guardians commented that they would be inclined to have their children use Ropot in situations other than commuting to and from school indicates a need for technical development to enable usage in a wider range of life settings in future.

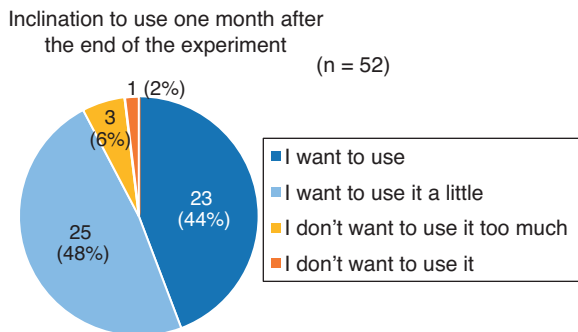


Fig. 26 Inclination to use after experiment

5. Conclusion

The authors developed a traffic safety advice robot to assist the teaching of traffic safety to children in the lower grades of elementary school.

They determined the educational functions that Ropot would need based on children's capabilities and characteristics and from the point of view of traffic safety education, and determined the receptive functions it would need based on interviews.

To achieve the educational functions, the robot requires high-precision positioning and the ability to detect objects behind the child. The robot was developed using GNSS to provide positioning precision and millimeter wave radar for the capability of detecting objects behind the child. To achieve the receptive functions, a partner design and silent function were adopted and a size and weight were chosen that would not burden the child.

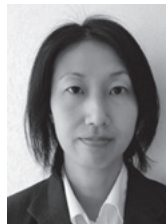
The educational trade fair and demonstration experiments showed that schools, children, and guardians are actually receptive to Ropot. This and the fact that increases in safety actions were observed after just 12 days of wearing Ropot confirmed the effectiveness of its educational functions and receptive functions.

The aim going forward is to consider expanding the range of Ropot's usage and contribute broadly to traffic safety education.

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Short Lead Time Development of Customized Vehicles with Preventive Measures for COVID-19 Infection - Social Contribution through Swift Provision of Vehicles -

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ABSTRACT

Honda has developed a vehicle for transporting infected persons in order to support local governments and medical institutions responding to COVID-19. Honda first developed specifications to protect drivers from infection while transporting infected persons or persons suspected to be infected to medical institutions and the like, then incorporated the specifications into an existing production vehicle and delivered the infected person transport vehicle to local governments within two weeks. In order to develop and provide the vehicle in a short period of time, simple infection-prevention mechanisms were adopted. These consisted of a flat partition attached to the rear of the driver's seat in the existing vehicle and the ventilation functions of the vehicle's air conditioner. Infection prevention performance indices were the differential pressure between the spaces fore and aft of the partition and the cabin ventilation capacity. The differential pressure target of over 2.5 Pa (standard for medical operating room) and the cabin ventilation capacity target value of over 12 times/h were achieved. Between April and December of 2020, 158 of these vehicles were assembled and provided to 25 municipalities and prefectures.

1. Introduction

In recent years, demand has been growing for social contribution from companies. The ESG approach, which stands for Environment, Social, and Governance, has attracted particular attention in recent years, and is playing an important role, in the same way as profitability, in the public determination of corporate value⁽¹⁾. As well, social contribution of the above "Social" category is being sought as an outcome of corporate activities, just as with environmental and corporate governance. Honda proactively works on social contribution, and has continued to contribute to society through traffic safety activities, disaster recovery support, and other activities⁽²⁾.

The global spread of the coronavirus disease (COVID-19) that has been ongoing since 2019 has not only threatened the health of citizens, but has also had a grave and serious impact on the scope of social activities due to movement restrictions and so on. In the midst of the first wave of the pandemic in Japan in April 2020, many issues appeared due to the rapid and wide-ranging spread of infection, and contributions in the medical field in particular were sought. In these circumstances, Honda took

on the increasing need for the safe transportation of infected individuals to medical institutions and medical supplies and medical equipment for the struggle against the infectious disease, viewing them as social issues that needed the company's support.

Honda has carried out the following three social contribution activities in response to the spread of the coronavirus pandemic.

- Provided vehicles for transporting infected persons to local governments
- Provided face shields to medical institutions
- Supported production of artificial respirators

Of these, this report will describe the development of vehicles for transporting infected persons. As this viral epidemic was not expected, Honda only began development when COVID-19 infections first began to spread. Therefore, with the shortage of vehicles for transporting infected persons, Honda found itself in a situation in which it had to start without any know-how to providing the vehicles as quickly as possible. The company developed infection prevention functionality, prepared for production, and assembled the vehicles within a short lead time.

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2. Development Goals

The goals in developing the vehicles for transporting COVID-19 infected persons (hereafter, “transport vehicles”) were as follows.

(1) Simple construction with infection prevention functionality

(2) Speedy provision of vehicles

At the start of development, many citizens who were infected or suspected of being infected had mild or no symptoms and were still capable of walking. In order to respond to the rapid increase in infections, not only ambulances but also commercial vehicles of health centers were used for transportation, and there was a risk of the infection spreading to medical staff such as ambulance crews and health center staff, inspiring Honda to begin developing a vehicle capable of protecting drivers from infection.

Development began on April 1, 2020. At that point, the shortage of vehicles for transporting infected persons due to the growing number of infections was not yet apparent. Honda made its own estimates about the need for transport vehicles, and set a provisional target of April 15, 2020, or two weeks from development start, to begin providing vehicles.

As well, at the start of development, the method of provision and number of vehicles were still undetermined. Honda aimed to make a wide-ranging societal contribution by adopting a simple structure in which production vehicles were used as the base and infection prevention functions could be easily added and removed.

3. Infection Prevention Functions and Structure

3.1. Design Concept and Performance Target

The schematic diagram and an internal photograph of the transport vehicle that was developed are shown in Figs. 1 and 2, respectively. In general, spaces in medical institutions are protected from infectious diseases through differential pressure designs, with positive pressure in the protected space preventing the inflow of air. The same concept was used for the transport vehicle, wherein the front seat space (driver’s/front passenger’s seats), which required infection protection, was maintained in a state of positive pressure with respect to the rear seat area where the transported persons would sit. Furthermore, in order to rapidly provide the transport vehicles, it was necessary to provide this functionality in production vehicles using a simple mechanism. Thus, a mechanism was used which had a partition on the rear of the front seats of a production vehicle, with the in-vehicle air conditioner providing positive pressure in the front seat area to create the pressure differential.

First, the partition on the back of the front seats blocks air flow between front and rear seats. This causes positive

pressure relative to atmospheric pressure to build up in the front seat space, where the outside air is brought in via air conditioner vents located there. At the same time, air pressure is released via the exhaust vent in the cabin aft of the partition, creating a relative pressure differential between the high pressure of the front seat space and low pressure of the rear seat space. This pressure differential serves to block air flow from the rear seats to the front seats, preventing infection. This concept originated in knowledge about operating rooms of hospitals, which are kept at a positive pressure to prevent infection, and the fact that vehicle air conditioners have powerful fans in order to make vehicle cabins comfortable in a short period of time. This report uses the STEPWGN as an example, but the same mechanism was used for infection prevention functions in other models.

The next task was to set target values for infection prevention performance. For the pressure differential between the spaces fore and aft of the partition, which is at the core of prevention functionality, a target of 2.5 Pa or more was chosen, which is the target management value for medical operating rooms according to Japanese hospital facility design guidelines⁽³⁾. Ventilation capacity was set at 12 times/h ventilation rate (a value obtained by dividing the

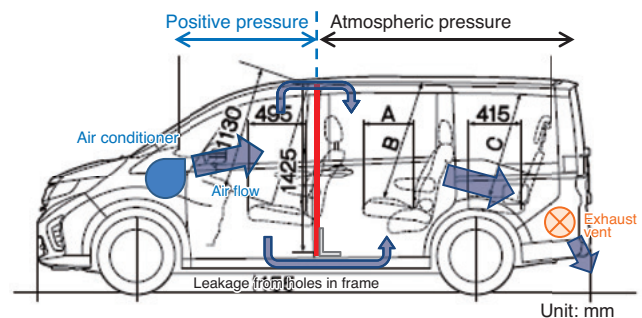


Fig. 1 Schematic diagram of vehicle



Fig. 2 Inside view of vehicle

hourly ventilation air volume by the cabin air volume). This was based on a request from local governments to meet a minimum number of air changes (ACH) of 12 times/h for airborne infections in isolated zones, as recommended by the U.S. Centers for Disease Control and Prevention (CDC)⁽⁴⁾.

The structural components are attached by bolts and can be easily removed. The materials are non-combustible and fire retardant. They were made to be safe when used and easy to install on production vehicles to create the transport vehicles. And to provide peace of mind for passengers, attention was also paid to the quality of the appearance.

3.2. Partition Structure

The partition on the rear of the front seats that blocks the flow of air is composed of panels, seals, and windows. In order to achieve the simplest structure possible, a single flat-plate structure was used without curves, welds, or other processing. To reduce weight, an aluminum alloy was used for the panel material, with rubber seal material protecting the edges. This maintains airtightness and helps avoid injury to occupants. The partition was installed at the rear edge of the center pillar that separates the front and rear door openings. Figure 3 shows the left side partition mounting point.

In vehicles with sliding doors, a grab rail was included near the rear edge of the center pillar to help occupants get in and out of the rear seats. Figure 3 shows how this grab rail is fastened together with the partition to the vehicle chassis. Using the grab rail as a fixing member for the partition hides the fixing bolts, as well as enabling occupants to use the grab rail when getting in and out of the rear seats. In addition, the left and right edges of the partition are positioned at the rear edge of the center pillars, and weather stripping is attached to seal the door openings. Using this weather stripping, the partition is fastened together with the chassis outer panels. Normally, the left and right edges of the partition would be visible to

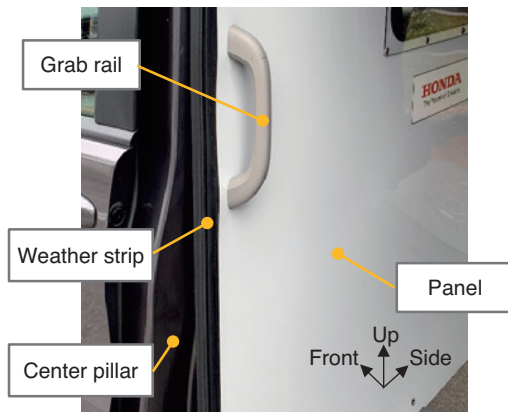


Fig. 3 Side part of panel fixed by using grab rail and weather strip

occupants who are in the rear seats, but because of this co-fastened structure, the edges of the partition are not visible to the rear seat occupants. The weather stripping was originally attached for sealing purposes, and here it also helps secure the airtightness of the partition.

In cases where the condition of the occupants being transported in the rear seats changes suddenly, a polycarbonate internal window is built into the center of the partition to provide a view of the rear seats. Figure 4 shows the partition window.

Generally, fastening parts of interior components are located so as not to be in the field of view of occupants. Therefore, while normally the partition window would be installed from the front seat side so the fastening parts were not visible to the rear seat occupants, at the suggestion of the welfare vehicle development team that cooperated in the design, the window was installed from the rear seat side to help prevent it being pushed out when a rear seat occupant leaned against the window in certain conditions. This window was assessed not only to confirm its safety but also for the sense of openness it provided in the rear seats.

3.3. Using the Air Conditioning System

Production vehicles have an air conditioning unit known as a Heating, Ventilating, and Air Conditioning unit (HVAC) built into the cabin. This conditions the air in the cabin with functions such as ventilation, heat exchange, switching between warm and cool air conditioning, and switching between internal circulation and outside air intake. In addition, there is an exhaust vent with a one-way valve in the rear of the vehicle, which discharges the air taken into the vehicle cabin. In other words, when the air conditioner is used in the mode that intakes outside air, the air flows from the front of the cabin to the rear in a positive pressure state relative to atmospheric pressure. In the case of the STEPWGN, the HVAC has a powerful ventilation capacity of 450 m³/h. With the belief that a sufficient pressure differential could be obtained using only the HVAC if the partition were airtight, a prototype was built and a target pressure differential of 2.5 Pa or more was confirmed. The

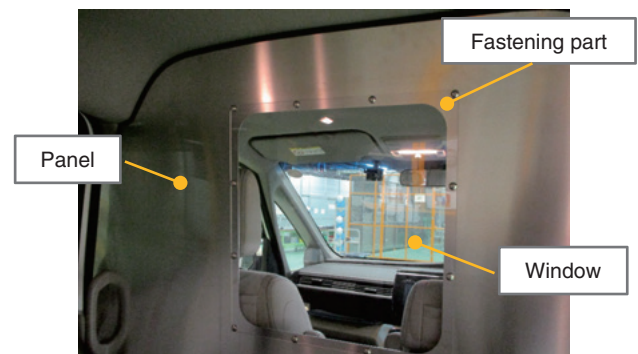


Fig. 4 Internal window of partition

appearance and installation location of the HVAC unit are shown in Fig. 5.

In the transport vehicle, it is necessary to set the air conditioner to “outside air intake” mode in order to generate a pressure differential fore and aft of the partition. If “internal circulation” is mistakenly selected, a pressure differential fore and aft of the partition is not generated, thus compromising the infection prevention function. Therefore, when assembling the transport vehicle, the actuator wiring of the HVAC flap was removed and the unit put in the “outside air intake” state. This meant the transport vehicle air conditioning was constantly operating in “outside air intake” mode. Also, to maximize the infection prevention performance, it was stipulated that the front seat air conditioner be run at full power.

3.4. Testing Fore and Aft Pressure Differential

To assess infection prevention function, the pressure differential fore and aft of the partition was measured. Measurements were taken with the front air conditioner at full “outside air intake.” An air hose was inserted from the side of the partition to measure the fore and aft pressure differential, using a differential pressure gauge. Figure 6 shows the pressure differential measurement setup.

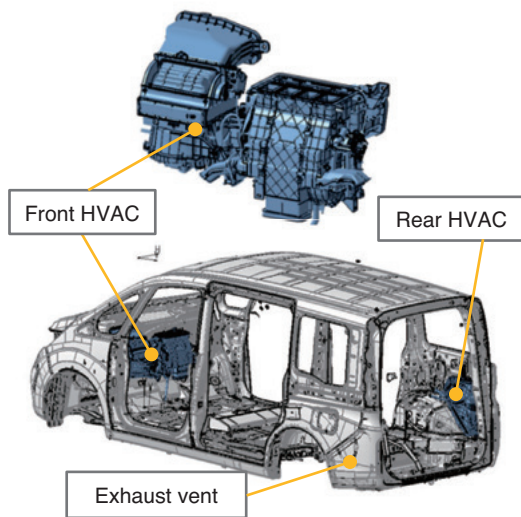


Fig. 5 HVAC unit and its layout in vehicle



Fig. 6 Pressure differential measuring test

The subject vehicles were 19 modified STEPWGN vehicles (DBA-RP1 1.5 L Turbo, CVT, FF, air conditioner blow rate manually set to full) that were assembled in April 2020. Measurements were taken while the vehicle was stopped, resulting in pressure differentials from 11 to 20 Pa (average of 15.4 Pa), greatly exceeding the target of 2.5 Pa. In addition, when the vehicle is moving, negative pressure is generated at the rear exhaust vent due to the external air flow, so the pressure differential fore and aft of the partition rises relatively. When the STEPWGN vehicles above were measured at 20 km/h, pressure differential increased by 5 Pa.

3.5. Testing Ventilation Capacity

Next, ventilation capacity was tested to see if it met local government requirements. Ventilation capacity was assessed according to CDC regulations as the ventilation rate per hour, a value obtained by dividing the hourly ventilation air volume by the cabin air volume. For the transport vehicle measurements, the wind speed at the exit of the interior exhaust vent in the rear of the cabin was measured, and the hourly ventilation volume was calculated from this figure and the cross-sectional area of the exhaust vent. This figure was divided by the cabin air volume to calculate the ventilation rate. Figure 7 shows the wind speed measurement setup at the exhaust vent.

As with the pressure differential measurements, the same STEPWGN vehicles were used and a ventilation capacity of 73 to 111 times/h (average of 90.2 times/h) was obtained, exceeding the target of 12 times/h.

3.6. Confirming Airtightness

A smoke test was performed to check visually for air leakage into the front seat area.

With all the doors closed, a tester sat in the driver’s seat, turned the air conditioner off, and used a remote control to activate a smoke machine in the rear seat space aft of the partition. After the rear space was filled with smoke, the air conditioner was started to generate a pressure differential fore and aft of the partition, and the tester checked for smoke intrusion into the front seat area from the corners of the partition, the window frame seal of the partition, and other locations. Figure 8 shows the smoke test setup.

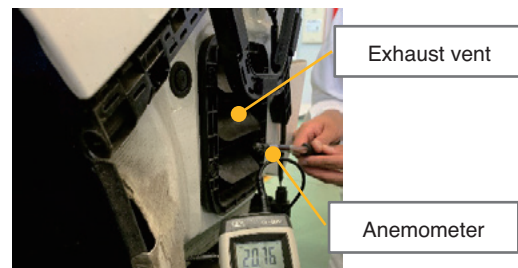


Fig. 7 Ventilation capacity measuring test



Fig. 8 Smoke leak test

3.7. Checking Droplet Scatter Prevention Performance

With COVID-19, airborne infection is an issue when infected persons cough or sneeze and cause droplets to scatter. The vigorous scattering of droplets was therefore replicated and checks were performed on the possibility of intrusion into the front seat area.

Airborne droplet scattering from coughing and sneezing is assumed to reach from 1 to 2 m⁽⁵⁾. To replicate and visualize droplet scattering, a test was adopted in which an aqueous solution of a fluorescent agent that emits light under an ultraviolet lamp is used to simulate the droplets, and this solution is scattered with compressed air. Test conditions were sought by gradually adjusting a volume of compressed air at 0.4 MPa until a volume of 5 ml of the fluorescent aqueous solution was sprayed 2 m or further. 5 ml was a sufficient volume to be visually confirmed under the ultraviolet lamp. The result was a test condition that simulated droplets being scattered 2.7 m in distance from a height of 1.6 m, which was judged to be the height of the mouth of an infected person. Under this condition, a device for scattering droplets was positioned behind the partition, and with a pressure differential generated fore and aft of the partition, the solution was horizontally scattered forward in the direction of the partition, from a height of 700 mm from the seat surface and 850 mm from the partition, which was the estimated position of the head of a person seated on the rear seat. The spread of the droplets was observed under the ultraviolet lamp, and it was confirmed that there was no droplet scatter ahead of the partition. Figure 9 shows the droplet scatter test setup.

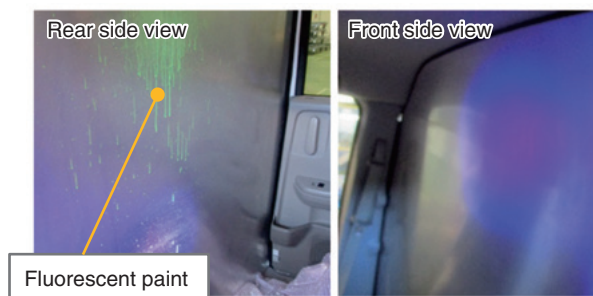


Fig. 9 Scattering test of cough droplets

4. Production Technology for Speedy Provision

In this development, production preparation took place in parallel with specification development in order to achieve the target of “delivery within two weeks.” The flexible production process developed by the Production engineering supervisory unit contributed to the shortening of the production preparation period. As a result, the lead time required from the start of partition design for one model of transport vehicle to the completion of assembly and testing of the transport vehicle was three to four days. An explanation of the transport vehicle production process and its characteristics follows.

4.1. Development and Prototyping

For each vehicle model, the shape of the partition had to be designed with due consideration of the installation location, installation method, edge parting line, and so on.

The shape was designed based on the cross-sectional shape of the cabin space at the partition installation position at the rear edge of the center pillars. The vertical dimensions were shortened to allow clearance for the rubber sealing material in order to achieve airtightness. Also, since the partition supports its own weight and withstands the pressure differential, it is installed so it curves slightly left and right. For this reason, the design dimensions were increased by several tens of millimeters on the left and right. The installation holes for the rear slide door grab rail used for installation were also reflected in the panel shapes. Since the actual partition deforms when installed in the vehicle body, repeated checks were performed as the partition was designed, prototyped, and installed in the actual vehicle, in order to determine the final cutting shape.

4.2. Partition Panel Cutting

The reduction in the partition production lead time was due to the use of single flat-plate partition panel that only required cutting to produce, and which used a flexible and high-speed Intelligent Laser Blanking System (ILBS) laser cutting machine.

Figure 10 shows an outline of the ILBS and applied technology.

The ILBS used in this production is a Honda original vehicle chassis steel sheet high-speed laser cutting machine. With the development of high-speed laser cutting technology, high-acceleration laser head drive technology, and high-speed synchronized conveyors, the system has a world top-class cutting speed of 120 m/min (Fe plate, 0.6 mm thickness). ILBS blanking is a process in which pre-pressed steel sheet blanks for vehicle bodies are produced from roll-shaped steel sheet coils. This is usually performed by pressing processes. Press blanking has a high production speed, but incurs die costs and die manufacturing lead times for each component. With its high-speed technology, the

ILBS removes the need for dies by replacing pressing with laser cutting. The system has been introduced at Honda's Saitama Factory Yorii Automobile Plant. Figure 11 shows a panel being cut with the ILBS.

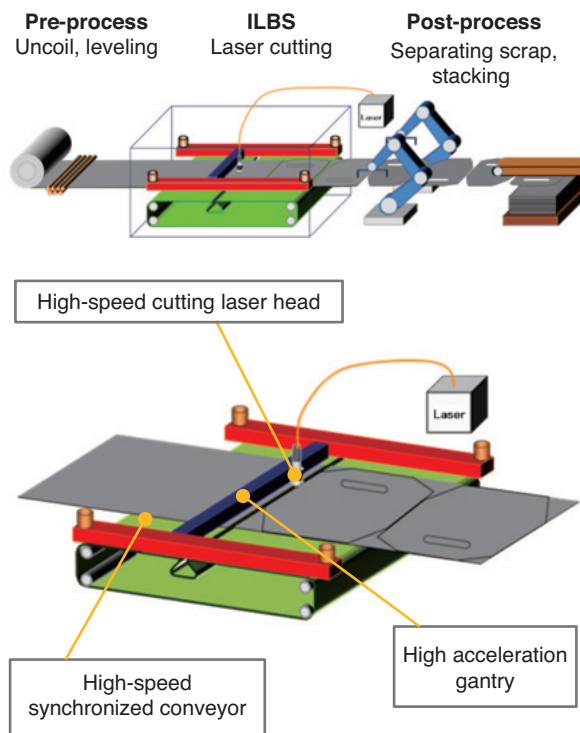


Fig. 10 ILBS and attached technology

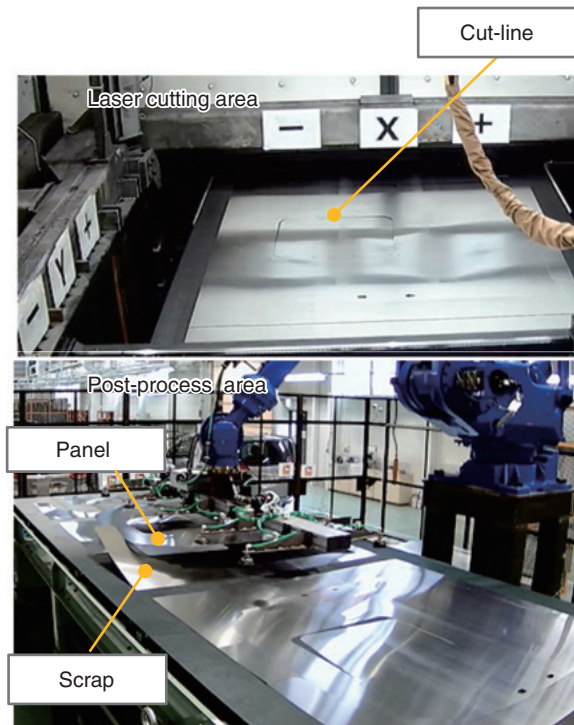


Fig. 11 Cutting panel by ILBS

Since ILBS does not require dies and performs laser cutting suitable for prototyping at a speed that can keep up with mass production, there is no need to change facilities when transitioning from prototyping to mass production. Therefore, once the cutting shape has been determined, a cutting program can be immediately created and mass production cutting launched, shortening production preparation lead times. In this project, partition panel dimensions had to be adjusted from one to three times for each vehicle model, but the lead time for design, prototyping, and the start of cutting was only one day. This is the result of work done in developing flexible production technologies.

4.3. Painting

The cut partition panels were immediately transported to Saitama Factory Sayama Automobile Plant or cooperating manufacturers for painting and appearance inspection.

4.4. Assembly

The painted panels were installed in vehicles as partitions and the transport vehicles assembled. Assembly was performed by installing the panels, window and edge seals, and modifying the HVAC unit to continuously take in outside air. The takt time for assembly was 20 to 30 minutes per vehicle, with two workers. Assembly was easy due to the simple construction. When supplying vehicles to local governments across the country, not only were vehicles assembled in company locations in Japan, but partitions could be supplied to sales companies throughout the country so that they could assemble transport vehicles and provide them to local governments. Figure 12 shows the assembly work.

4.5. Inspection

After assembly, all vehicles were inspected.

Tests were performed for pressure differential and ventilation capacity, and a smoke test for infection prevention. In addition, product quality was checked with external inspections and noise inspections conducted as the vehicle was driven around company grounds. Only then were the transport vehicles provided to local governments.

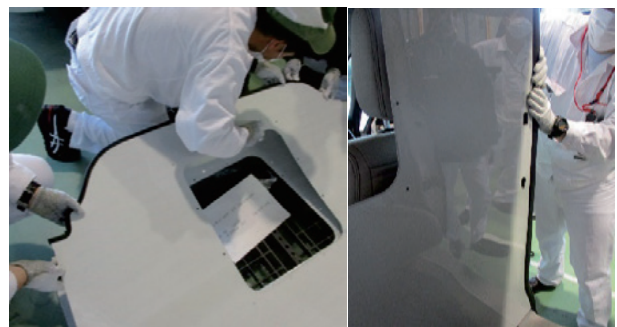


Fig. 12 Assembly process

5. Social Contribution Results

Vehicles with simple construction and effective infection prevention functions were rapidly developed, enabling them to be provided to local governments across the country before infection spread. At the beginning of development, the target date for start of vehicle provision was set at April 15, 2020. However, the first vehicle was provided two days earlier, on April 13, from the Saitama Factory to Shibuya Ward. This was 10 days after development began. Figure 13 shows the number of transport vehicles provided and the number of positives for coronavirus tests throughout the country⁽⁶⁾.

In accordance with the development aim, Honda was able to provide vehicles in response to the spread of the first wave of infection in April. Provision of vehicles continued in May and onward in response to requests from local governments, and many vehicles were able to be provided in advance of the large increase in infection from the second and subsequent waves.

Figure 14 shows vehicles as they were provided. By the end of December 2020, 158 transport vehicles had been delivered to 25 municipal and prefectural governments.

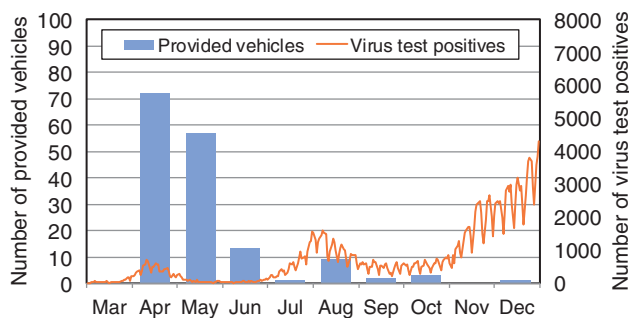


Fig. 13 Actual result of customized vehicle supplies



Fig. 14 Delivering for autonomy

Centered on the Tokyo metropolitan area, vehicles were delivered to municipalities and prefectures throughout the country.

The following feedback was received from local government supervisors who actually used the vehicles.

- The metal partition gave a sense of security
- The partition window was large, making it easy to monitor the condition of the transported persons
- As standard vehicles were used, they did not stand out, which helped protect privacy

Many responses were received about the provided vehicles not just from users, but from traditional media and social media.

6. Conclusion

Honda developed and provided a vehicle for transporting infected persons to support local governments and medical institutions responding to the spread of coronavirus disease.

- (1) By installing partitions in the cabins of production vehicles and using their air conditioning units, vehicles were assembled with a differential pressure of 2.5 Pa or more and a ventilation capacity of 12 times/hour or more, targets established in domestic and foreign guidelines for the prevention of infectious disease.
- (2) Efforts were made to shorten production preparation lead times by using a simple single flat-plate construction for the partition. By adopting high-speed laser cutting processes and using existing grab rails and weather strips for part of the partitions, completed vehicles were provided only 10 days after development began.

The simple modifications that added infection prevention functions to production vehicles enabled speedy development and production preparation, and ultimately the delivery of 158 vehicles to 25 municipal and prefectural governments throughout the country.

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Unmanned Vehicle Transportation System Using Pair of Thin Robots

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ABSTRACT

An unmanned vehicle system that transports cars in place of humans was devised. To enable application to a wide range of vehicle types including those without automated driving functions, vehicle transportation robots that are not constrained by car body performance are used for vehicle transportation. Additionally, in order to transport vehicles even in limited indoor and urban spaces, the system employs a pair of robots that move freely underneath the target vehicle, lift up the tires of the vehicle at the same time, and cooperate to achieve free omni-directional transportation. A prototype of the vehicle transportation robot was developed to verify system feasibility. Operation verification experiments were conducted using the developed prototype in a limited space, and confirmed realization of the desired transport operation.

1. Introduction

Honda has proposed the statement to “serve people worldwide with the ‘joy of expanding their life’s potential’” in its 2030 Vision⁽¹⁾. Cars are convenient tools that expand the potentials of life and satisfy travel needs easily and quickly. However, the use of cars also involves various labors that are not directly related to travel, such as parking, refueling, and charging.

Specifically, some 30% of all drivers feel they are not adept at or experience anxiety when parking⁽²⁾. In addition, over half of novice drivers feel that driving in parking lots or garages is dangerous⁽³⁾. Thus, the act of parking is a psychological obstacle to traveling by car. Around 30% of all traffic accidents in Japan occur in parking lots⁽⁴⁾, so these feelings of being not good at or having anxiety about parking also appear in the actual state of traffic accidents.

Valet parking (VP) is widespread in Europe and the United States as a service that takes care of parking. In VP, the driver leaves their car key with an attendant (valet) who parks the car and then delivers the car to the entrance for departure. While VP is a convenient service for drivers, it is no different from personal parking, and operates only in limited environments such as high-class restaurants and hotels.

Vehicles equipped with parking-assist functions that assume use near parking slots have already been

commercialized as a means of directly assisting parking, and are helping to reduce the psychological burden on drivers as well as accidents in parking lots⁽⁵⁾.

Automated valet parking (AVP) that combines automated operation and VP is also attracting increasing attention. In AVP, the user drives to an AVP-compatible parking lot reserved in advance, exits the vehicle at a location convenient for access to adjacent facilities, etc., and requests automated parking using a terminal such as a smartphone, at which time the service parks automatically by unmanned operation without presence of the driver⁽⁶⁾. Active efforts are underway to develop AVP technology, but some reports also say that it will take decades for the level 4-equivalent automated driving cars required for AVP to spread around the world⁽⁷⁾.

In response to this issue, practical operation has begun of large-sized vehicle transportation robots intended for use mainly in large-scale outdoor parking lots such as those found at airports⁽⁸⁾. By using robots, all the necessary functions and infrastructure can be provided on the facility side, enabling automated parking even for vehicles without automated driving functions.

Meanwhile, systems intended for use in small indoor or urban spaces where parking is a challenge and only a few vehicles can be parked have yet to be practically applied. Factors for this include challenges in robot miniaturization and precise control. The authors have therefore devised

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an unmanned vehicle transportation system that can be operated even in small spaces.

This paper describes the system concept, the development of a prototype of the vehicle transportation robot that plays a central role, and operation verification experiments using the prototype to transport a mock-up vehicle for the purpose of verifying system feasibility.

Figure 1 shows the prototype of the developed vehicle transportation robot.



Fig. 1 Prototype of robot

2. Development Goals

Figure 2 shows an example of application of an unmanned vehicle transportation system that assumes AVP able to operate even in a small space.

The driver can easily board and exit the vehicle and

load luggage by leaving the vehicle in the expansive boarding and exiting space. After the driver exits the vehicle, the robots automatically recognize the vehicle type, size, and position, and cooperate as a pair to transport the unmanned vehicle to the parking area. As there is no need for boarding and exiting space in the parking area, high-density placement can be performed by commands from the management server. When departing the parking lot, the vehicle is transported to the boarding and exiting space according to the driver's command. This series of operations helps to reduce the labor and stress of parking, while increasing parking efficiency and safety.

The devised unmanned vehicle transportation system was developed with the following two goals in order to realize this type of service and provide a more comfortable car life for people.

- (1) Capable of operation in a small space
- (2) Capable of application to diverse vehicle types

3. Concept of Vehicle Transportation System

3.1. Basic Concept

Figure 3 shows the concept scheme of vehicle transportation operation using robots. When performing transportation with a single robot, the robot itself must be larger and operation in a small space is challenging. Therefore, a system was adopted wherein a pair of robots move freely underneath the target vehicle, lift up the tires of the vehicle at the same time, and cooperate to perform free omni-directional transportation.

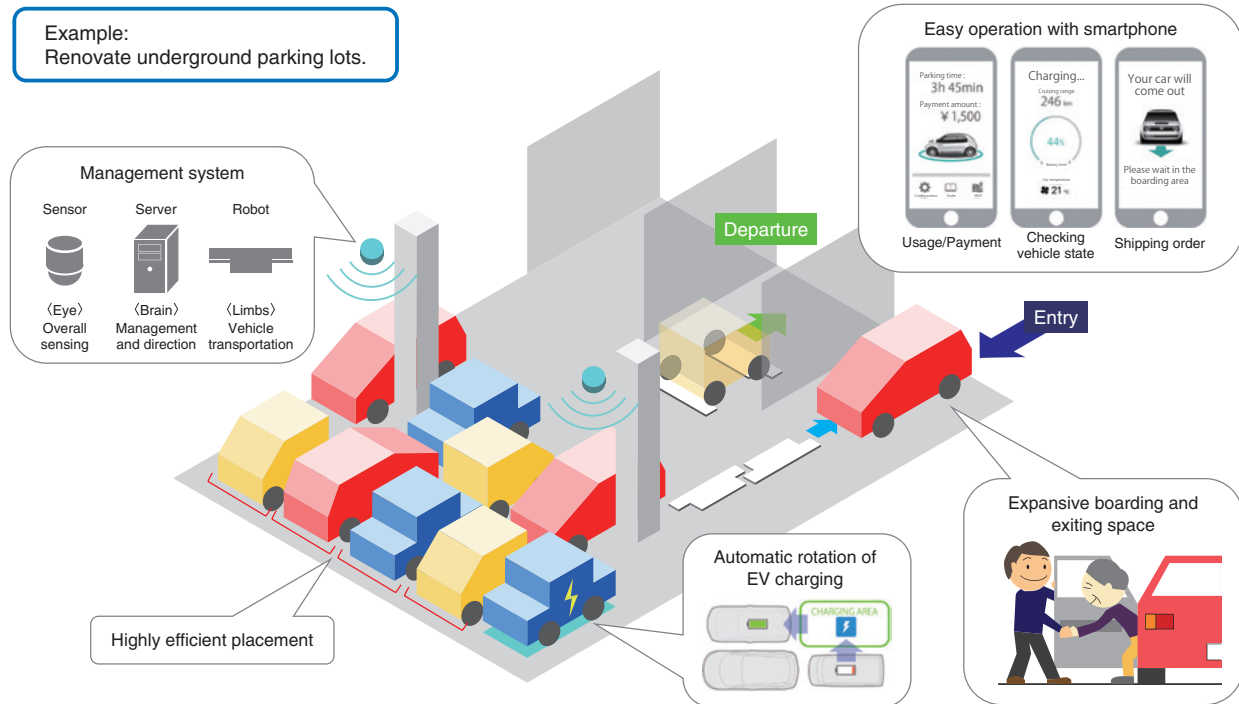


Fig. 2 Image of AVP operation using robots

3.2. Operation in a Small Space

When transporting a vehicle, the robots fit underneath the vehicle so the original vehicle size is maintained as shown in Fig. 3. When operating alone, space is saved by moving and storing the robots using the space underneath vehicles and other narrow dead space as shown in Fig. 4. In addition, as cars generally change direction by turning the front wheels and there is a limit to the steering angle, multiple switchbacks are needed depending on the destination, making it unsuited for movement in a small space. The robots are therefore equipped with an omni-directional movement mechanism that enables operation such as moving sideways and turning in place, realizing operation with a high degree of freedom independent of the movement capabilities of the car in a small space.

3.3. Application to Various Vehicle Types

The developed robot is intended to support vehicles from general Japanese Kei small cars to large vehicles. Transportation of a wide variety of vehicles calls for a system that can flexibly respond to differences in vehicle type and size. This section describes the vehicle lift up system and design requirements that enable application to various vehicle types.

3.3.1. Lift up method

Vehicle lift up is performed using pairs of arms mounted on the robot as shown in Fig. 5. After the two robots enter underneath the vehicle, the arms are rotated 180 degrees on a horizontal plane for each tire on the left and right, and the tires are clasped between the rotation arms and fixed arms to lift up the vehicle. The arms have a structure where the outer circumferences of the arms rotate freely to reduce the

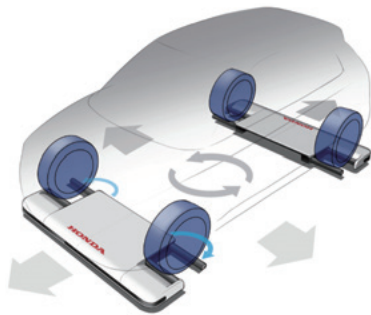


Fig. 3 Concept scheme of transportation by robots

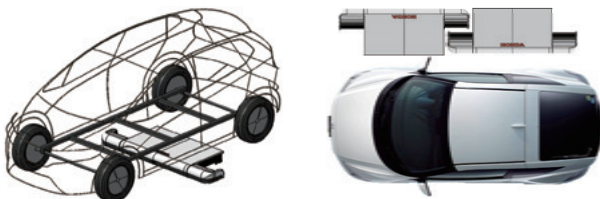


Fig. 4 Efficient use of space

contact friction with the tire as shown in Fig. 6.

Furthermore, even if deviation occurs in measurement or operation, rotational force is produced on the robot body by the arm that contacts the tire first, so the robot is aligned to a position parallel to the axle as shown in Fig. 7, enabling robust lift up.

3.3.2. Design requirements

This clause describes the requirements for robots to be applied to various vehicle types, in reference to the Road Transport Vehicle Law and safety standards in Japan, and the approach toward those requirements.

While no clear safety standards are established for tread width, the Road Transport Vehicle Law stipulates a total width of 1480 mm or less for Japanese Kei small cars, 1700 mm or less for vehicles with a class code beginning with "5," and 2500 mm or less for vehicles with a class code beginning with "3," so the outer dimension including the tire width needs to be within these values. The developed robot utilizes a system that supports the differences in each vehicle type by providing a margin in the tire on-board position that enables to support the minimum tire inner dimension and maximum tire outer dimension of all target

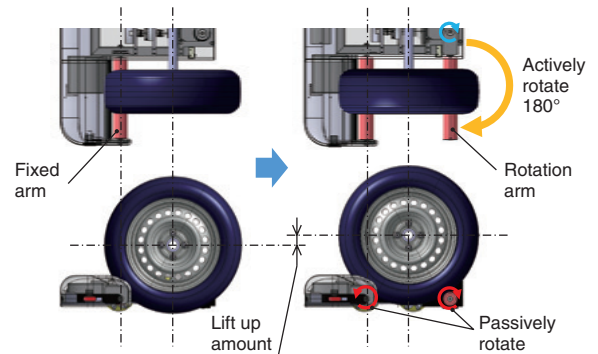


Fig. 5 Sequence of lift up motion

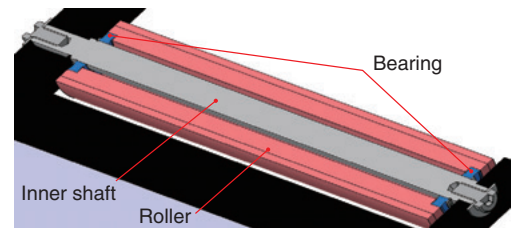


Fig. 6 Sectional view of arm

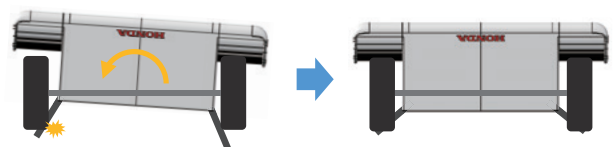


Fig. 7 Self-alignment motion

vehicle types, as shown in Fig. 8(a).

Safety standards stipulate a ground clearance of 90 mm or more in the unladen state, but most general vehicles have a ground clearance of approximately 140 mm. If the thickness of the robot can be kept to 120 mm or less, the system can accommodate around 90% of target vehicle types in Japan.

While no clear safety standards have been established for the wheelbase, the Road Transport Vehicle Law stipulates a total length of 3400 mm or less for Japanese Kei small cars, 4700 mm or less for vehicles with a class code beginning with “5,” and 12000 mm or less for vehicles with a class code beginning with “3,” so the wheelbase does not exceed these values. The developed robot can theoretically transport any full-length vehicle by controlling the distance between the two robots to an arbitrary position in accordance with the wheelbase as shown in Fig. 8(b).

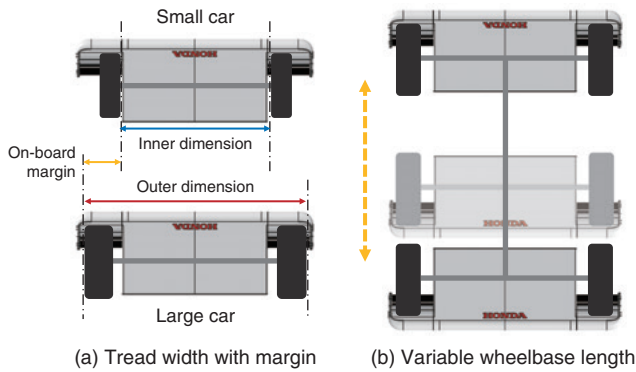


Fig. 8 Supports any size

4. Development of Prototype

4.1. Verification Items

A prototype was developed for the purpose of verifying transportation operation of a mock-up vehicle in small spaces. The verification items were as follows:

- (1) Robust tire lift up operation using the arm rotation mechanism;
- (2) Synchronization of operation timing and cooperative transport of vehicles by real-time communication between the two robots; and
- (3) Operation in a small space by omni-directional movement such as turning in place and moving sideways.

4.2. Mock-up Vehicle

Figure 9 shows the mock-up vehicle for transport that was used in verification. This mock-up was made based on the widely used Honda FIT (2013 model year), which is a standard-sized vehicle positioned midway between a Japanese Kei small car and a full-sized vehicle. The mock-up consisted of an aluminum base frame combined with

Table 1 Specifications

Weight [kg]		80 / 1 unit
Forward speed [m/s]		Max. 1.9
Withstand load [kg]		800 / 2 units
Actuator		Wheel x 4, Arm x 2
Motor	Type	Brushless DC motor
	Performance [W]	260
Battery	Type	Li-Fe
	Capacity	24 V x 36 Ah
CPU		Renesas RX62G
Control period [ms]		10

a brass wire frame in the shape of the body outlines and actual vehicle tires to enable the robot operation during transportation to be easily understood. The mock-up had outside dimensions of total length of 4000 mm, total width of 1700 mm, total height of 1500 mm, ground clearance of 210 mm, and total weight of approximately 200 kg.

4.3. Mechanical Design

The prototype was based on the requirements set forth in Chapter 3, and had specifications sufficient for confirming the verification items presented in Section 4.1. using the mock-up vehicle shown in Fig. 9. Figure 10 shows the hardware of the prototype, and Table 1 shows the specifications.

4.3.1. Movement mechanism

Mecanum wheels⁽⁹⁾ were adopted for the wheels, and Fig. 11 shows their appearance. Mecanum wheels enable free omni-directional movement by independently controlling each of the four wheels. Figure 12 shows a

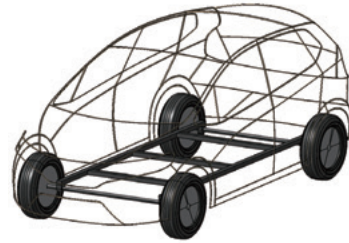


Fig. 9 Wire frame model for experiment

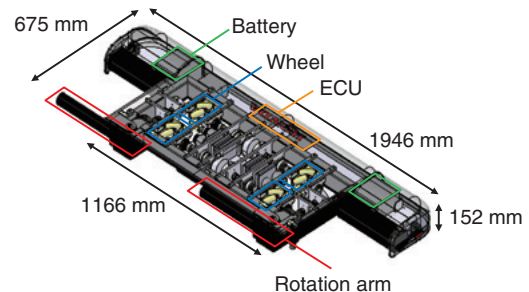


Fig. 10 Appearance of robot prototype hardware

diagram expressing the direction of main body movement produced by the direction of rotation of the wheels. Mecanum wheels are increasingly used not only in research but also for unmanned vehicles used to transport heavy objects⁽¹⁰⁾. The use of mecanum wheels to perform operations such as moving sideways and turning in place, which are challenging to achieve by a car, reduces the space needed for switchbacks and achieves high-density transportation.

4.3.2. Arm mechanism

The drive mechanism of the arm uses a bevel gearbox that amplifies the motor torque and translates the rotation axis by 90 degrees in a different direction. In addition, the distance between the fixed arm and the rotation arm was set so that the lift up amount for a tire size of 185/55R16 is 30 mm from the bottom of the tire to the road surface.

4.4. Control Design

This section describes the motion control for the robot unit and synchronous control between two robots needed to realize vehicle transportation operation.

4.4.1. Motion control

Figure 13 shows a kinematic model of the robot. Here,

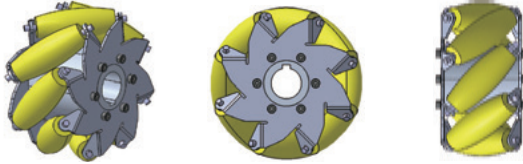


Fig. 11 Appearance of mecanum wheel hardware

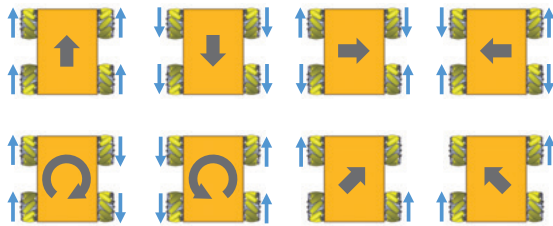


Fig. 12 Moving direction by mecanum wheel

ϕ is the rotation angle of the robot body as viewed from the absolute coordinate system Σ_w , x and y are the origin of the robot coordinate system Σ_{RB} , and v_1 to v_4 are the respective tangential velocities of the wheels. Equation (1) shows the inverse kinetics of the robot. v_1 to v_4 are derived by giving the target velocities $\dot{x}$, $\dot{y}$, and $\dot{\phi}$ and performing matrix operations.

$$\begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix} = \begin{bmatrix} -1 & 1 & W+L \\ 1 & 1 & -(W+L) \\ -1 & 1 & -(W+L) \\ 1 & 1 & W+L \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\phi} \end{bmatrix} \quad (1)$$

In addition, Eq. (2) is used to convert the tangential velocity v of the wheels to angular velocity $\dot{\theta}$. Here, r is the wheel radius.

$$\dot{\theta} = \frac{v}{r} \quad (2)$$

Figure 14 shows the block diagram of the control system. PI controller is applied to reduce the cumulative position deviation, using the robot velocities $\dot{x}$, $\dot{y}$, and $\dot{\phi}$ as outputs and the wheel motor torques $\tau_{1...4}$ as inputs. By applying arbitrary target velocities to $\dot{x}_d$, $\dot{y}_d$, and $\dot{\phi}_d$, control is performed to track those velocities. Note that the wheel rotation angles were measured using encoders, and the angular velocities used the values estimated using a state observer.

4.4.2. Synchronous control

In order to transport vehicles using two independent robots, it is necessary for the robots to operate

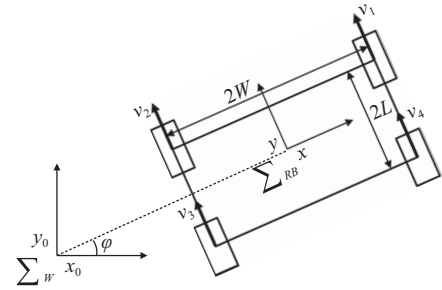


Fig. 13 Kinematic model of robot

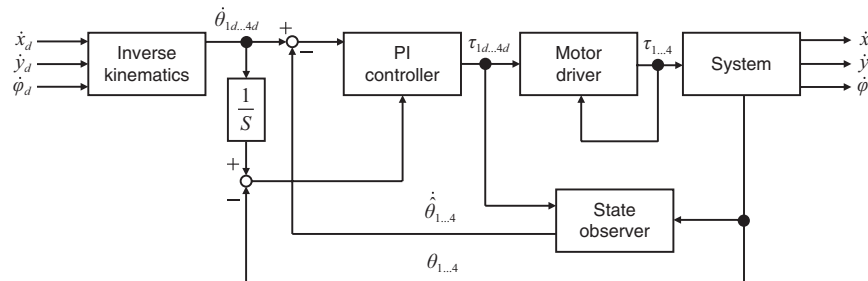


Fig. 14 Block diagram of control system

cooperatively. In this system, one robot is defined as the parent unit and the other as the child unit, and the robots perform vehicle transportation operation while confirming each other's operational status by wireless communication. Specifically, cooperative transport is performed by dividing the operation tasks during vehicle transportation into multiple steps, mutually confirming the situation and deviation state in the current step before the initiation of each step, and synchronizing the start time of the next step as shown in Fig. 15. In this system, operation was modeled using a finite state machine⁽¹¹⁾. Note that the transition of each step occurs when all of the conditions (1) to (3) below are met:

- (1) When a task in the current step is completed;
- (2) When both robots are in the same state; and
- (3) When a task completion command for the current step is received from one robot.

As a failsafe specification, the robots were designed to halt each other's operation in the event of inoperability or communication loss due to some factor.

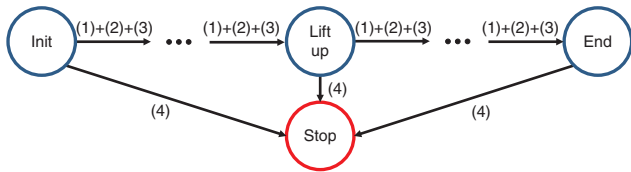


Fig. 15 Example of state flow diagram

5. Operation Verification Experiments

Verification experiments were conducted using the developed prototype to confirm mock-up vehicle lift up operation and vehicle transportation operation. This chapter describes the contents and results of each experiment.

5.1. Vehicle Lift Up Operation

This experiment verified the basic lift up operation and the lift up operation when control deviation occurred during robot unit movement, as indicated in Section 4.1. (1). Figure 16 shows the conditions of the lift up operation experiment. After the robot entered underneath the vehicle [(1) in the figure], the two arms were rotated 180 degrees on a horizontal plane [(2) and (3) in the figure], and the target lift up operation of 30 mm was achieved by clasp the tires between the arms and lifting up the vehicle [(4) in the figure]. In addition, even when deviation of around 120 mm occurred on one side when entering underneath the vehicle, the robot posture was aligned by the rotational force of the arm to realize robust lift up operation as shown in Fig. 17.

5.2. Vehicle Transportation Operation

5.2.1. Motion planning

In this experiment, operation assuming parallel parking

was performed in a small indoor space just $4.3 \text{ m} \times 7 \text{ m}$, where parking only by steering the car would be challenging. Figure 18 shows the operation order and paths of the robots. As shown in (1) in the figure, the mock-up vehicle is positioned 4 m away and rotated by 90 degrees relative to the target grid in which a single vehicle will fit, and the robots initiate operation at positions 2 m directly to the side of the mock-up vehicle. Note that PTP control⁽¹²⁾ was applied to the movement trajectories of the robots. The waypoints through which the robots pass are set in advance (green dots in the figure), and the paths between each of the set multiple waypoints are interpolated using a 5th-order polynomial⁽¹³⁾.

5.2.2. Experimental results

Figure 19 shows the conditions of the transportation operation experiment.

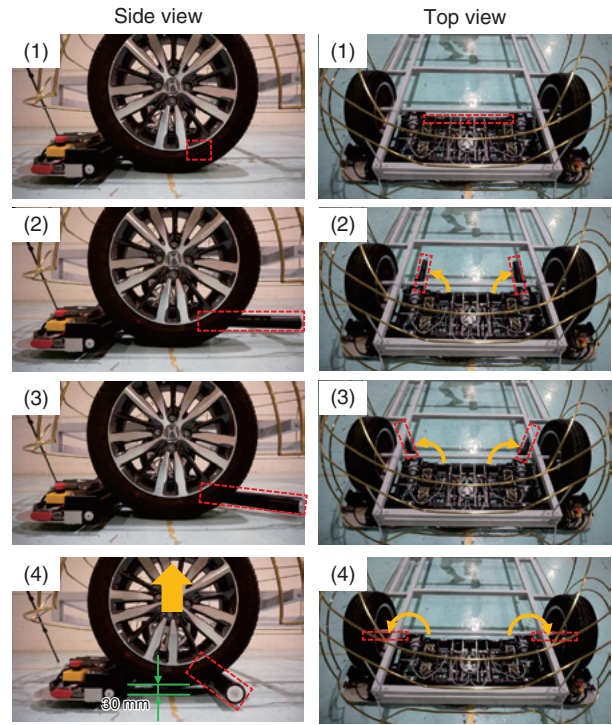


Fig. 16 Lift up motion by prototype

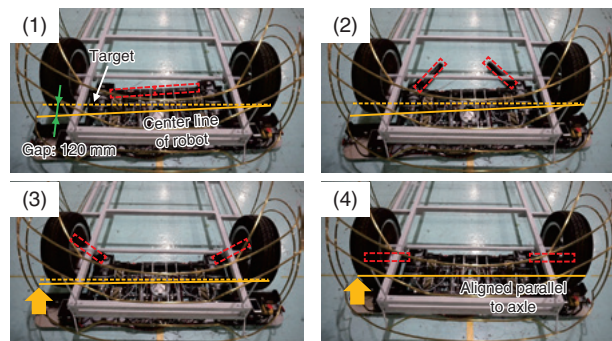


Fig. 17 Self-alignment motion by prototype

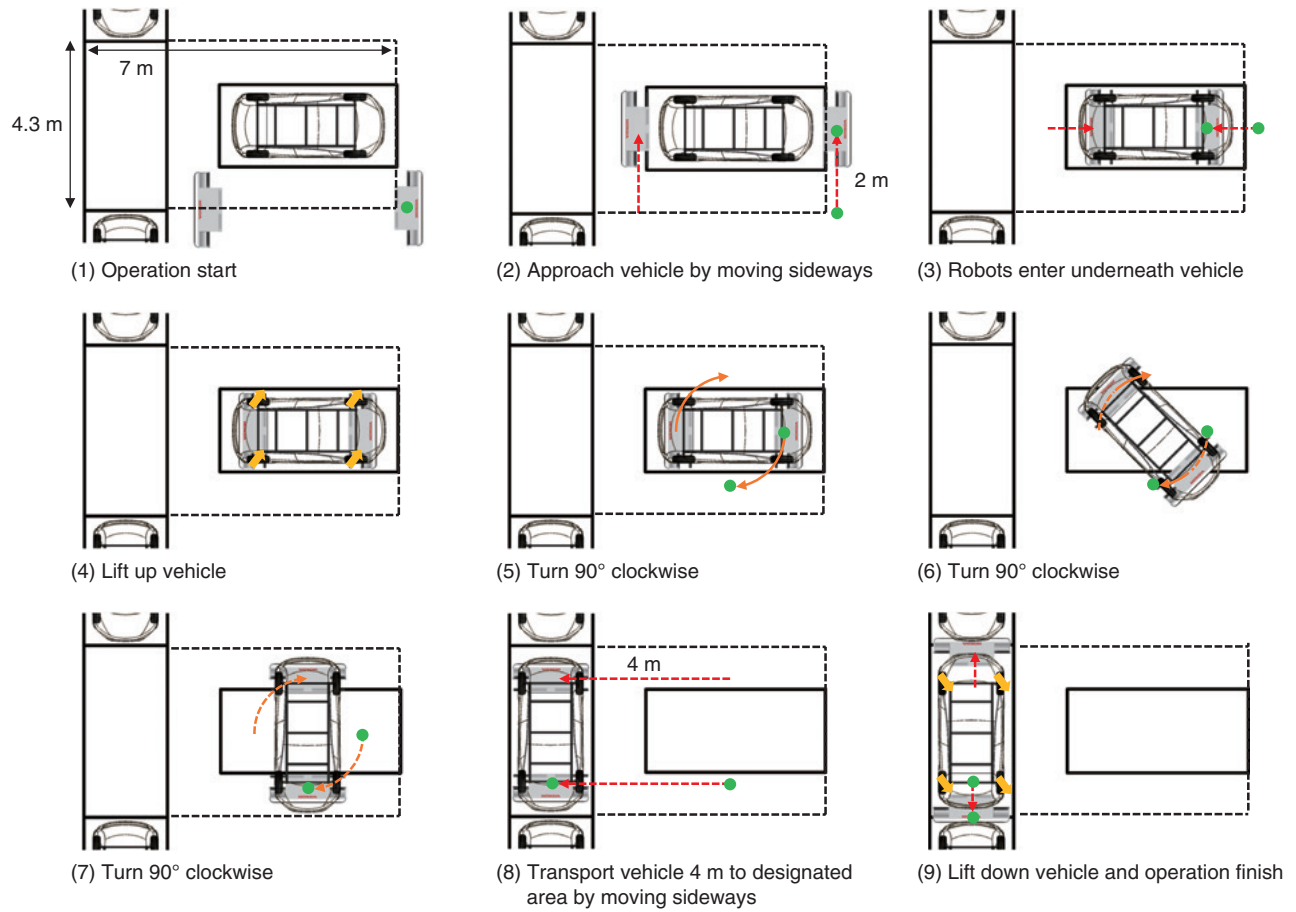


Fig. 18 Motion planning for experiments

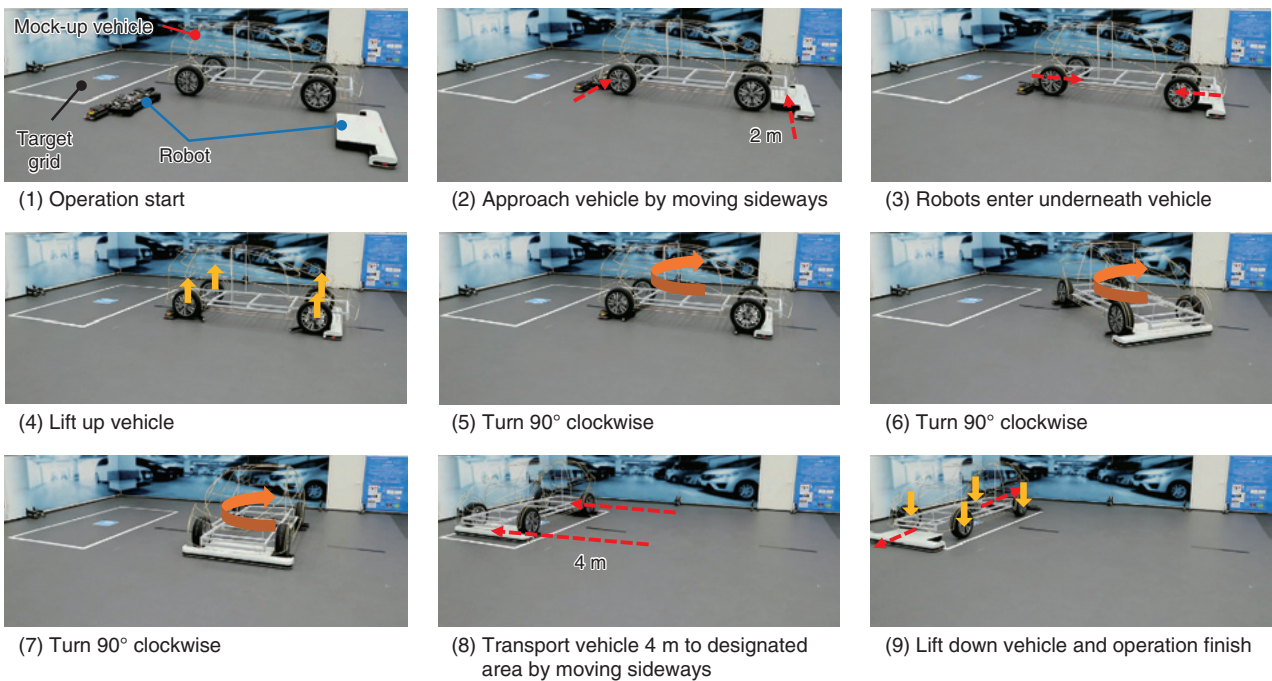


Fig. 19 Cooperative transportation by prototype

(2) and (3) in the figure show that the two robots were able to synchronously enter underneath the vehicle by combining sideways and longitudinal movements.

(4) in the figure shows that after detecting contact between the mock-up vehicle tires and the fixed arms of the robots, the rotation arms were synchronously rotated 180 degrees, enabling lift up while maintaining the level state of the mock-up vehicle.

(5) through (7) in the figure show that the two robots were able to turn the mock-up vehicle 90 degrees in place by tracing circular trajectories while cooperatively transporting the vehicle.

(8) in the figure shows that the robots cooperatively transported the vehicle by moving sideways while maintaining the vehicle rotation angle of 90 degrees, enabling accurate parallel parking within the target grid.

These results confirmed that operation using robots for cooperative transport and omni-directional movement of a vehicle can be realized. This verified that both vehicle switchback and the space needed for switchback can be reduced, and that vehicles can be efficiently transported within a small space.

6. Conclusion

The concept of an unmanned vehicle transportation system was presented, vehicle transport robots that play a central role in that system were devised, and a prototype was developed to verify the principles of operation. Operation verification experiments using the prototype confirmed the effectiveness of the following functions and demonstrated the validity of the concept of “a system that can be operated within a small space”:

- (1) Cooperative vehicle lift up and transport operation using a pair of thin robots; and
- (2) Vehicle transportation operation in a small space by omni-directional movement operation such as turning in place and moving sideways.

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Simultaneous Reduction of NO_x and Smoke by Divided Diffusion Combustion Using High Dispersion Staggered Layout Nozzle

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ABSTRACT

In order to realize extremely low emissions with diffusive diesel combustion, a study was made of methods for smoke suppression under the high-boost, high-EGR conditions that are effective in reducing NO_x. Divided combustion that combines a reduction in the injected amount of main fuel with premixed combustion in which the amount of fuel injected early is increased was adopted in order to reduce the rich portion of the main diffusion combustion, which was the main generator of smoke in conventional combustion. The adoption of this divided combustion made it possible to raise the fuel injection pressure, which had previously been limited due to combustion noise, and a smoke reduction effect was confirmed together with the effect of divided combustion. In addition, a staggered spray layout was adopted in order to reduce dilution of the premixed injection. Combining these methods achieved diffusive diesel combustion with extremely low emissions, and reduced NO_x by 40% while not causing increases in combustion noise or smoke, or reduction of thermal efficiency relative to conventional combustion.

1. Introduction

As environmental controls on internal combustion engines grow ever more stringent, diesel engines with their characteristic higher efficiency are expected to contribute to CO₂ reduction. There is also a movement in European countries to ban the sale of vehicles with internal combustion engines from around 2030, and in this context, it has become urgent to keep pace with the strengthened controls on the emissions of the gas constituents of NO_x and PM that will be coming in the future. The cost involved in increasing the sophistication of systems for enhancing NO_x after-treatment capabilities, in particular, has become an issue. In order to simplify after-treatment systems, the smoke and feed NO_x emitted from the combustion chamber need to be reduced. In the technologies to enhance diesel combustion studied in the past, as typified by premixed charged compression ignition (PCCI) combustion⁽¹⁾, achieving low emissions involved one or more of reduced thermal efficiency, increased combustion noise, and increased oil dilution, making practical application

not readily achievable. The approach that was devised, therefore, was not to use premixed combustion for all combustion formats, but instead to use partially premixed combustion, which makes separate use of premixed combustion and diffusion combustion. Extensive research has been done on this approach, with varied results such as bi-modal combustion⁽²⁾, ZPCI-DI⁽³⁾, and so on. However, these research efforts face issues of in-cylinder combustion behavior and they have not yet achieved low emissions.

Table 1 shows the transitions of European emission regulations by year. European exhaust gas regulation introduced a real driving emissions (RDE) regulation with Euro 6.2. In addition, the European Commission is considering making its controls more stringent, for example by lowering the conformity factor (CF), which is a multiplier for determining allowable exhaust gas regulation values, to 1.0⁽⁴⁾. To support emissions regulations that are moving toward a CF of 1.0, there is demand for enhanced performance of NO_x after-treatment systems together with emission reduction technology for enhancement of combustion itself.

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Table 1 Transitions in emission regulations in Europe

	Euro 6.2 (6d-TEMP)	Euro 6.3 (6d)
Year of enforcement	2017-	2020-
Mode	WLTC and RDE	WLTC and RDE
NO _x regulation [mg/km]	80	80
NO _x CF	2.1	1.43

WLTC: Worldwide Light-duty Test Cycle

The purpose of the present research was to reduce NO_x in diffusive diesel combustion without decreasing thermal efficiency, or increasing combustion noise and smoke.

2. Conventional Combustion Issues

For emissions in diffusion combustion, both NO_x and smoke are determined by the concentration of air-fuel mixture in the flame portion of combustion and the combustion temperature. The concentration of air-fuel mixture is expressed by the equivalence ratio Φ . This is the value of the stoichiometric air-fuel ratio divided by the actual air-fuel ratio. The stoichiometric ratio of 1 is the boundary at which higher values indicate a rich air-fuel mixture and lower values indicate a lean air-fuel mixture. When a Φ -T map is used in the present research, soot that is particulate carbon matter is labeled as soot, while actual measurement results are obtained with a smoke meter, and are thus labeled as smoke. With regard to NO_x, the stoichiometric high-temperature portion in the vicinity of Φ 1 is the generation zone, and with regard to smoke, the rich portion at Φ 1.9 or higher is the generation zone. Typical measures to deal with emissions include NO_x reduction by lowering combustion temperature and smoke reduction by reducing the rich portion that accompanies homogenization of the spray.

The following shows the influence of these in conventional combustion together with the issues involved.

2.1. Issues Under High-boost, High-EGR Conditions

Lowering the combustion temperature is effective in reducing NO_x. Combustion temperature can be lowered by raising the boost pressure so as to keep Φ constant and increasing the EGR amount while maintaining the amount of air. An increase in the ambient pressure, however, is accompanied by a reduction in spray penetration so that the rich region grows, inviting an increase in smoke. This means that the trade-off between NO_x and smoke does not yield more than a certain enhancement when this approach is applied to conventional diesel combustion. In addition, it is apparent when multi-cylinder engines are taken into account that measures that involve raising the boost pressure will invite increased pumping loss due to the increased turbocharger work. This is yet another constraint on the margin of enhancement obtainable with the trade-off relationship between NO_x and smoke.

2.2. Issues Under High Fuel Injection Pressure

The measure of raising fuel pressure high for the purpose of spray homogenization by enhancing spray penetration can achieve a reduction of smoke. On the other hand, however, this invites an increase in NO_x, while the shortened combustion time also causes the heat release rate to rise sharply, which increases combustion noise. In conventional diesel combustion, therefore, the measure of raising fuel pressure high is limited by combustion noise.

2.3. Issues Under Premixed Injection Conditions

Premixed combustion by means of early injection as a measure to simultaneously reduce the rich region and the stoichiometric high-temperature portion is effective in enhancing the trade-off between NO_x and smoke. However, this invites an increase in heat loss and combustion noise due to pre-ignition as well as oil dilution due to adhesion of fuel on the liner. An increase in oil dilution also increases the frequency of oil maintenance and so needs to be kept as low as possible. For these reasons, it is no simple matter to address the conflicting relationship that exists from the decrease in thermal efficiency, reduction in user maintenance, and increase in combustion noise that occur with the reduction of NO_x and smoke in conventional diffusion combustion.

3. Formulating Targets and a Concept of Divided Combustion

3.1. Targets

As shown in Table 1, the target NO_x reduction rate is set by taking as a reference the feed NO_x of the 2018 model year i-DTEC engine⁽⁵⁾, which supports the Euro 6.2 standard of CF 2.1. When following the 2018 model year NO_x Storage Catalyst after-treatment system, in order to support the stricter regulation value of CF 1.0 in the future, it is estimated that the feed NO_x will need to be reduced by 50% or more. The target value for feed NO_x reduction rate was therefore set as 50% relative to the 2018 model year i-DTEC engine. Targets were also set for thermal efficiency, combustion noise, and smoke to maintain their same levels.

3.2. Simultaneous Reduction of NO_x and Soot

A new concept for reducing emissions was studied for the purpose of addressing the issues of conventional combustion.

Figure 1 shows the distribution of mass on the Φ -T map during main combustion. In order to reduce NO_x and soot simultaneously, their respective emission generation zones in the stoichiometric portion and the rich portion would need to be reduced. As explained earlier, with regard to the stoichiometric portion, the NO_x generation zone can be avoided and NO_x can be reduced by lowering the combustion temperature through higher boost and EGR. With regard to the rich portion, however, it is apparent that

the richer region with equivalence ratio of $\Phi 1.9$ or higher that appears during main combustion needs to be reduced in order to reduce soot. Higher fuel pressure cannot be adopted, however, since reducing the rich portion will increase NOx and combustion noise.

A method was therefore studied for lowering Φ in the main combustion portion and reducing the soot generation zone. Figure 2(a) shows the ratio to the crank angle of the region that is richer than $\Phi 1.9$, which is the soot generation zone. Conventional combustion is shown by the dotted line and the divided combustion concept by the solid line. Figure 2(c) shows Φ during main combustion by color distribution. Since combustion chamber space is limited near compression top dead center (TDC), high dispersion is needed, and with the same main injection fuel amount, reducing the rich region becomes an issue. Note that there

is an extensive unused space in the combustion chamber before TDC in Fig. 2(b), indicating that the rich region was lessened by reducing the main fuel amount during main combustion. It was thus decided to disperse the rich region by using that portion of the fuel amount to increase the pilot injection amount before TDC where there is extensive space. However, when the pilot injection amount is increased in the vicinity of TDC, there is concern that diffusion combustion caused by instantaneous ignition will result in an increase in the generation of NOx and soot. It was reasoned that in order to secure retarded ignition time, this needed to be combined with advancing the pilot injection timing. With a view to avoiding liner spray collision, which would invite oil dilution with the increased amount and advanced timing of pilot injection, a multi-staged approach may be effective in qualitative terms. It was on the basis of these approaches that we determined the concept of divided combustion.

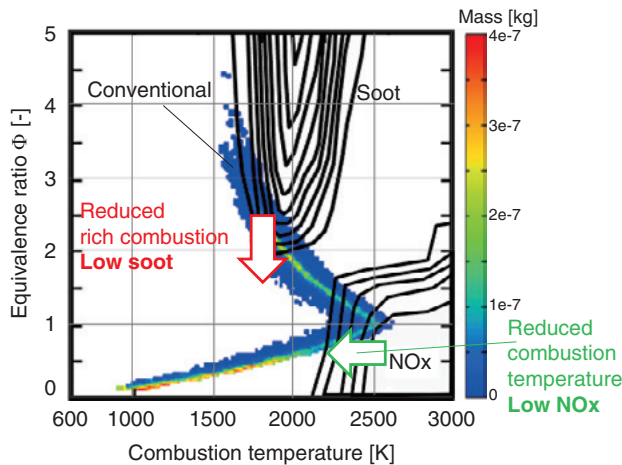


Fig. 1 Φ -T map during main combustion

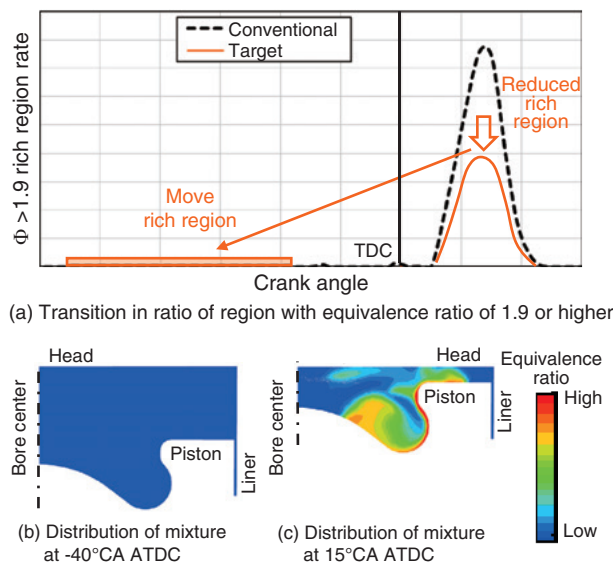


Fig. 2 Concept of rich region control

3.3. Support for Premixing

In the divided combustion concept, premixed combustion is implemented by means of early injection for the purpose of reducing the main injection amount. Oil dilution due to adhesion of fuel on the liner thus needs to be limited. In order to achieve the balance between premixed injection and main injection while maintaining spray penetration, while two injectors with differing specifications are thought to be needed, our goal was to achieve that balance with just one injector. In order to avoid adhesion of fuel on the liner exposed by early injection, four of the eight injector nozzle holes were directed downward. The remaining four nozzle holes were oriented as before, and those with different orientations were alternately arranged. The measure called staggered layout of injector nozzle holes⁽⁶⁾ is adopted for divided combustion in order to mitigate the liner adhesion of fuel by thus giving the nozzle holes separate orientations while the injector nozzle holes simultaneously yield a high dispersion effect.

4. Study of Specifications

4.1. Test Engine and Evaluation Load

Verification was conducted with a single-cylinder engine fabricated on the basis of the mass-production 1.6 L in-line four-cylinder specification. Table 2 shows the main specifications of the engine used in verification.

Figure 3 shows the emission mode load distribution in the envisioned vehicle. For the present research, the evaluation load point was set at the WLTC mode emission center point of 2000 rpm engine speed, 150 Nm engine torque, and 28.3 mg/st total fuel injection amount. All verification from this point forward was conducted at this evaluation load point.

The combustion noise level is considered to be represented by multiplying the structural response of the engine by the cylinder pressure, which is the source of

Table 2 Test engine specifications

Number of cylinders	1
Displacement volume [cm ³]	400
Bore [mm]	76
Stroke [mm]	88
Compression ratio	14.6, 16.1 (base)
Fuel injection system	Bosch CRI 2-25 (max. 250 MPa)
Injector	8 holes, 0.114 mm diameter
Fuel	EU spec diesel (sulfur < 10 ppm)
Boost device	Super charger

Table 3 Calculation method

CFD software	CONVERGE v2.4
Turbulence model	RNG k- ϵ
Spray model	Kelvin-Helmholtz and Rayleigh-Taylor
Combustion model	SAGE detailed chemical reaction
Chemical reaction	100 species and 432 reactions n-dodecane (with NO _x reaction)

vibration⁽⁷⁾. The combustion noise index (CNI) is a value based on the correlation between combustion noise and cylinder pressure in most internal combustion engines developed up to now. It is obtained by calculating the specific structural response and multiplying it by the measured cylinder pressure, and is an indicator that enables estimation of the combustion noise level from the cylinder pressure alone. This enables evaluation of the combustion noise level in a multi-cylinder engine, and even from a single cylinder. From this point forward, therefore, the CNI will be treated as the combustion noise index.

4.2. Calculation Method

The study of specifications was conducted using combustion simulation in addition to single-cylinder engine testing. CONVERGE version 2.4 was used for the computational fluid dynamics (CFD), and Table 3 shows an overview of the calculation method used. In calculating the combustion chemical reaction, the chemical reaction model by Wang et al. that adds the NO_x reaction to the n-dodecane mechanism⁽⁸⁾ was used. The engine specifications were made the same as for the test engine.

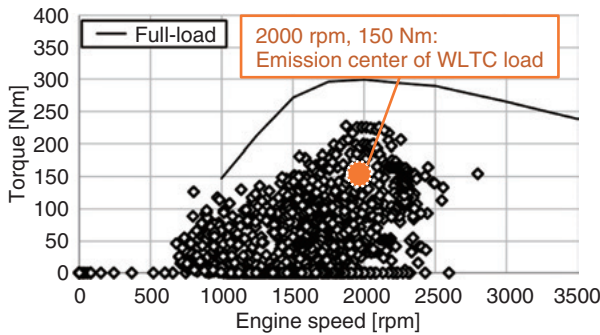


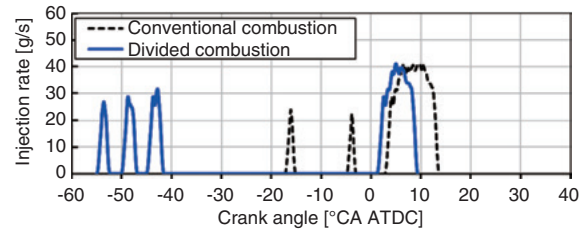
Fig. 3 Engine operation area in WLTC mode and evaluation load point

Table 4 Experimental conditions by premixed pilot injection amounts

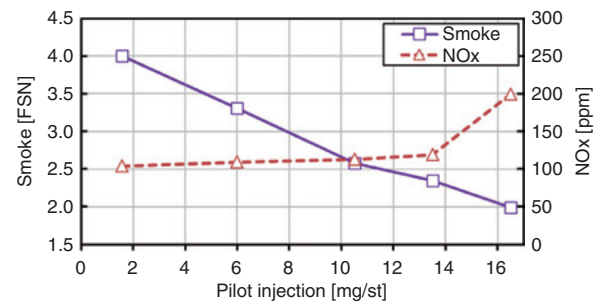
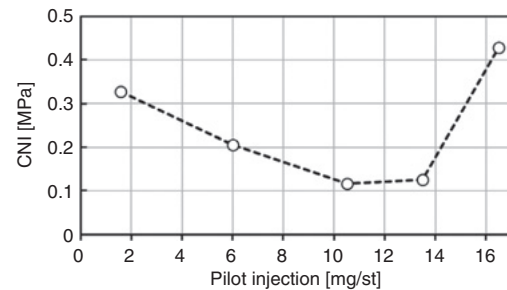
	Conventional combustion	Divided combustion				
Total injection [mg/st]	28.3	28.3				
Pilot injection [mg/st]	1.58	6.0	10.5	13.5	16.5	
Pilot injection start timing [°CA ATDC]	-17.3	-55.0				
Number of pilot injection shots	2 shots	3 shots				

4.3. Demonstration of the Divided Combustion Concept

Demonstration of the divided combustion concept determined here was carried out. Table 4 shows the experimental conditions by premixed injection amount. Figure 4 shows the results from actual engine testing at the evaluation load point. The injection patterns shown in Fig. 4(a) have the same Φ , EGR rate, boost pressure, and fuel injection pressure. As shown in Fig. 4(b), increases in the pilot injection amount are accompanied by a reduction



(a) Injection rate


 (b) Smoke and NO_x


(c) CNI

Fig. 4 Effects of premixed pilot injection amounts

in smoke that is generated with main diffusion combustion as the major cause. In addition, the division of combustion causes a change in the pattern of heat release with respect to crank angle from a single peak to a double peak, and as the pressure amplitude decreases, the combustion noise is reduced as shown in Fig. 4(c), creating an extra margin with respect to the combustion noise target. Consequently, the fuel injection pressure, which had been limited by the combustion noise, can be raised to a high level. The optimal pilot injection amount that can simultaneously achieve smoke reduction, NO_x reduction, and combustion noise reduction is 10.5 mg/st. It was confirmed that when this is done, a 37% reduction in smoke is achieved with the same injection pressure as set for the conventional pilot injection amount.

With regard to the influence of the premixed injection timing, the experimental conditions are shown in Table 5 and the results from testing with an actual engine at the evaluation load point are shown in Fig. 5. Here, the pilot injection start timing shown in Fig. 5(a) has been changed, and the values for Φ , EGR rate, boost pressure, and fuel

Table 5 Experimental conditions by premixed pilot injection start timings

	Divided combustion				
Total injection [mg/st]	28.3				
Pilot injection [mg/st]	10.5				
Pilot injection start timing [°CA ATDC]	-60.0	-55.0	-50.0	-45.0	-40.0
Number of pilot injection shots	3 shots				

injection pressure are all the same. As shown in Fig. 5(b), advancing the premixed injection start timing helped ensure spray diffusion time for the pilot injection, and it is apparent that since enrichment is suppressed, smoke is reduced. The optimal pilot injection timing here was set to -55°CA ATDC, which can simultaneously achieve smoke reduction, NO_x reduction, and combustion noise reduction. This approach can realize higher fuel pressure without increasing combustion noise. The result is that spray penetration is increased under high boost, high EGR conditions and the rich portion is reduced, making it possible to reduce smoke.

4.4. Support for Premixed Injection

In the divided combustion concept, as staggered spray layout is adopted, a study was made of the spray layout in premixed injection. Figure 6 shows a comparison performed using CFD simulation between injection spray distribution in the cylinder with conventional pilot injection and with premixed pilot injection with a staggered spray layout. It is apparent that the spray from downward-pointing nozzle holes in a staggered layout shown in Fig. 6(b) limits liner contact.

The dilution that occurs at the evaluation load point in divided combustion with a conventional injector and

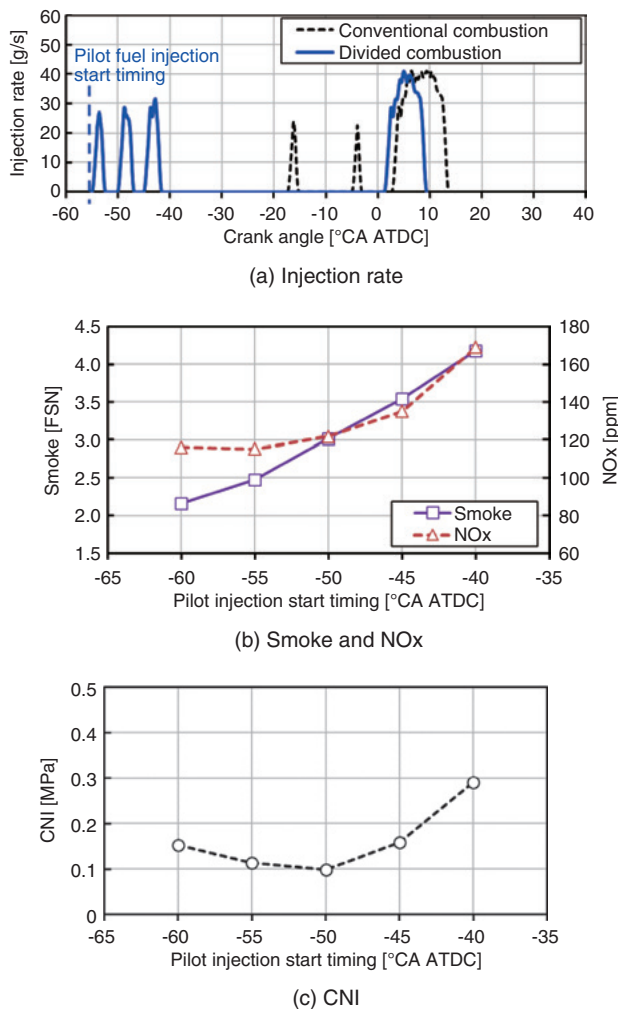


Fig. 5 Effects of premixed pilot injection start timings

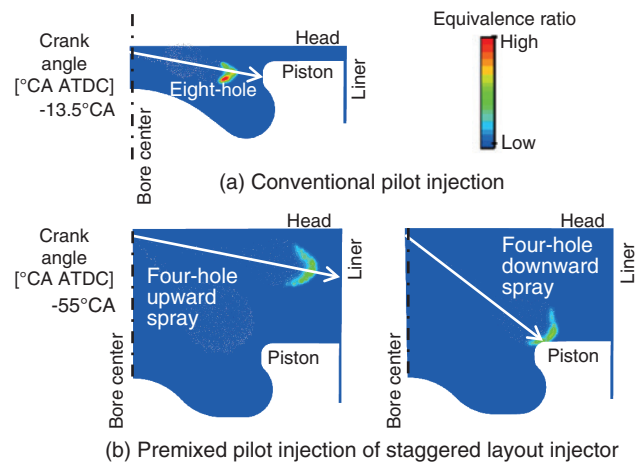


Fig. 6 Comparison of conventional pilot spray and premixed pilot spray with staggered layout injector

with a staggered spray layout was also estimated by CFD simulation. By staggering the layout of injector nozzle holes, the oil dilution that occurs when applying premixed injection was reduced by 24%.

At this point, actual measurements were made of oil dilution levels occurring in an actual engine with the injection timing and injection amount of pilot injection varied. Figure 7 shows the results for conventional spray and Fig. 8 shows the results with the staggered spray layout. This confirms that the oil dilution level has been lowered by the staggered spray layout relative to the conventional spray with the same pilot injection timing and amount. The staggered spray layout can thus be considered better than conventional spray with pilot injection that is early and in large amounts. These results were applied in setting the number of injection shots, the injection amount, and the injection timing with the staggered spray layout. The number of pilot injections was set at three, and the pilot injection amount and timing were set to 2.5 mg/st at -55°CA ATDC, 3.5 mg/st at -50°CA ATDC, and 4.5 mg/st at -45°CA ATDC.

Together with the above, verification was also carried out of the after-treatment combustion mode that performs post-injection with the staggered spray layout. The after-treatment combustion mode causes spray adhesion to the sleeve from post-injection in the expansion process. Since the use of a staggered spray layout can reduce the dilution during post-injection, it was confirmed by CFD simulation that dilution can also be reduced in the case of the after-

Table 6 CFD conditions of divided combustion

	Conventional combustion $\varepsilon 16.1$	Divided combustion $\varepsilon 14.6$
Fuel injection pressure [MPa]	140	200
Boost pressure [kPa_abs]	172	182
Equivalence ratio	0.81	0.81
EGR rate [%]	28.0	32.0
Pilot injection [mg/st]	1.58	10.5
Pilot injection start timing [$^\circ\text{CA}$ ATDC]	-17.3	-55.0
Number of pilot injection shots	2 shots	3 shots

treatment combustion mode. These observations made it possible to help prevent an increase in the frequency of oil maintenance under the divided combustion concept.

4.5. Main Diffusion Combustion

Having implemented divided injection and adopted the staggered spray layout, a downward spray flow is added in main diffusion combustion that differs from the conventional flow, and its influence was confirmed. Although the compression ratio is lower than in the conventional combustion chamber where ε is 16.1, a combustion chamber with ε 14.6 was devised for divided combustion that secures the greatest combustion chamber volume for the staggered flow, and the transition in

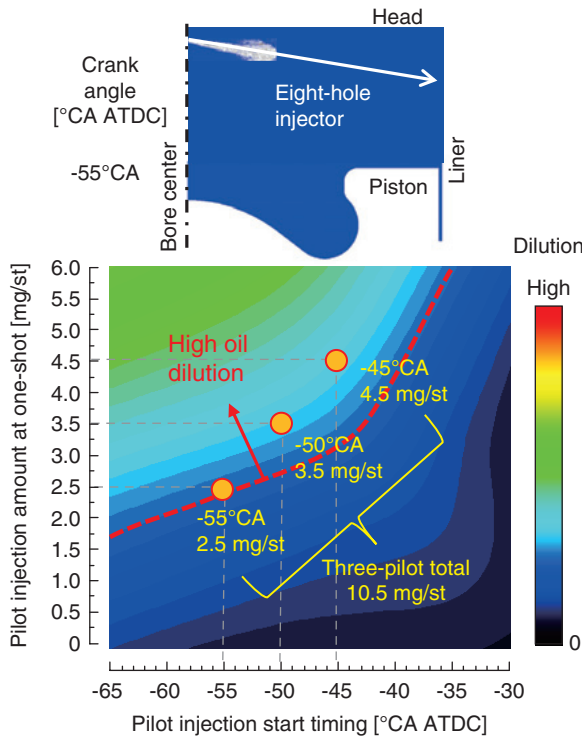


Fig. 7 Oil dilution level of one-shot pilot injection with conventional injector

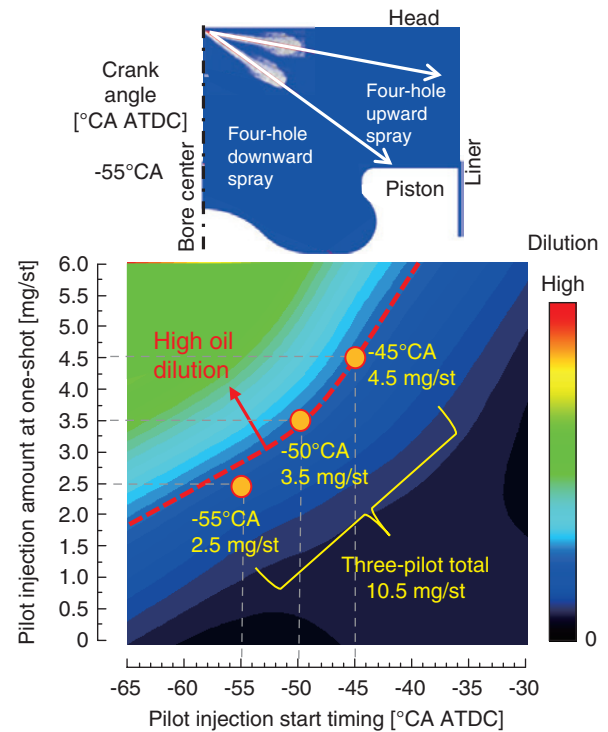


Fig. 8 Oil dilution level of one-shot pilot injection with staggered layout injector

distribution of equivalence ratio was verified by CFD simulation.

The divided combustion with its higher boost, higher fuel pressure up to the allowable combustion noise, and application of the staggered spray layout is shown in comparison with conventional combustion. Table 6 shows the conditions at the evaluation load point for study by CFD simulation. Figure 9 shows the transitions in ratio in the region where Φ is 1.9 or higher, and Fig. 10 shows maps

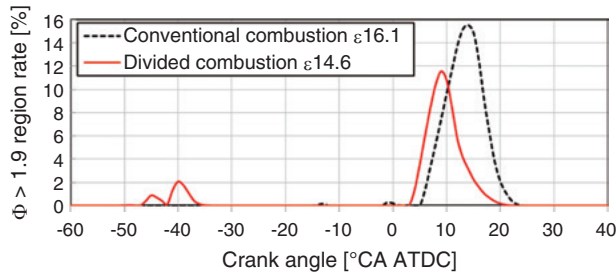


Fig. 9 Transitions in ratio in region with equivalence ratio of 1.9 or higher

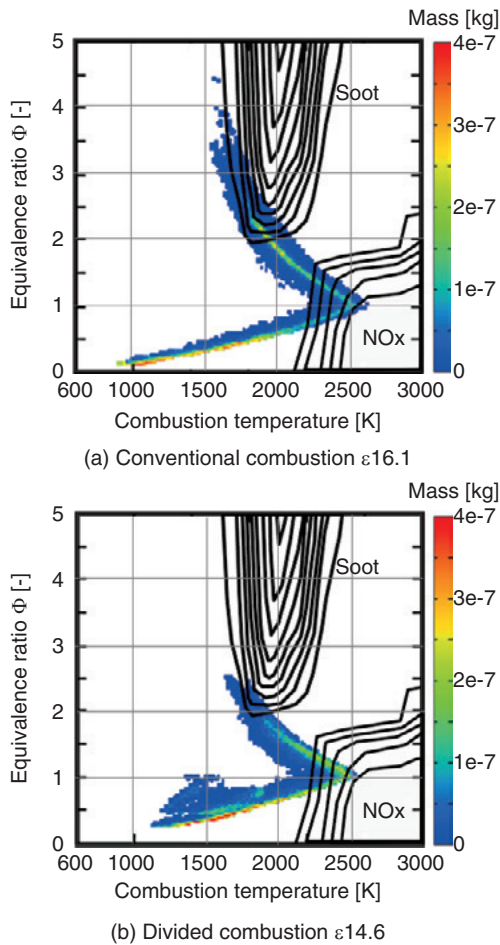


Fig. 10 Φ -T maps of conventional combustion and divided combustion during main combustion

for Φ -T during main combustion. In the divided combustion specification with ε of 14.6, the effects of reducing the main injection amount, raising fuel pressure higher, and having the staggered spray layout yield a reduction in the rich portion of main combustion. It can be confirmed by CFD simulation that as a result, the soot generation zone is successfully avoided, as was the aim of the initially formulated concept of divided combustion.

Attention was also focused on the main combustion, which has a large influence on smoke emission. Figure 11 shows the equivalence ratio distribution isosurfaces for the region with Φ of 1.9 or higher. A check of the equivalence

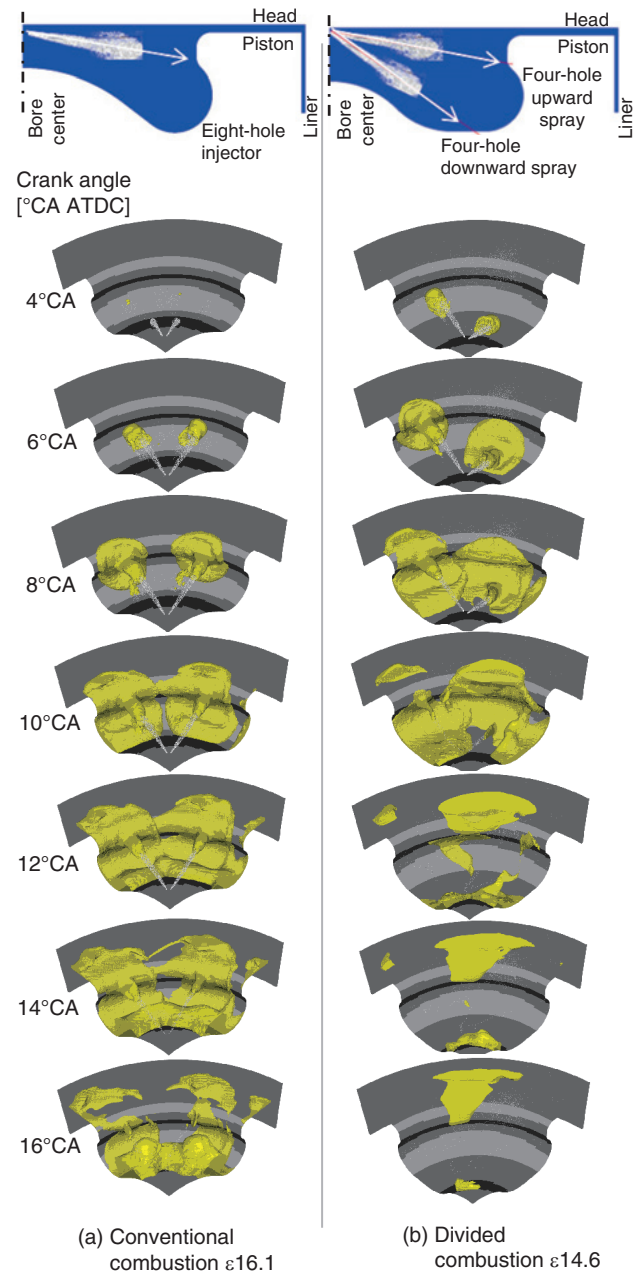


Fig. 11 Isosurfaces for region with equivalence ratio of 1.9 or higher during main combustion

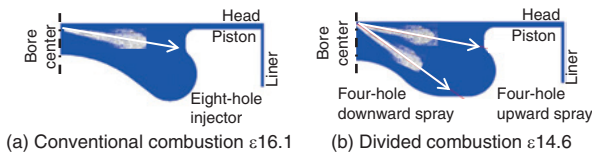
ratio distribution isosurfaces makes it possible to confirm that by comparison with conventional combustion, the divided combustion specification with ε of 14.6 has achieved reduction of the main injection amount due to divided combustion, and this in combination with the effect of higher fuel pressure reduces the volume of the rich portion in the latter part of main combustion from the crank angle of 12°CA ATDC on. Due to the adoption of the staggered spray layout, in particular, interference from adjoining sprays in the combustion chamber no longer occurs, contributing to the reduction in the volume of the rich portion.

5. Results of Verification with Single-cylinder Engine

Verification was carried out under high-boost, high-EGR conditions in the single cylinder of an actual engine embodying the divided combustion concept with the ε 14.6 specification that applied divided injection and the staggered spray layout. Regarding the higher boost amount, an upper limit of 10 kPa was set to the rise in boost pressure so that pumping loss would not be increased by the greater turbocharger activity involved when a multi-cylinder engine is used.

Figure 12 shows the experimental conditions at the evaluation load point for a conventional combustion specification and divided combustion specification with ε of 14.6. Figure 13 shows the injection rate and heat release rate. With the injection pattern shown in Fig. 13(a) in the divided combustion specification with ε of 14.6, the application of divided combustion consisting of premixing and diffusion causes the pressure amplitude to be divided in half, as can be observed from the heat release rate shown in Fig. 13(b).

Figure 14 shows the CNI. The division of the pressure amplitude causes the CNI to decrease from 0.16 MPa to 0.11

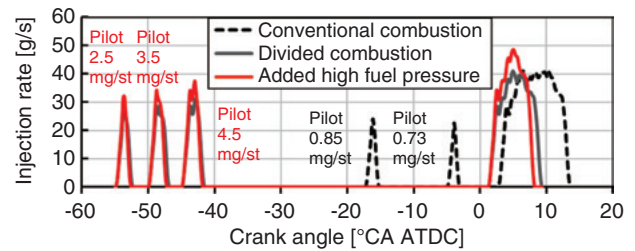


	Conventional combustion base ε 16.1	Divided combustion base ε 14.6	Added high boost pressure	Added high fuel pressure	Added high EGR rate
Fuel injection pressure [MPa]	140	140	140	200	200
Boost pressure [kPa_abs]	172	172	182	182	182
Equivalence ratio	0.81	0.81	0.81	0.81	0.83
EGR rate [%]	28.0	28.0	32.0	32.0	34.0

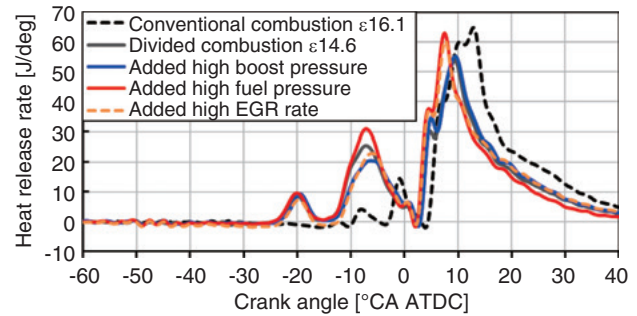
Fig. 12 Experimental conditions of conventional combustion and divided combustion

MPa in divided combustion. In conventional combustion, there is no extra margin with regard to the combustion noise target, but in divided combustion, the combustion noise can be held within the target value even when the boost, fuel pressure, and EGR are raised higher.

Figure 15 shows smoke, NOx, and thermal efficiency in conventional combustion and in the divided combustion specification with ε of 14.6. A comparison with conventional combustion from the smoke and NOx emission amounts shown in Fig. 15(a) indicates that divided combustion can reduce smoke by 47% by means of higher boost and fuel pressure, and that combining these with higher EGR makes it possible to reduce NOx emission by 40%, which approaches the emission target, with the same amount of smoke. This can be considered



(a) Injection rate



(b) Heat release rate

Fig. 13 Injection strategy and heat release rate of conventional combustion and divided combustion

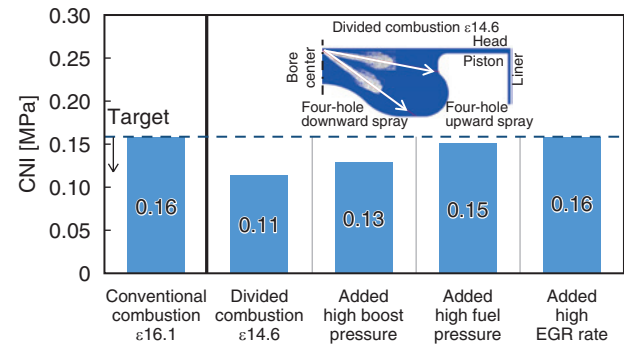


Fig. 14 CNIs of conventional combustion and divided combustion

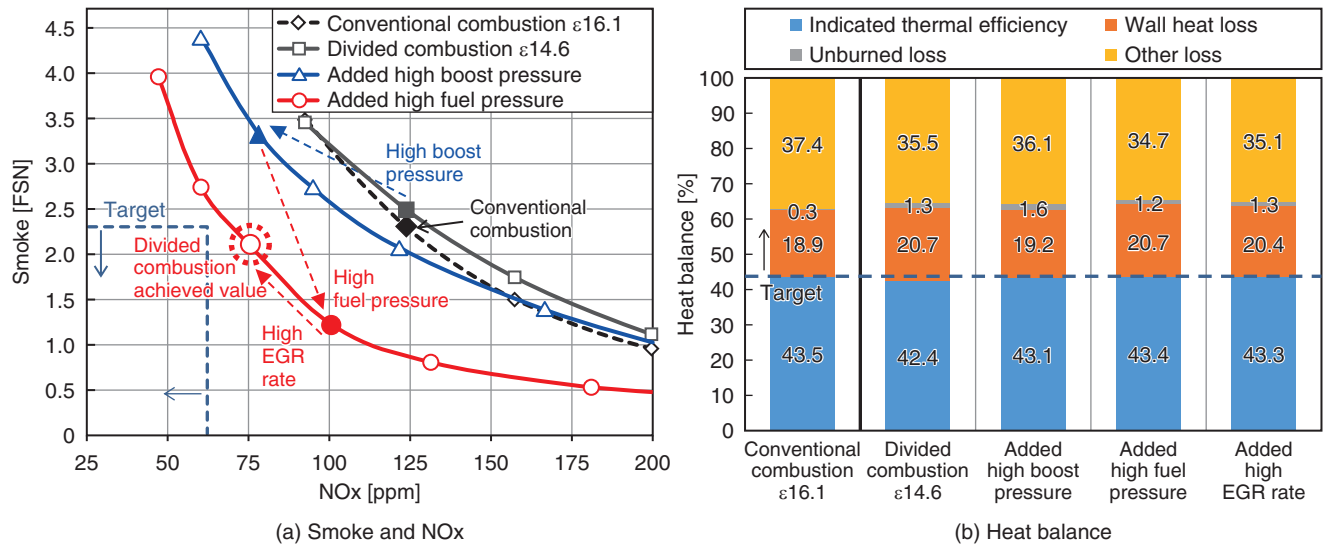


Fig. 15 Smoke and NOx and thermal efficiency of conventional combustion and divided combustion

to have obtained the reduction in the rich portion of main combustion by the effects of reducing the main injection amount, raising fuel pressure, and adopting the staggered spray layout, as was the aim of the initially formulated concept of divided combustion. It is also the case with thermal efficiency, as shown in Fig. 15(b), that while the adoption of premixed combustion increases wall heat loss, the wall heat loss is also mitigated by the effect of lowered combustion temperature that comes from the higher boost and EGR in divided combustion. As a result, where the target is 43.5%, the indicated thermal efficiency recovers to 43.3%, and this can be considered equal to the target level.

These results from verification in an actual engine indicate that the divided combustion specification with ε of 14.6 has achieved a 40% reduction in NOx emissions relative to conventional combustion, which closely approaches the emission target, while retaining the same levels of indicated thermal efficiency, smoke, and combustion noise.

6. Conclusion

The introduction of the divided combustion concept with application of the staggered spray layout yields a higher dispersion effect than the conventional specification. This achieved a 40% reduction in NOx emissions while retaining the indicated thermal efficiency, smoke, and combustion noise at the same levels with the evaluation load point at 2000 rpm engine speed, 150 Nm engine torque, and 28.3 mg/st total fuel injection amount. The findings obtained are given in the following.

(1) The divided combustion approach was devised as a combination with premixed combustion by early injection with the aim of reducing the fuel injection amount under high-boost, high-EGR conditions in main

diffusion combustion, which was the major generator of smoke in conventional combustion. It was confirmed that this approach reduced smoke by 37% relative to conventional pilot injection with the same fuel injection pressure.

- (2) The adoption of divided combustion successfully reduced combustion noise by 30%, enabling a 60-MPa increase in the fuel injection pressure that had formerly been limited by combustion noise. The effect of divided combustion together with the high dispersion effect of the staggered spray layout was confirmed to reduce smoke by 47%. This, in addition to the combination with higher EGR, achieved a 40% reduction in NOx with the same level of smoke.
- (3) The adoption of the staggered spray layout yielded a 24% reduction in the dilution occurring in premixed injection, making it possible to help prevent an increase in the frequency of oil maintenance.

Going forward, there appears to be a reasonable possibility that NOx emissions can be further reduced by changing the combustion chamber shape to suit divided combustion, raising EGR even higher, and other such means.

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Reproduction of Engine Torque Fluctuation with Low Inertia and High Stiffness Dynamometer

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ABSTRACT

The dynamometer used in a Virtual and Real Simulator was enhanced to increase the analysis efficiency of issues and events arising from engine torque fluctuation. The contribution of the dynamometer components was clarified using 1D CAE and structural changes were made to expand the reproducible frequency range. As a result, the reproducible torque fluctuation frequencies were expanded, and analysis could be performed using a Virtual and Real Simulator in the operating range where noise and vibration are issues in 4-cylinder and 6-cylinder engines. This bench system can be used to test analyses of mechanisms of drivetrain torsional vibration, such as rattle noise, arising from engine torque fluctuation, without recombining parts. This research can enhance the analysis efficiency of drivetrain torsional vibration issues arising from engine torque fluctuation and contribute to early determination of specifications.

1. Introduction

Electrification continues to accelerate with the goal of enhancing automobile power plant efficiency in order to reduce CO₂ emissions.

Hybrid systems are often used as power sources, most of which are equipped with two motors for driving and power generation. In these systems, the engine is mainly applied to generate the power needed by the driving motor, and is often separated from the tires. This enables to use the efficient rotational speed and torque generation ranges of the engine without being constrained by the driving state and driver demands. When the engine is used in the highly efficient operating range, however, both generated torque and torque fluctuation increase, and the torque fluctuation transmitted to the transmission increases as well. Moreover, a higher compression ratio tends to be set for the engine to increase the thermal efficiency, and torque fluctuation often increases⁽¹⁾. In addition, start from standstill is performed by the motor, so start devices such as a clutch and torque converter are no longer needed, and a structure directly connected with the engine is adopted. The absence of buffer devices in this case leads to an increase in torque fluctuation to the transmission in the

low-load range.

With these changes, rattle noise, etc. produced by gear tooth hitting due to torque fluctuation is becoming an issue. Analysis of these events calls for tests with different combinations of parts, such as replacing the damping device in a completed vehicle, which increases the repeated process time. Therefore, the application of a Virtual and Real Simulator (VRS) was investigated to achieve efficient analysis⁽²⁾.

The dynamometers for conventional VRS have been developed to support transient events such as start from standstill, acceleration and deceleration, beginning with responses to steady-state events. However, as for torque fluctuation, which is a dynamic event, the ranges of torque and frequency that can be generated are limited, and cannot cover the ranges currently used by hybrid vehicles.

Therefore, this research reduced the moment of inertia and increased the stiffness of the dynamometer parts to expand the magnitude and frequency band of torque fluctuation that can be reproduced by the dynamometers. This paper reports the result that oscillation events produced by torque fluctuations in a two-motor hybrid system could be analyzed with greater efficiency.

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² Innovative Research Excellence Power Unit & Energy

2. VRS Architecture and Dynamometer Issues

Figure 1 shows an overview of the VRS. The constructed drive unit VRS uses the actual hardware for the transmission and power control unit (PCU) to be evaluated. An input dynamometer is installed on the transmission input side in place of the engine, and output dynamometers that simulate the vehicle load are installed on the output side. The torque calculated by the engine model and vehicle model is input.

In analysis techniques using a VRS, a verification technique has been proposed that calculates tire torque fluctuation with a model and reproduces the calculation results with equipment⁽³⁾. This enables analysis of event mechanisms by using the VRS to vary the torque fluctuation input to the transmission, and capturing the change in rattle noise. However, this calls for the ability to input torque fluctuation equivalent to that of the engine.

Figure 2 shows the areas of the main combustion order of torque fluctuation that can be generated by dynamometers used by conventional VRS. Engine torque fluctuation includes combustion torque fluctuation arising from the pressure generated by combustion and inertial torque fluctuation produced by the inertia force of reciprocating parts⁽⁴⁾. Inertial torque fluctuation increases proportionally

with the square of the rotational speed, so the inertia force is the main factor in the rotational speed range of 4000 rpm or more in an L4 engine, which makes reproduction a challenge. In addition, even at 4000 rpm or less, the combustion interval is wide, so torque fluctuation is large and the reproducible area is limited.

The 3rd-order is the main component in a V6 engine, and the torque fluctuation frequency is higher than that of the L4 engine, so the torsional resonance of the dynamometer becomes an issue and there are areas over which the excitation torque cannot be properly generated. In addition, since the displacement is large, the torque fluctuation is also large and cannot be reproduced in areas with a high average torque.

To address this issue, it is necessary to reduce the moment of inertia and increase the stiffness of the dynamometer. When examining the specifications, a 1D model of the related parts was used and appropriate moments of inertia and torsional stiffness were set for each part.

3. Low Inertia and High Stiffness Dynamometer for Reproduction of Torque Fluctuation

Figure 3 shows the appearance of the input dynamometer.

Issues such as tooth hitting noise that arise from engine torque fluctuation often occur at 100 Hz or less^{(5), (6)}. The moment of inertia has a large influence at an excitation torque of 100 Hz or less, and in higher frequency bands, the resonant frequency determined by the moment of inertia and the torsional stiffness has an effect. Noise and vibration produced by engine torque fluctuation easily occur at low frequencies, so first the moment of inertia and then the resonant frequency were examined.

3.1. Moment of Inertia Target Setting

In order to examine the excitation torque and resonant frequency, a torsional vibration model of the bench system is considered simply as shown in Fig. 4. In this simple model, the moment of inertia of the dynamometer is J_1 [kgm²], the torsional stiffness of the overall apparatus is k [Nm/rad], the viscous damping coefficient is c [Nms/rad], and the moment of inertia of the test piece is J_2 [kgm²].

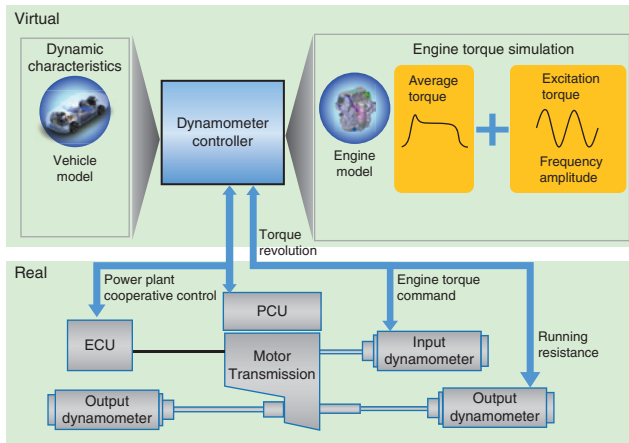


Fig. 1 Overview of VRS

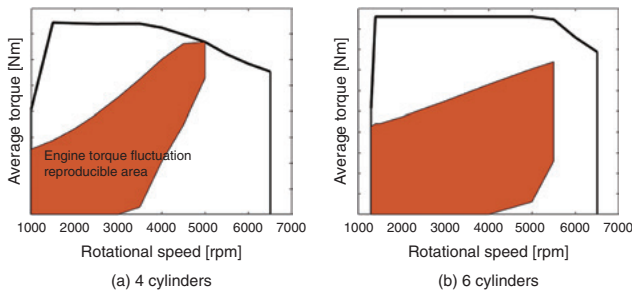


Fig. 2 Conventional specification of bench system

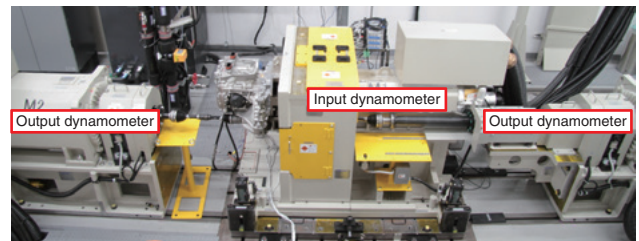


Fig. 3 Appearance of input dynamometer

Here, when $p = \sqrt{k/J_2}$, $\beta = J_2/J_1$, $\zeta = c/2\sqrt{J_2 k}$, the angular displacement θ_1 of the dynamometer and the angular displacement θ_2 of the test piece are expressed as shown in Eq. (1) using the excitation torque T_d [Nm] and excitation frequency ω [rad/s] of the dynamometer.

$$\begin{bmatrix} \theta_1(\omega) \\ \theta_2(\omega) \end{bmatrix} = \frac{T_d/J_1}{\omega^2(\omega^2 - p^2) - \beta p^2 \omega^2 - 2i\zeta p \omega (1 + \beta) \omega^2} \begin{bmatrix} p^2 - \omega^2 + 2i\zeta p \omega \\ p^2 + 2i\zeta p \omega \end{bmatrix} \quad (1)$$

The torque fluctuation T_c input to the test piece at this time is expressed using θ_1 and θ_2 as shown in Eq. (2).

$$T_c = |\theta_1 - \theta_2| \sqrt{k^2 + c^2 \omega^2} \quad (2)$$

Assuming that the excitation frequency ω is sufficiently small relative to the torsional stiffness k , Eq. (2) can be approximated as shown in Eq. (3).

$$T_c = \frac{J_2}{J_1 + J_2} \cdot T_d \quad (3)$$

Likewise, when the engine torque fluctuation is T_e , and the moment of inertia of the crankshaft is J_1' , the torque fluctuation T_c' input to the test piece at that time is as shown in Eq. (3)'.

$$T_c' = \frac{J_2}{J_1' + J_2} \cdot T_e \quad (3)'$$

In order to realize the same torque fluctuation with the dynamometer as that of the engine, T_c and T_c' should be equal, and the demanded moment of inertia can be calculated from Eq. (4).

$$J_1 = \frac{T_d}{T_e} (J_1' + J_2) - J_2 \quad (4)$$

The value of each parameter is as shown in Table 1, so the target moment of inertia of the apparatus was set to 0.2 kgm² or less.

3.2. Resonant Frequency Target Setting

The resonance range is entered under the condition where the torque fluctuation input to the test piece defined by Eq. (2) exceeds the dynamometer excitation torque T_d . Therefore, the target resonant frequency was set so that the resonance range is not entered at the main combustion order frequency of 350 Hz at the upper limit engine speed. When

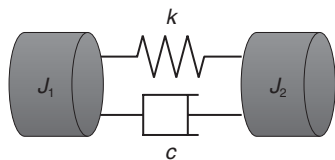


Fig. 4 Torsional vibration model of bench system

Table 1 Calculation condition for requested value of inertia

Excitation torque upper limit of dynamometer [Nm]	1200
Inertia of crankshaft [kgm ²]	0.04
Inertia of test piece [kgm ²]	0.12
Max torque fluctuation of engine [Nm]	600

the frequency ω_1 that exceeds the dynamometer excitation torque is calculated based on Eq. (2) under the condition of viscous damping coefficient $c = 0$, it is as shown in Eq. (5).

$$\omega_1 = \sqrt{\frac{k}{J_2}} \quad (5)$$

The resonant frequency was calculated from Eqs. (5) and (6), and the target resonant frequency was changed to 450 Hz from the current 350 Hz.

$$\omega_n = \sqrt{\frac{(J_1 + J_2)k}{J_1 J_2}} \quad (6)$$

3.3. Examination of Dynamometer Specifications

Dynamometer shaft design should take into account not only the torsional resonance of the dynamometer but also the bending resonance, making it necessary to increase the bearings from the viewpoint of durability to bending vibration. Adoption of a high-stiffness wireless torque meter in order to increase the resonant frequency was also examined, but there is an area where metal parts cannot be positioned so as not to shield the antenna part, and it was necessary to install multiple couplings. For this reason, the initial specifications were as shown in Fig. 5, the total moment of inertia was 0.3 kgm², and the torsional resonant frequency was 270 Hz.

The torsional stiffness k needs to be increased in order to increase the shaft resonant frequency. However, when the dynamometer is considered simply as a cylindrical shape with external diameter D_1 , internal diameter D_2 , shaft length L , material density ρ , and lateral elastic modulus G , the moment of inertia J and torsional stiffness k of the flanges and other parts used in the apparatus can be respectively expressed by Eqs. (7) and (8), and the moment of inertia and torsional stiffness can be seen to have a tradeoff

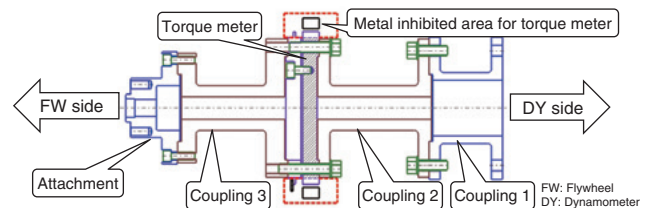


Fig. 5 Initial component of input dynamometer

relationship that depends on the radial dimension.

$$J = \frac{\pi}{32} \rho \cdot L \cdot (D_1^4 - D_2^4) \quad (7)$$

$$k = \frac{G \cdot \pi (D_1^4 - D_2^4)}{32L} \quad (8)$$

In order to reduce the moment of inertia of the rotating part, calculations were performed using the 1D model shown in Fig. 6 to determine the contribution of the torsional stiffness of each part to the 1st-order resonant frequency of the torsional vibration. Figure 7 shows the results.

The torque meter has sufficiently high torsional stiffness and a low contribution to the resonant frequency of the overall system, so the parts configuration was reviewed and specifications making it possible to increase the resonant frequency with low inertia were selected as shown in Fig. 8. In addition, bending vibration was addressed by limiting the mountable weight to 20 kg, which is the upper limit of the test pieces to be attached.

Table 2 compares the specifications with those of the conventional apparatus.

These structural changes raised the torsional resonant frequency of the input dynamometer from 350 Hz to 500 Hz as shown in Fig. 9, expanding the upper limit of the excitation frequency from 280 Hz to 440 Hz.

The adoption of a low-inertia and high-stiffness dynamometer as described above greatly expanded the

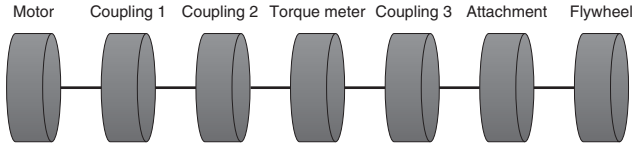


Fig. 6 1D CAE model of input dynamometer

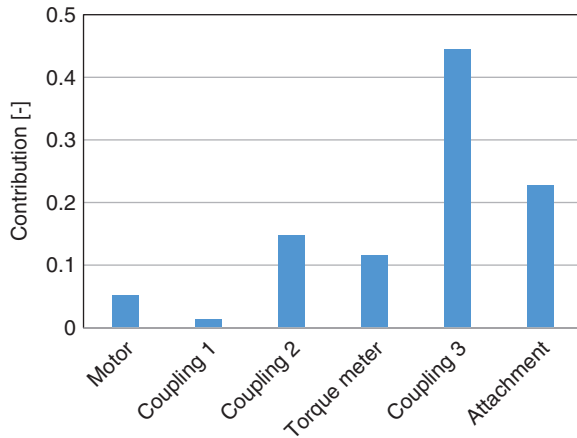


Fig. 7 Contribution of components

Table 2 Comparison of apparatus specifications

	Conventional specification	Proposed specification
Inertia [kgm ²]	0.15	0.2
Stiffness [kNm/rad]	270	485
Max torque [Nm]	500	1600

engine torque fluctuation reproducible area and enabled reproduction of torque fluctuation over the entire range of 3000 rpm or less, in which torsional vibration issues easily occur, for both the 4-cylinder and 6-cylinder engines as shown in Fig. 10.

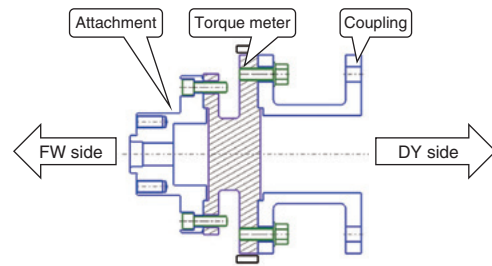


Fig. 8 Final component of input dynamometer

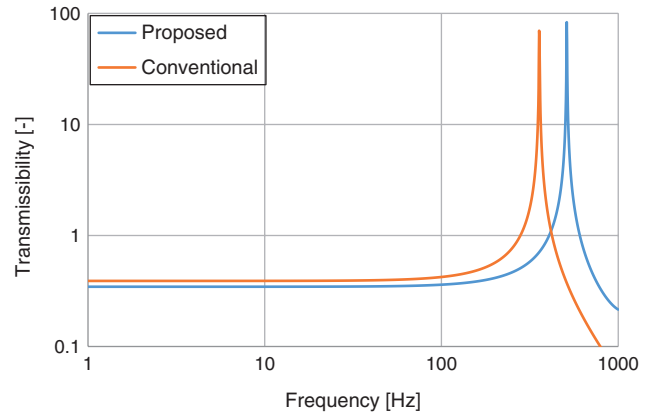


Fig. 9 Comparison for frequency response

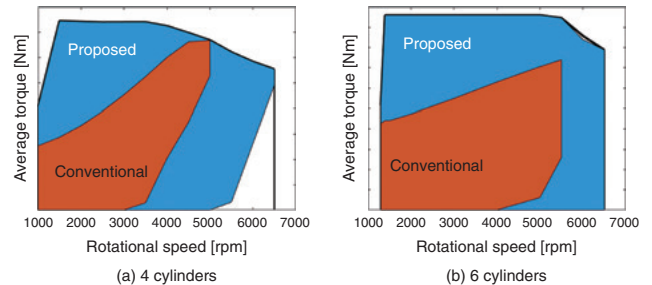


Fig. 10 Proposed specification of bench system

4. Proving Tests

Rattle noise is generated by tooth surface separation of gears on the torque flow at low torque, and by idle gear tooth hitting regardless of the torque. Torque fluctuation in the low torque range could be reproduced even by a conventional dynamometer, but the small excitation torque hindered sufficient parameter studies. In addition, torque fluctuation in the high torque range could not be reproduced.

Tests were conducted to verify that use of the developed dynamometer enables excitation torque parameter studies over the entire torque range, as well as analysis of rattle noise mechanisms without replacing parts. Rattle noise is noise produced when the engine torque fluctuation, which is amplified and damped by a vibration system that has the flywheel (FW) damper spring and drive shaft as springs as shown in Fig. 11, is transmitted to the transmission, internal parts with clearance vibrate, and other parts collide with each other. Therefore, torque fluctuation arising from the FW damping characteristics and vibration of internal parts due to torque fluctuation input were analyzed.

4.1. Analysis of Torque Fluctuation due to Flywheel

Figure 12 shows the frequency analysis results of the crankshaft rotational speed when rattle noise occurs in a two-motor hybrid vehicle.

2nd-order or higher rotational fluctuation normally occurs in a 4-cylinder engine. However, 1st-order rotational

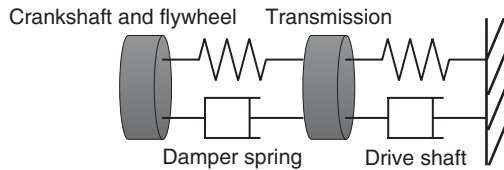


Fig. 11 Overview of torsional vibration model for vehicle

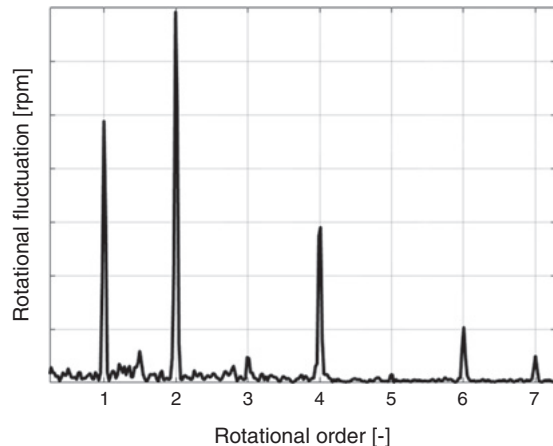


Fig. 12 Rotational fluctuation of crankshaft

fluctuation also occurs, and is thought to be due to subharmonic oscillation. Subharmonic oscillation is an event that occurs when the spring stiffness of the damper spring fluctuates across k_1 and k_2 as shown in Fig. 13.

The target FW has a structure where the hysteresis torque changes when the input torque changes by 30 Nm or more⁽⁷⁾. Figure 14 shows the engine torque waveform on the ECU when rattle noise occurs, and the change in torque is 30 Nm or more, so the high friction area is used. It is thought, therefore, that the transition to the high friction area changes the torsional stiffness of the damper spring as shown in Fig. 15, with the result that subharmonic oscillation occurs.

Next, when the static spring stiffness of the damper spring is k_s [Nm/rad] and the dynamic spring stiffness when the friction changes is k_d [Nm/rad], the FW is modeled as a parallel spring as shown in Fig. 16. At this time, the spring

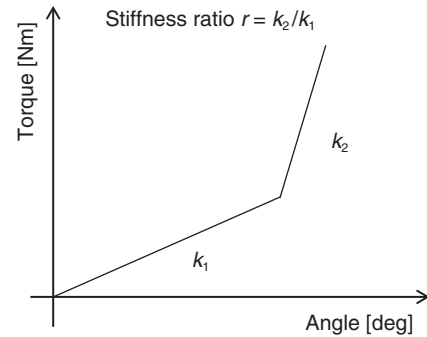


Fig. 13 Overview of damper spring stiffness

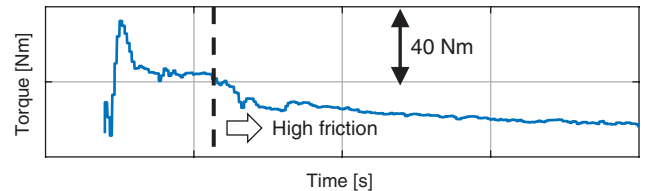


Fig. 14 Time-series data of engine torque

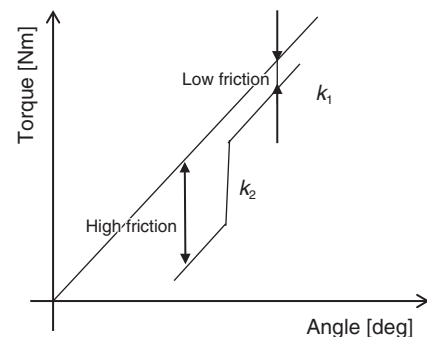


Fig. 15 Stiffness change with friction transition

stiffness k_1 and spring stiffness k_2 are expressed as shown in Eq. (9).

$$\begin{aligned} k_1 &= k_s \\ k_2 &= k_s + k_d \end{aligned} \quad (9)$$

When the spring stiffness at friction part start-up is k_f [Nm/rad] and the friction torque is f [Nm], the dynamic spring stiffness k_d is modeled as shown in Fig. 17. k_d can also be expressed by Eq. (10) using the torsion angle displacement amplitude θ [rad]⁽⁸⁾.

$$k_d = \frac{f}{\theta} \tanh \frac{\theta \cdot f}{k_f} \quad (10)$$

It has been reported that reducing the stiffness ratio r decreases the level of subharmonic oscillation generated⁽⁹⁾. As θ increases, the $\tanh$ term of Eq. (10) becomes asymptotic to 1, so both k_d and the composite spring k_2 decrease. As a result, it is thought that increasing the excitation torque amplitude as well as θ reduce the level of subharmonic oscillation generated.

Figure 18 compares the result of confirming the change in the level of subharmonic oscillation generated

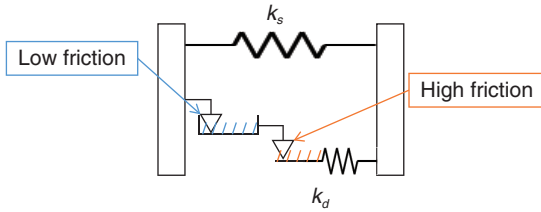


Fig. 16 FW model with parallel spring

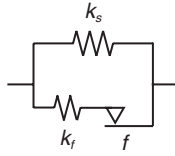


Fig. 17 Damper spring and friction model

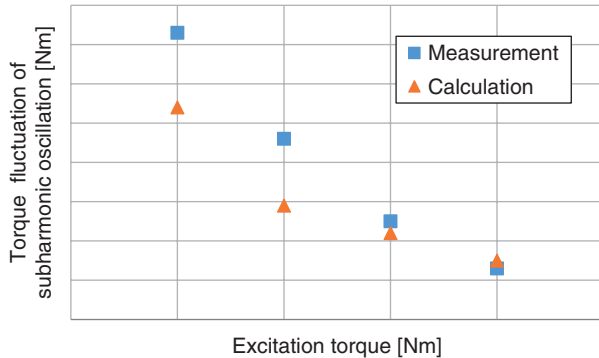


Fig. 18 Torque fluctuation of subharmonic oscillation

in an actual engine when the excitation torque amplitude is increased with the result of CAE analysis incorporating the damper spring model shown in Fig. 16. Both the measurement and CAE show the tendency of the 1st-order torque fluctuation to decrease when the excitation torque amplitude is increased.

The ability to perform torque fluctuation parameter studies made it possible to analyze that the mechanism of subharmonic oscillation generated has nonlinear characteristics due to the friction plate, without recombination to FW with different characteristics.

4.2. Analysis of Internal Part Behavior due to Torque Fluctuation

When rattle noise occurs, reducing backlash and clearance and suppressing part oscillation are effective as countermeasures inside the drivetrain⁽¹⁰⁾. However, as there is significant clearance inside the drivetrain, in order to implement effective countermeasures it is important to identify the clearance sites that are the source of rattle noise. If countermeasure amounts are not sufficient when recombining parts and performing tests, however, the change in the rattle noise level is minute and it is not easy to identify tooth hitting sites.

It was thought, therefore, that tooth hitting sites could be identified by controlling the excitation torque to vary the level of rattle noise generated and comparing the rattle noise to the behavior of drivetrain parts when tooth hitting occurs.

Based on past knowledge, it is clear that events related to part behavior are limited to rotational fluctuation generated by torque fluctuation input, and thrust fluctuation and radial fluctuation due to component force generated from the gear tooth surface. To measure these behaviors, displacement sensors were attached inside the transmission as shown in Fig. 19, and the shaft behavior was measured.

The state in contact with the engine was used as the origin of each part, and the coordinate axes were defined as shown in Fig. 20.

The normal vector n of the plane that passes through the three measurement points A, B, and C of each part is expressed by Eq. (11). The thrust direction displacement S and tilt angle ϕ of each part from the normal vector n are calculated as shown in Eqs. (12) and (13).

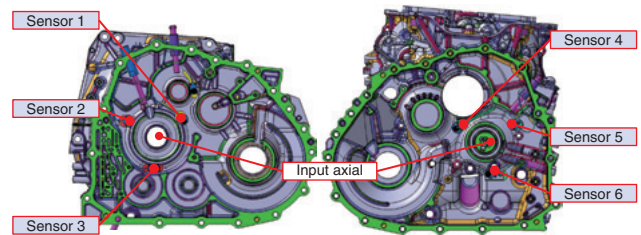


Fig. 19 Positions of displacement sensors

$$\vec{n} = \begin{pmatrix} x_n \\ y_n \\ z_n \end{pmatrix} = \begin{pmatrix} (y_b - y_a) \cdot (z_c - z_a) - (z_b - z_a) \cdot (y_c - y_a) \\ (z_b - z_a) \cdot (x_c - x_a) - (x_c - x_a) \cdot (z_c - z_a) \\ (x_b - x_a) \cdot (y_c - y_a) - (y_b - y_a) \cdot (x_c - x_a) \end{pmatrix} \quad (11)$$

$$S = \frac{x_n x_a + y_n y_a + z_n z_a}{z_n} \quad (12)$$

$$\phi = \tan^{-1} \sqrt{\left(\frac{x_n}{z_n}\right)^2 + \left(\frac{y_n}{z_n}\right)^2} \quad (13)$$

Figure 21 shows an example of the measured time series results. The upper graph shows the acceleration in the film surface direction of the L side cover, the middle graph shows the overdrive gear thrust displacement, and the lower graph shows the input shaft thrust displacement. These results show that each part exhibits large displacement when rattle noise occurs.

Figure 22 shows the frequency analysis result of L side cover acceleration. Unsteady noise such as rattle noise calls for high time resolution, so analysis is performed using the wavelet transformation already in use for rattle noise analysis⁽¹¹⁾. The frequency analysis results reveal a strong rattle noise peak between 500 Hz and 1000 Hz.

The Partial Overall (POA) between 500 Hz and 1000 Hz, which is the frequency band at which rattle noise occurs, was calculated for each behavior under conditions of different excitation torque, and compared with the

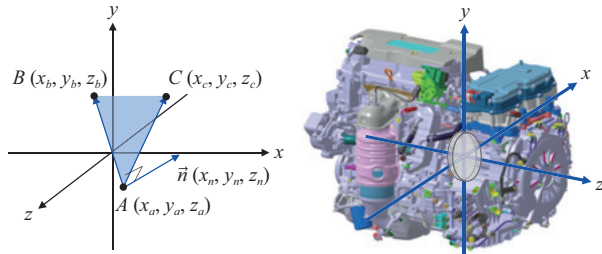


Fig. 20 Definition of coordinate axes

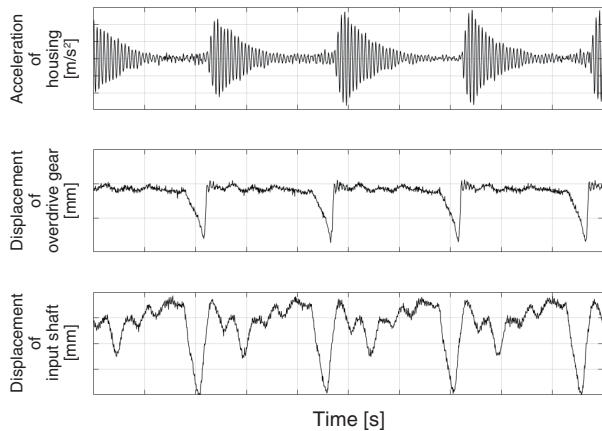


Fig. 21 Results of measurement

Table 3 Correlation coefficient to acceleration

Overdrive gear thrust displacement	0.8994
Input shaft rotation	-0.1645
Input shaft thrust displacement	-0.1303
Input shaft radial angle	0.2105
Overdrive gear radial angle	0.0864

acceleration of the L side cover. As an example, Fig. 23 shows a graph of highly correlated behavior.

Next, Table 3 shows the correlation coefficients between each behavior and acceleration obtained from this scatter diagram.

Of the various behaviors, as overdrive gear thrust displacement and acceleration exhibit a strong correlation, overdrive gear thrust displacement is thought to be the source of the rattle noise.

Next, Fig. 24 shows the test results under the same conditions when changed to a press-fit specification so that overdrive gear thrust displacement does not occur.

Since overdrive gear thrust displacement is suppressed, the generation of rattle noise is also suppressed, and rattle noise generation sites can be identified by varying the excitation torque, without replacing parts.

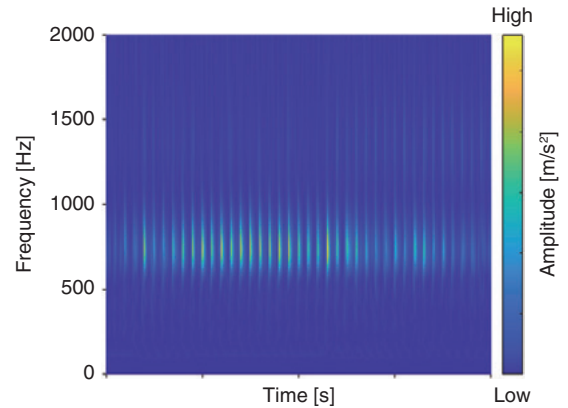


Fig. 22 Result of frequency analysis

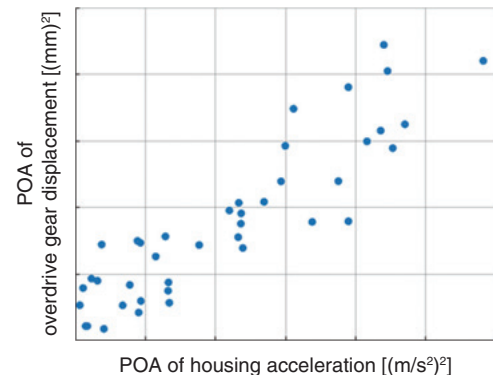


Fig. 23 Relationship of displacement and acceleration

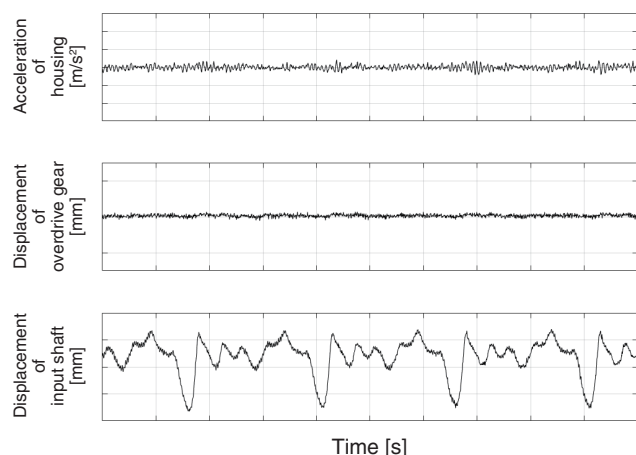


Fig. 24 Result of countermeasure

5. Conclusion

In examination of the dynamometer used in VRS, the structure was changed to reduce inertia and increase stiffness while using 1D CAE to clarify the contribution of the torsional stiffness of each part. This resulted in a moment of inertia of 0.2 kgm^2 and a resonant frequency of 500 Hz, which made it possible to reproduce torque fluctuation over the entire operating range needed for analysis of events arising from torque fluctuation. Thus, a parameter study using a VRS with an expanded excitation torque area verified that the FW damping characteristic mechanism and rattle noise generation sites could be identified without recombination of parts.

This research allowed analysis of drivetrain torsional vibration issues arising from engine torque fluctuation in transmission development by varying the excitation torque, without replacing parts. It is thought that this can contribute greatly to increasing efficiency and early decision on specifications.

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Comprehensive Study of Solvents for Wet Process Applied to Sulfide-based All Solid State Battery

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ABSTRACT

In the process of creating a wet process for a sulfide-based all solid state battery, it was necessary to search for suitable solvents. A systematic examination was therefore made of solid electrolytes and the reactivity of solvents. A halogen-doped argyrodite solid electrolyte that shows high lithium-ionic conductivity did not react with a hydrocarbon compound containing no polar group. With ethers, esters, ketones, and nitriles, however, the oxygen atoms and nitrogen atoms in their respective polar groups interact strongly with the solid electrolyte and were expected to form complexes with the lithium ions in the electrolyte. However, solvents having an alkyl chain length with a carbon number of four were not found to form complexes and the ionic conductivity of the solid electrolyte had not been markedly diminished. This is thought to occur because the increase in length of alkyl chains decreases the surface area accessible to coordinating oxygen atoms in the solvent molecules, thereby inhibiting the approach of the solvent to the surface of the solid electrolyte. Setting the carbon number of four or greater for the alkyl group chain length as a solvent search index yielded a direction to pursue for practical application of a wet process.

1. Introduction

The lithium-ion battery is an electrical energy storage device that achieves a balance between high energy density and power density, and so its applications are expanding not only in mobile electronic devices but in electric vehicles⁽¹⁾ as well. At the same time, the research continues for energy storage devices that combine still higher energy density with higher power density and great safety⁽²⁾. One candidate for such a device that is receiving attention is the all solid state battery. Sulfide solid electrolyte, in particular, has lithium ion transport number of unity⁽³⁾ and furthermore has at least the same degree of ionic conductivity as the electrolytes in the conventional lithium-ion batteries⁽³⁾⁻⁽⁶⁾. For that reason, research aimed at its practical application, together with oxide solid electrolyte, as a candidate material for a next-generation all solid state battery is underway⁽⁷⁾.

The methods for fabrication of all solid state batteries can be categorized as dry processes and wet processes. Dry processes have been applied for use at the laboratory level in small-scale testing that does not use solvent, directly pressing powder to fabricate all solid state batteries^{(4), (5)}.

For industrial production, on the other hand, wet processes are adopted in manufacturing conventional lithium-ion batteries. These include the preparation of slurry using the large-scale mixers, and the processes of roll-to-roll coating, drying, and pressing. Therefore, there are hopes that wet processes can also be applied in manufacturing all solid state batteries because this approach is expected to raise productivity and reduce costs⁽⁸⁾⁻⁽¹¹⁾. Issues remain with the use of wet processes, however, due to the reaction of sulfide solid electrolyte with highly polar solvents⁽⁸⁾⁻⁽¹⁷⁾. The solvents used in wet processes have the function both of dissolving the polymer binder and of dispersing the component materials, so it may also be anticipated that polar solvents will be used^{(9), (10)}. For that reason, polar solvents that do not react with sulfide solid electrolytes or that have low reactivity are being sought^{(8), (17)}.

The reaction of polar solvent with solid electrolyte can be understood as a kind of solid-liquid interface reaction. This type of reaction proceeds by going through the steps by which the solvent molecules approach the surface of the solid electrolyte, a reaction between the solvent molecules and solid electrolyte occurs, and the reaction product is

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dissolved into the solvent, and so on^{(18), (19)}. It is known that polar groups react with lithium ions in the solid electrolyte, and it is to be expected that if the approach to the surface of the solid electrolyte is inhibited, then the reaction can be inhibited. In this case, non-polar alkyl groups contained in the solvent molecules can be expected to repulse the solid electrolyte surface that has polarity⁽²⁰⁾ and so, as steric hindrance, inhibit the approach of solvent molecules.

Research into the interaction of solvents and solid electrolytes that has been reported to date includes reports that take the solvent donor number⁽⁸⁾ or the solubility parameter⁽¹⁰⁾ as an indicator of polarity. No reports have yet been found, however, that clarify the mechanism of the reaction between solvent polar groups and sulfide solid electrolyte, or that refer to factors that inhibit such reaction.

This paper, therefore, reports on its purpose to search for solvents that do not react with sulfide solid electrolytes or that have low reactivity with them, on its clarification of the mechanism of the reaction of polar groups in the solvent molecules with solid electrolytes, and on its demonstration by experiment and by the methods of computational science that alkyl groups function as a steric hindrance.

2. Experiment

2.1. Materials

For the solid electrolyte, a halogen-doped argyrodite compound expressed by the chemical formula $\text{Li}_{7-3y}\text{PS}_{6-y}\text{X}_y$ ($\text{X} = \text{Cl}$ or Br , $0 < y < 2$) was used⁽⁶⁾. In order to clarify the mechanism of the reaction between the solid electrolyte and polar groups in the solvent molecules, and to clarify steric hindrance by an alkyl chain, the 14 compounds in the five categories shown in Fig. 1 were used as solvents in immersion tests. Category I was ethers, and compounds (1) through (4) in Fig. 1 were used in order to examine the effect of the number of oxygens and the bulkiness of alkyl side-chains. Category II was esters, including those with two or four carbons on the carboxylic acid side, and those with two to four carbons in the alkyl chain on the alcohol side, which were used to examine steric hindrance by side-chains. These were compounds (5) through (9) in Fig. 1. Category III was ketones, which were used to examine the differences between those in chain form and those in ring form. These were compounds (10) through (12) in Fig. 1. Category IV was nitriles, which was compound (13) in Fig. 1. This was used to examine the interaction between nitrile groups and solid electrolyte. Category V was aromatic hydrocarbons. This was examined as a low-polarity solvent. The compounds used as solvents were off-the-shelf reagents subjected first to dehydration by molecular sieve and then to distillation. The residual moisture content was under 30 ppm for all the solvents. The commercially available xylenes [compound (14) in Fig. 1] were mixtures of isomers and included o-, m-, and p-xylene, and these are entered as xylenes. The text from this point on will refer to the solvents by their numbers in Fig. 1.

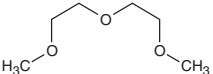
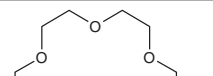
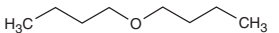
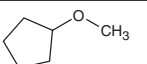
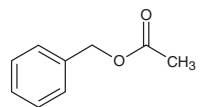
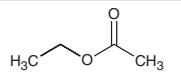
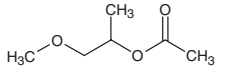
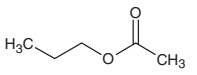
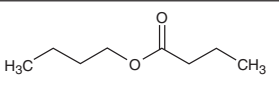
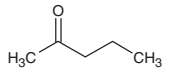
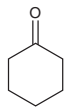
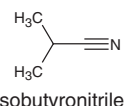
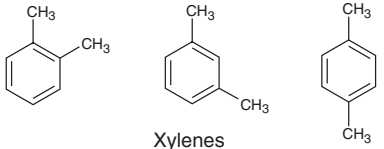
No.	Solvents	Chain length of side groups		
(1)	 Diethylene glycol dimethyl ether	C1	C1	I
(2)	 Diethylene glycol diethyl ether	C2	C2	
(3)	 Dibutyl ether	C4	C4	
(4)	 Cyclopentyl methyl ether	C5	C1	
(5)	 Benzyl acetate	-	C2	II
(6)	 Ethyl acetate	C2	C2	
(7)	 Propylene glycol monomethyl ether acetate (PGMEA)	C1	C2	
(8)	 n-Propyl acetate	C3	C2	
(9)	 n-Butyl n-butoate	C4	C4	
(10)	 2-Pentanone	C1	C3	III
(11)	 Cyclohexanone	-	-	
(12)	 Cyclopentanone	-	-	
(13)	 Isobutyronitrile	C4	0	IV
(14)	 Xylenes			V

Fig. 1 Solvents used for immersion tests

2.2. Evaluation of Solvent and Solid Electrolyte Reactivity

The reactivity of solvent and solid electrolyte was evaluated by means of solvent immersion testing, which was conducted as follows. Solid electrolyte 2 g and solvent 4 g were mixed and left standing for 12 hours in a glass container in a glove box that was constantly purged with argon gas. The mixture was then transferred to a glass tube oven and the solvent was removed under vacuum. All procedures were carried out without exposure to the atmosphere.

In order to evaluate the performance of the solid electrolytes before and after solvent immersion testing, their degrees of ionic conductivity were measured. Pellets of compressed solid electrolyte were fabricated in zirconia tubes of 10 mm inner diameter and their ionic conductivity was measured by the electrochemical impedance spectroscopy (EIS). The voltage amplitude was set to 10 mV and the frequency was swept from 1 MHz to 0.1 Hz during EIS measurement. The figure obtained by dividing the conductivity value of the solid electrolyte after solvent immersion testing by the value before immersion was taken as the conductivity retention rate.

2.3. Infrared Absorption Spectra

The degradation reaction in the solid electrolyte caused by solvent molecules is thought to occur due to coordination of polar groups in the solvent molecules to the solid electrolyte, which is followed by dissolution of the coordinated intermediate into the solvent⁽¹⁵⁾⁻⁽¹⁷⁾. In order to verify the course of this reaction, solid electrolyte was immersed in each of the solvents and then the infrared absorption spectra (IR spectra) of the electrolytes were measured before and after vacuum drying. If the polar groups were coordinated to the lithium ions in the solid electrolyte, then a shift in the infrared absorption bands could be expected^{(21), (22)}. In addition, the dissolution of the coordinated intermediate into the solvent can be expected to destroy the skeleton structure of the solid electrolyte, and the absorption bands of the solid electrolyte could also be expected to change. Measurements were made using a TENSOR 37 infrared absorption spectrophotometer made by Bruker Corporation, and they were carried out using a Platinum ATR, diamond attenuated total reflection (ATR) attachment. An original airtight sample chamber was used for sample setting and measurement without exposure to the atmosphere.

2.4. Gas Chromatography Mass Spectrometry

In order to evaluate the solvent degradation reaction, the solvents were subjected to gas chromatography mass spectrometry (GCMS). The GCMS-QP2010 Ultra manufactured by Shimadzu Corporation was used for measurement. For the column, the Restek Rtx-5MS glass capillary column with a length of 30 m, inner diameter of 0.25 mm, and membrane thickness of 0.25 μm . Helium gas

Table 1 Calculation conditions of DMol³

Basis function	dnp
Pseudopotential	None (All electron)
Functional	GGA-blyp
Orbital cutoff length	3.7 Å
SCF tolerance	1×10^{-6}

was used for the carrier gas. Compounds were identified using the NIST08 library with the GCMS solution analysis software (version 2.70) that was supplied with the device. The peaks from impurities that became mixed in during the course of testing were removed from the analysis results.

2.5. Estimation of Coordinating Oxygen Atom Reactivity by Computational Science

In order to clarify the influence of steric hindrance by alkyl chains that inhibit the approach by solvent molecules to the solid electrolyte surface, the surface area accessible to coordinating oxygen atoms in the solvent molecules was estimated from the structure of a molecular model. The molecular model structure was decided using DMol³⁽²³⁾⁻⁽²⁵⁾, which is a first-principles electronic structure calculating program in Materials Studio 2020. The main calculation conditions are shown in Table 1. The surface area of coordinating oxygen atoms determined to be accessible relative to the decided molecular structure was estimated by the conceptual approach of the Connolly surface⁽²⁵⁾ (Fig. 2), which uses a sphere as a probe of the atoms represented as spheres in the molecular model. The probe sphere is placed in contact with an atom and rolled across it, and the track made by the probe is taken as the surface area. This estimate was calculated using an original program developed here and coded in the Python language. In order to examine the influence of the steric hindrance, the esters (6), (8), and (9) in category II and the ketone (10) in category III, all in Fig. 1, were selected for calculation.

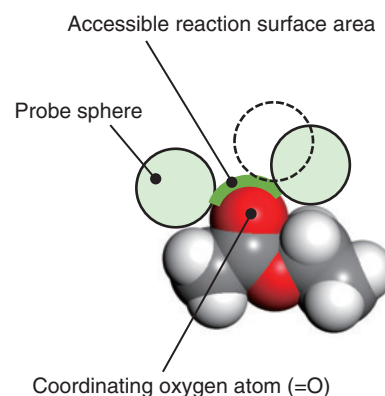


Fig. 2 Accessible reaction surface area based on Connolly surface

3. Results

3.1. Results of Solvent Immersion Testing

Figure 3 shows the results for measurement of the ionic conductivity of solid electrolyte after immersion. The retention of ionic conductivity by solid electrolyte after immersion relative to its ionic conductivity before immersion is shown as a bar graph. The electrolytes that had been immersed in the ether in category I, dibutyl ether [solvent (3) in Fig. 1], the ester in category II, n-butyl n-butoate [solvent (9) in Fig. 1], the isobutyronitrile in category IV [solvent (13) in Fig. 1], and the low polar solvent xylene in category V [solvent (14) in Fig. 1] showed retention of 98% or higher. In addition, the electrolytes that had been immersed in the category I ether cyclopentyl methyl ether [solvent (4) in Fig. 1] and the category II ester n-propyl acetate [solvent (8) in Fig. 1] showed retention of 87% and 79%, respectively. In contrast with these, the electrolytes that had been immersed in the category I ether diethylene glycol dimethyl ether [solvent (1) in Fig. 1], the category III ketones cyclohexanone [solvent (11) in Fig. 1] and cyclopentanone [solvent (12) in Fig. 1] showed almost no signs of ionic conductivity. When the solvents other than these were used, the ionic conductivity retained ranged between 17% and 47%.

The solid electrolyte used for this research was a light beige-colored powder. Figure 4 shows a photograph of the solid electrolyte immersed in a number of solvents. When immersed for 12 hours in ethyl acetate [solvent (6) in Fig. 1], the solvent took on a yellow color while the powder turned brown [(6) in Fig. 4]. After immersion for 12 hours in solvent (9) and solvent (13), those solvents turned a light yellow and light blue, respectively, but the color of the solid electrolyte remained largely unchanged [(9) and (13) in Fig. 4]. After immersion of the solid electrolyte in solvent (11), the solvent took on a yellow color and the powder became a viscous paste [(11) in Fig. 4]. Although

there is no photograph showing this, the other solvents in which immersion resulted in a lower retention of ionic conductivity tended to exhibit changes in color, increases in viscosity, and other such changes.

3.2. Infrared Absorption Spectra of Solid Electrolyte Before Drying

In order to compare the effect from polar groups and the effect of steric hindrance from alkyl chains, the results for a total of five solvents, consisting of two solvents each from category I and II and one from category III, were compared. Figure 5 shows a comparison of spectra for the solvent and solid electrolyte before and after immersion, arranged from top to bottom. For solvent (1) and solvent (6), which produced large decreases in ionic conductivity of the solid electrolyte after immersion testing, comparison with results before immersion showed major changes [Fig. 5(a) and (c)]. In the case of solvent (1) [Fig. 5(a)], almost all the solvent absorption peaks were split apart, suggesting that the solvent molecules were coordinated to the solid electrolyte⁽²²⁾. An absorption shift resulting from the P-S bond of the solid electrolyte at 560 cm^{-1} was also observed⁽²⁶⁾, suggesting that a change in the solid electrolyte skeleton had occurred. In the case of solvent (6) [Fig. 5(c)], the peak attributable to the P-S bond of the solid electrolyte at 560 cm^{-1} had become broader (marked with a ○ symbol), and of the peaks attributable to the solvent, the peak (1736 cm^{-1}) attributable to the C=O bond of the ethyl acetate became a shoulder peak (1707 cm^{-1} , marked by ▼). This suggests that a portion of the solvent has coordinated to solid electrolyte components⁽²¹⁾. When using the category III solvent (12) [Fig. 5(e)], the series of peaks resulting from H_2O (marked with a ▼ symbol) were stronger than the solvent and solid electrolyte absorption peaks. It can be estimated from this that the solvent and solid electrolyte were degrading and that H_2O was being generated.

In contrast with these, when solvent (3) [Fig. 5(b)] and solvent (9) [Fig. 5(d)] were used as the solvent, no changes in spectra were observed that would have been due to coordination of solvent molecules to solid electrolyte or

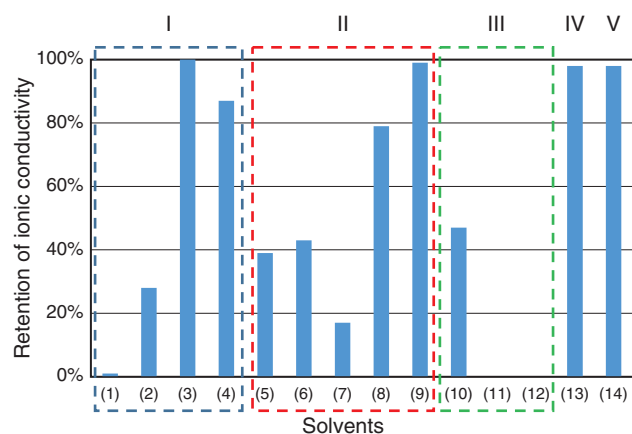


Fig. 3 Retention of ionic conductivity of solid electrolyte after immersion tests

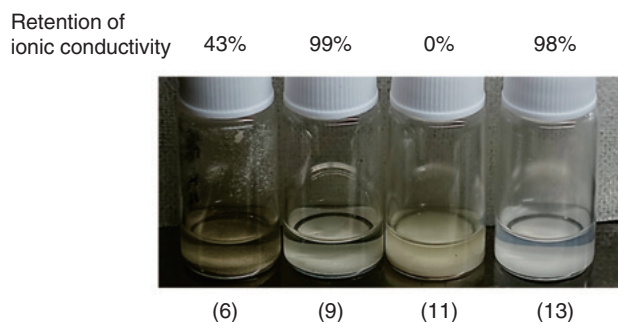


Fig. 4 Photographs of solid electrolyte immersed in solvents (6), (9), (11), and (13)

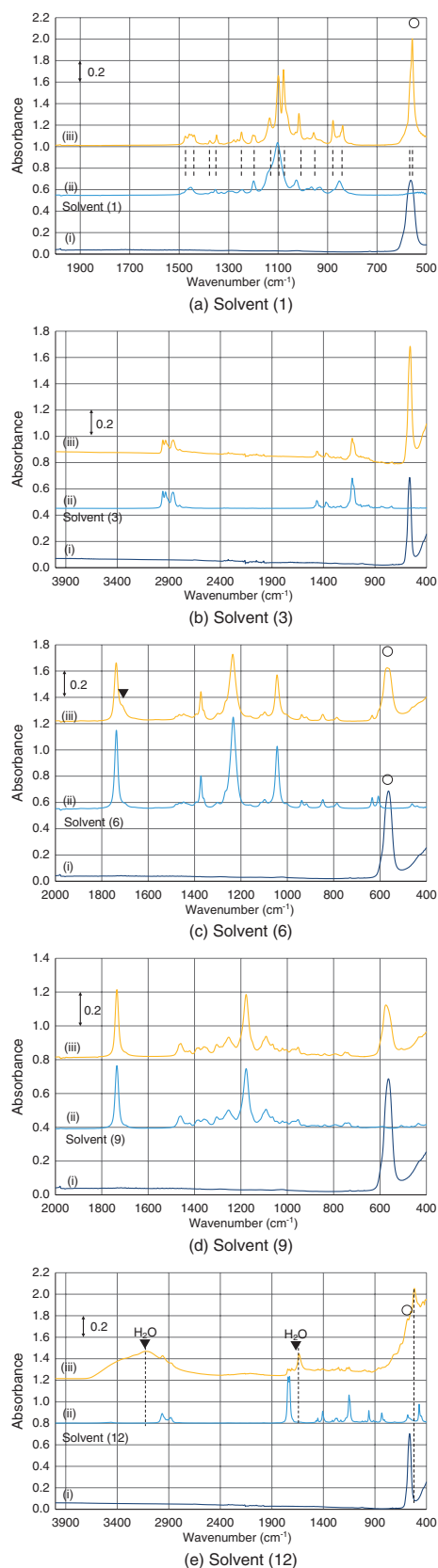


Fig. 5 Infrared absorption spectra of argyrodite solid electrolyte (i), solvents (ii), and wet electrolytes after immersion tests (iii)

collapse of molecular skeleton of solid electrolyte. Although the graphs of this are not shown here, no changes in spectra were observed, either, when solvent (13) and solvent (14) were used.

3.3. Infrared Absorption Spectra of Solid Electrolyte in Dried State

Figure 6 shows the infrared absorption spectra of solid electrolytes before immersion in their respective solvents and following vacuum drying after immersion, or in other words, after the volatile components and nonvolatile components have separated. Absorption attributable to P-S bonds in molecules of the solid electrolyte ($\text{Li}_{7-y}\text{PS}_{6-y}\text{X}_y$, $0 < y < 2$) have their main peak (marked with a ∇ symbol) at $560\text{ cm}^{-1(26)}$. The absorption of Li-S and Li-X bonds, however, appears at 250 cm^{-1} in the far infrared region, and so is omitted here. A small peak at 1033 cm^{-1} (marked with a $\bullet$ symbol) attributable to the P-O bond was also observed⁽²⁷⁾.

After immersion of the solid electrolyte in solvent (1), as shown in Fig. 6, the electrolyte's infrared absorption spectra main peak at 560 cm^{-1} has split into the two peaks

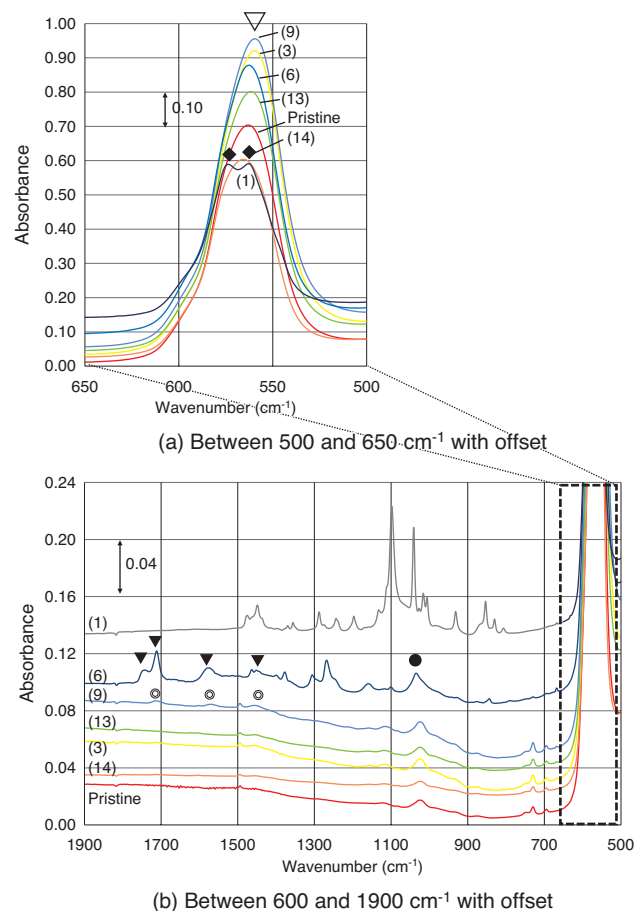


Fig. 6 Infrared absorption spectra of argyrodite solid electrolyte before and after immersion tests in solvents (1), (3), (6), (9), (13), and (14)

at 563 cm^{-1} and 574 cm^{-1} in Fig. 6(a) (marked with a $\blacklozenge$ symbol), suggesting that the argyrodite skeleton has degraded. A number of new peaks also appeared in the range from 800 to 1500 cm^{-1} , suggesting the existence of degradation products. With solvent (3), which belongs to the same category I, practically no change in the infrared absorption spectra was observed even after immersion and drying [(3) in Fig. 6], so it appears that the solid electrolyte did not experience any degradation due to the solvent. The ionic conductivity of the solid electrolyte did not decrease, either, after immersion in this solvent. With the solvents other than these, conspicuous change was not found after immersion in solvent (13) [(13) in Fig. 6] and solvent (14) [(14) in Fig. 6], and the solid electrolyte retained ionic conductivity of 98% or higher even after immersion in these solvents.

Next, a comparison was made of the solid electrolyte spectra after immersion in solvent (6) and solvent (9), which are two esters in category II. Of the ester molecules, solvent (6) has a carbon number of two both on the alcohol side and on the carboxylic acid side [(6) in Fig. 6], and no change was seen in the main peak of the spectrum at 560 cm^{-1} . New peaks did appear, however, at 1743 , 1711 , 1574 , and 1451 cm^{-1} (marked with a $\blacktriangledown$ symbol) and the absorption strength had increased at 1033 cm^{-1} (marked with a $\bullet$ symbol). The absorption at 1743 cm^{-1} can be attributed to ester bonds in residual solvent, and the absorption at 1711 cm^{-1} can be attributed to solvent molecule coordination to solid electrolyte⁽²¹⁾. The remaining absorption at 1574 cm^{-1} can be attributed to lithium acetate, which is a hydrolysis product of the ester. The broad shoulder peak at 1451 cm^{-1} and the absorption at 1033 cm^{-1} (marked with a $\bullet$ symbol) can be attributed to P=O or P-O-Li ⁽²⁷⁾. There were also a number of unattributed peaks in the range from 1100 to 1400 cm^{-1} , and these can be inferred to be from degradation products. It can be implied from these results that immersion of solid electrolyte in solvent (6) caused a portion of ester molecule to coordinate to the solid electrolyte so that a portion of the solid electrolyte degraded, but that the main skeleton was maintained.

Solvent (9) has a carbon number of four both on the alcohol side and on the carboxylic acid side, and it was noted above that ionic conductivity of 99% was maintained after immersion of the solid electrolyte. Its infrared absorption spectra did not show change in the main peak at 560 cm^{-1} [(9) in Fig. 6(a)]. New absorption was seen at 1707 , 1562 , and 1438 cm^{-1} [(9) in Fig. 6(b); marked with a $\odot$ symbol], and these can be attributed to solvent molecules coordinated to sulfide solid electrolytes and to the hydrolysis product *n*-butyric acid lithium salt, respectively. The strength of these absorption peaks is low by comparison with the case of solvent (6), however, indicating that there were only small amounts of the coordinated solvent and the hydrolysis product. No absorption was observed at 1748 cm^{-1} , which indicates that no residual free solvent was to be found.

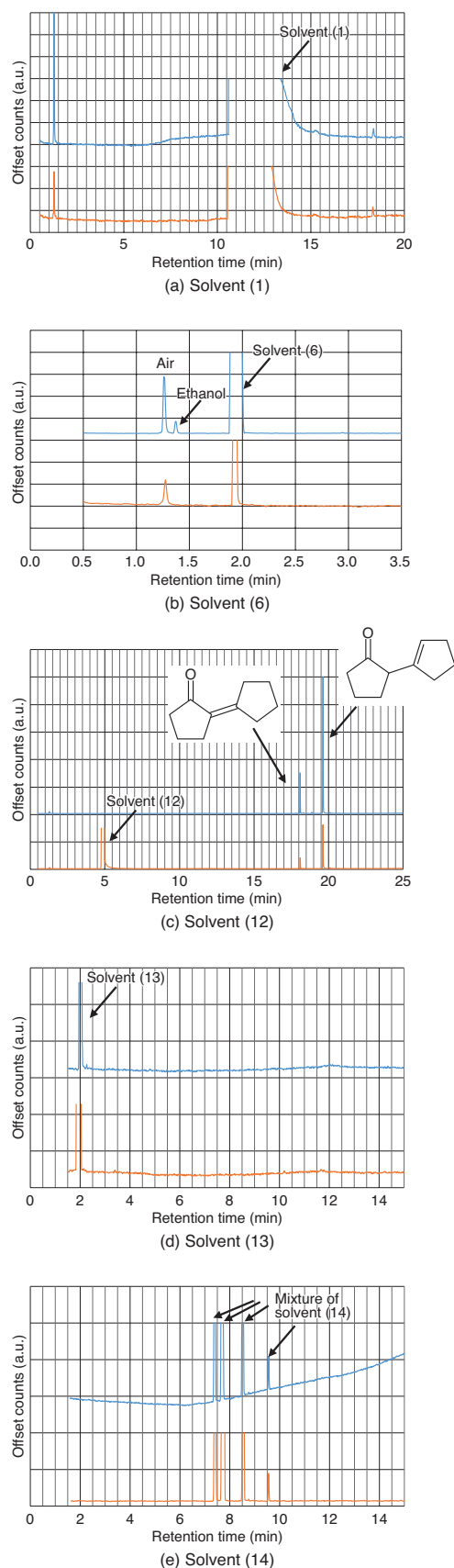


Fig. 7 GCMS chromatograms of solvents before (lower) and after (upper) immersion tests

3.4. Mass Spectrometry of Solvent After Immersion

Following immersion, the volatile components, including solvent, and the nonvolatile components, including solid electrolyte, were separated by vacuum drying in order to ascertain the solvent degradation products resulting from immersion testing. GCMS was then used to conduct qualitative analysis of the volatile components. Figure 7 shows the GCMS analysis results for the volatile components.

No volatile solvent degradation products were detected

in the four ethers of category I. Figure 7(a) shows the results for solvent (1) as an example. With the esters in category II, however, alcohol, which is a hydrolysis product, was detected. Figure 7(b) shows the results for solvent (6) as an example. Ethanol was detected, and it can be inferred that hydrolysis occurred during immersion testing. These results agree with the infrared absorption spectra results. With the ketones in category III, aldol condensation products of the various ketones were detected. Figure 7(c) shows the example of solvent (12). Since H₂O is produced

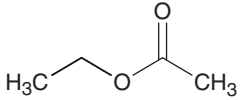
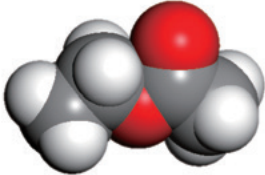
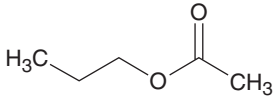
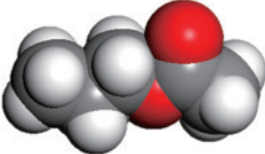
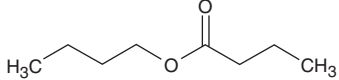
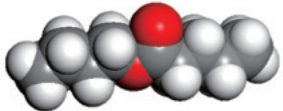
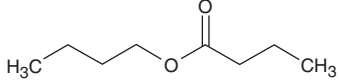
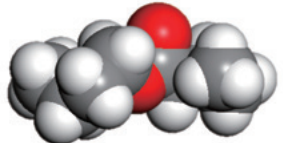
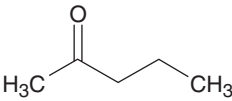
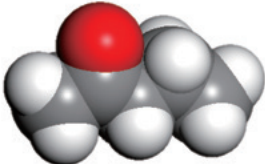
No.	Solvents	Molecular model	Reaction surface area (Å ²)		
			Probe radius 1.82 Å	Probe radius 10 Å	
(6)	 Ethyl acetate $\text{CH}_3\text{-C(=O)O-C}_2\text{H}_5$		10.55	4.94	II
(8)	 n-Propyl acetate $\text{CH}_3\text{-C(=O)O-C}_3\text{H}_7$		10.41	4.94	
(9)	 n-Butyl n-butoate $\text{CH}_3\text{-CH}_2\text{-CH}_2\text{-C(=O)O-C}_4\text{H}_9$		6.47	1.69	
(9')	 n-Butyl n-butoate $\text{CH}_3\text{-CH}_2\text{-CH}_2\text{-C(=O)O-C}_4\text{H}_9$		6.31	1.53	
(10)	 2-Pentanone $\text{CH}_3\text{-C(=O)-CH}_2\text{-CH}_2\text{-CH}_3$		9.43	4.58	III

Fig. 8 Calculation results of molecular structure and accessible reaction surface area

as a by-product of aldol condensation, these results agree with the infrared absorption spectra results [Fig. 7(c)].

With the category IV solvent (13) [Fig. 7(d)] and the category V solvent (14) [Fig. 7(e)], on the other hand, no new reaction products were detected from their volatile components after immersion. This suggested that immersion testing did not result in solvent degradation, or that the degradation products were not volatile.

3.5. Surface Area Accessible to Coordinating Oxygen Atoms

For the category II esters (6), (8), and (9) and the category III ketone (10) that were selected for calculation, the molecular model structure calculated using DMol³ and the surface area accessible to coordinating oxygen atoms calculated from that are shown in Fig. 8. The calculations were made with the respective assumptions for a molecule (probe) that approaches the surface assumed as a sphere the size of a lithium atom with a radius of 1.82 Å and as a sphere with a radius of 10 Å assumed as having the unevenness of the solid electrolyte surface. Regarding solvent (9), the case of a structure that is not linear is assumed, and so a folded structure was calculated and an additional calculation was performed as solvent (9)' in Fig. 8. The alkyl chain with a folded structure of solvent (9)' shows a slight difference in area from the solvent (9) structure, which is not folded. There was no major difference.

The indications were that this surface area accessible to coordinating oxygen atoms decreases as the alkyl chain lengthens. It was also found that when the probe radius is 10 Å, the value for solvent (9), which retained the ionic conductivity of the solid electrolyte after immersion testing, was one-half or less the values for solvents (6), (8), and (10), which saw the ionic conductivity decrease.

4. Discussion of the Mechanism of Reaction between Solid Electrolyte and Solvent

It is known that hydrocarbons, including aliphatics and aromatics, do not react with sulfide solid electrolytes^{(8), (10)}. In the present research, the solid electrolyte retained 98% of its ionic conductivity after immersion in solvent (14), which is an aromatic hydrocarbon. Given results that include the solid electrolyte infrared absorption spectra [(14) in Fig. 6] and the fact that GCMS analysis of the solvent [Fig. 7(e)] did not detect any reaction product, the solid electrolyte and solvent (14) can be considered not to have reacted.

The oxygen atoms contained in ethers, esters, and ketones, and the nitrogen atoms contained in nitriles are known to coordinate to lithium ions because of their respective electron-donating properties^{(21), (22), (28)}. Among those compounds, it is known that those with alkyl chain lengths of about carbon number two coordinate to the lithium ions in the sulfide solid electrolyte and cause the electrolyte components to dissolve or to swell⁽²⁹⁾⁻⁽³¹⁾. Given

that coordination by a portion of the solvents has been observed in the infrared absorption spectra, as noted above, it was determined that coordination by solvents was also occurring under the conditions of the present research. Even among those compounds that contain polar groups, however, there were those that did greatly decrease the ionic conductivity of the solid electrolyte and others that mainly did not decrease it. Specifically, compounds that have an

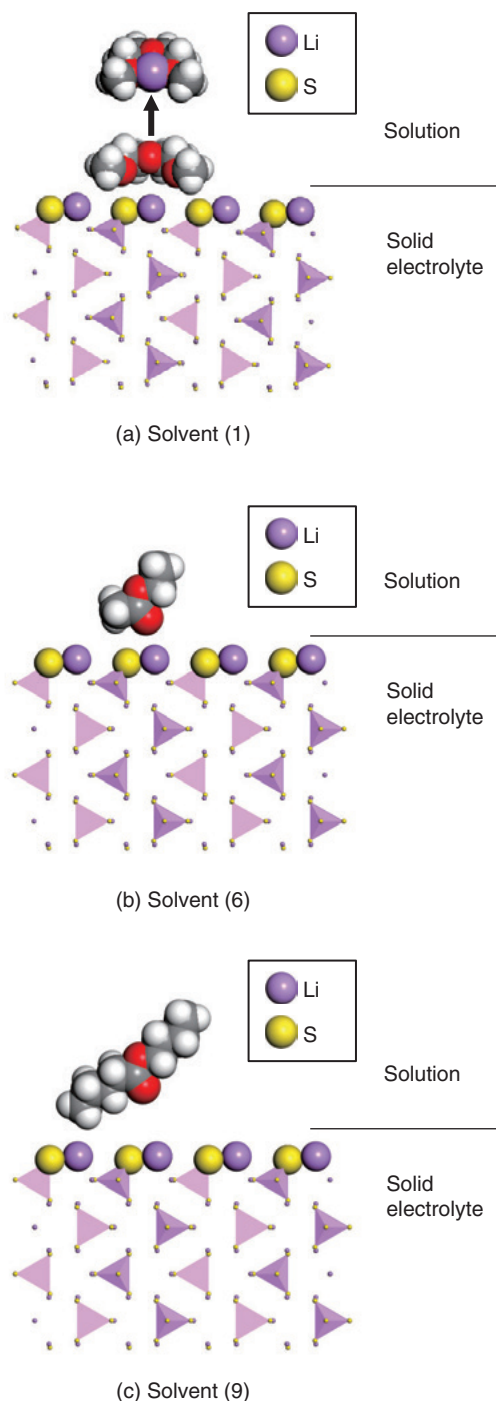


Fig. 9 Schematic chart of interaction between solid electrolyte and solutions

alkyl chain with a carbon number of four on both sides of the functional group generally did not decrease the ionic conductivity of the solid electrolyte, but those having alkyl chains with a carbon number of two did greatly decrease the ionic conductivity. It can be considered from these results that alkyl chains with a carbon number of four, by their steric hindrance, inhibit reaction between solvent molecules and solid electrolyte.

Various methods are used to quantify steric hindrance, and there have been reports about taking the volume derived from the van der Waals radii of the molecules as a standard^{(32), (33)}. For the present research, however, the accessible surface area was used as an index of how readily coordinated atoms can approach the solid electrolyte. This chapter focuses primarily on solvents having an alkyl chain length with a carbon number of two to four, and argues in terms of the relationship between the carbon number of the alkyl chain and the surface area.

4.1. Mechanism of Reaction between Solid Electrolyte and Ethers

The oxygen in ether molecules is known to coordinate to ions of alkali metal, including lithium, because of its electron-donating properties^{(22), (28)}. It has also been reported that ether oxygen coordinates to the lithium ions in Li_2S and causes dissolution of the Li_2S , and also that it forms a complex with Li_3PS_4 ^{(12), (13), (28)}. When ether as a solvent comes in contact with a sulfide solid electrolyte, therefore, it is thought to coordinate to the lithium ions on the surface of the solid electrolyte. Considering the infrared absorption spectra of the solid electrolyte after immersion and the solvent [Fig. 5(a) and (1) in Fig. 6], it is considered that solvent (1), which is a polyether, has separated from the surface in the form of a complex that remains coordinated to solid electrolyte components and so has caused degradation of the solid electrolyte [Fig. 9(a)]. The spectra for solvent (2), which is also categorized as a polyether, are not shown in the graph, but it was found from experimental results to show a tendency similar to solvent (1). The alkyl chains bonded to oxygen atoms in these molecules have lengths with carbon numbers of one and two. The alkyl chains bonded to oxygen atoms in solvent (3), however, have lengths with a carbon number of four, and it became clear from the infrared absorption spectra results [Fig. 5(b) and (3) in Fig. 6] that the ether oxygen is not coordinated to the lithium ions. When the calculation results for surface area accessible to coordinating oxygen atoms are taken into account, it is reasonable to consider that the approach of solvent molecules to the surface of the solid electrolyte is inhibited by the steric hindrance of the alkyl chains, weakening their ability to coordinate to the lithium ions, so that the lithium ions in the sulfide solid electrolyte cannot be dissociated from the solid state. It was for this reason that solvent molecules did not remain on the surface of the solid electrolyte after drying [(3) in Fig. 6]. As a result, it is thought that degradation of the solid electrolyte

did not occur and no decrease in ionic conductivity due to immersion in solvent (3) was observed.

The reaction between solid electrolyte and solvent is a reaction that occurs at the solid-liquid interface, and in order for the reaction to proceed, it is necessary for a new active interface to stay in constant contact with the liquid. In the case of solvents (1) and (2), which are polyethers, there are multiple electron-donating oxygens in the molecules. It is considered that the capability to form complexes is therefore high, so that complexes more readily form and begin to dissolve into the liquid solution [Fig. 9(a)], and new solid state surface is constantly being exposed. On the other hand, there is only one oxygen atom in the molecule, and in the case of solvent (3), which is an ether having alkyl chains with length of carbon number four, the complex is not formed and the components of the solid electrolyte do not readily begin to dissolve into the solvent. It is considered that a reaction did not proceed because of this.

4.2. Mechanism of Reaction between Solid Electrolyte and Nitriles

It has already been reported that acetonitriles having an alkyl chain length with a carbon number of two dissolve the solid electrolyte^{(30), (31)}. This is thought to be because the nitrogen atoms in the nitrile groups form complexes with the lithium ions in the sulfide solid electrolyte and, with themselves as solvent, dissolve the complexes⁽²¹⁾. The solvent (13) used in this research, however, is a compound with the carbon number of four, and although a portion of solvent changed color due to immersion, the volatile component nitrile was not observed among the degradation products [Fig. 7(d)] and the ionic conductivity of the solid electrolyte was not greatly decreased (Fig. 3). The solvent having changed to a bluish color suggested that a portion of Li_2S had dissolved out⁽³⁰⁾, but the fact that the infrared absorption spectra did not show nitrile having coordinated to the lithium ions, and the fact that the ionic conductivity of the solid electrolyte did not decrease, can be explained as being because the extent of Li_2S components dissolving out was small. This can be considered to occur because compounds having alkyl chains with a large steric hindrance interfere with the degradation of the solid electrolyte, as in the case of the ethers.

4.3. Mechanism of Reaction between Solid Electrolyte and Esters

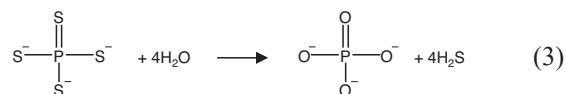
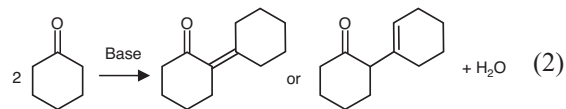
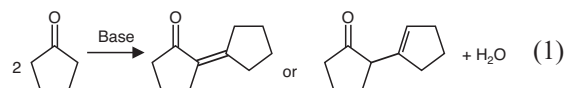
Solvent (6) is an ester having an alkyl chain length with a carbon number of two, and it has already been reported that it forms complexes with Li_2S and Li_3PS_4 ⁽¹⁵⁾⁻⁽¹⁷⁾. It has also been confirmed in the present research that solvent (6) is coordinated to the lithium ions in the solid electrolyte [Fig. 5(c)]. No coordination was found, however, in solvent (9), which has an alkyl chain length with a carbon number of four [Fig. 5(d)]. It is also the case in the present research, as noted in the previous chapter, that immersion of the solid electrolyte in esters results in hydrolysis products of esters.

These are, in other words, the nonvolatile components consisting of carboxylic acid and carboxylic acid lithium salt [(6) and (9) in Fig. 6], and the volatile component consisting of alcohol [Fig. 7(b)]. In light of the fact that carboxylic acid lithium salt was detected in the solid electrolyte after drying, it was inferred that the hydrolysis products of esters also contribute to the degradation of the solid electrolyte. The residual moisture content of solvents used in this research was under 30 ppm, and even this extremely small amount of moisture resulted in hydrolysis taking place. On the other hand, it was also found from the infrared absorption spectra results noted above that the amount of hydrolysis product differed according to the type and length of alkyl chains making up the esters. The strength of the infrared absorption peak attributable to the hydrolysis product of solvent (9) with its longer alkyl chain was weaker than that of solvent (6), which has a shorter alkyl chain, indicating that the amount of that product was smaller [(6) and (9) in Fig. 6(b)]. In addition, the amount of hydrolysis product was larger with solvent (5), which has a benzyl group.

In light of the above results, it can be said that both the coordination of ester groups to the solid electrolyte and the binding of the hydrolysis product to the solid electrolyte are contributing to the degradation reaction of the solid electrolyte due to esters. When the probe radius is 10 Å, it became clear from the calculation results for surface area accessible to coordinating oxygen atoms with solvents (6) and (9) that the value for solvent (9) with an alkyl chain length with a carbon number of four was smaller than the value for solvent (6) with an alkyl chain length with a carbon number of two [(6) and (9) in Fig. 8]. It can be inferred that the molecules of solvent (6) were able to approach the solid electrolyte [Fig. 9(b)], but those of solvent (9) were inhibited from approaching the solid electrolyte by the alkyl chains [Fig. 9(c)].

4.4. Mechanism of Reaction between Solid Electrolyte and Ketones

As a result of the immersion of solid electrolyte in ketones, the ionic conductivity of the solid electrolyte was greatly reduced [(10), (11), and (12) in Fig. 3]. GCMS analysis of the volatile components detected aldol condensation products of the ketones [Fig. 7(c)]. In the presence of acid catalyst or base catalyst, ketones cause an aldol condensation reaction⁽³⁴⁾. This reaction causes condensation of two ketone molecules and also produces H₂O as a by-product [Eqs. (1) and (2)]. In the case of the present research, the sulfide solid electrolyte is thought to act as a solid-state base catalyst. The sulfide solid electrolyte, however, is known to react with H₂O and undergo degradation [Eq. (3)]. It is considered, therefore, that the degradation reaction with water that is a by-product of aldol condensation also contributes to the decrease in ionic conductivity of the solid electrolyte resulting from immersion in ketones.



In addition to forming complexes with the components of sulfide solid electrolyte, therefore, ketones also produce H₂O through the aldol condensation reaction, and two degradation reactions are thought to occur simultaneously. Compared with the ketone (10) in chain form, immersion in ketones (11) and (12) in ring form caused greater reduction of the ionic conductivity of the solid electrolyte. This can be explained by the fact that self aldol condensation reaction rate is faster with ring form ketones⁽³⁵⁾. In light of the above results, it is to be expected that when using ketones as solvent, it is preferable to use compounds with greater steric hindrance that inhibit the approach to the surface of the solid electrolyte acting as a catalyst because this will inhibit aldol condensation.

When the above results are combined, it can be said that the mechanism of the reaction between solvent and solid electrolyte differs with the differences in functional groups, and that the steric hindrance of the solvent molecules inhibited the reaction. In order to examine the solvents used in a wet process, it is necessary to think comprehensively about the functional groups of the solvents and their steric hindrance. It has become clear from the present research that solvents with greater steric hindrance tend not to react readily with the solid electrolyte.

5. Conclusion

A systematic examination was made of the reactivity of a series of solvents and sulfide solid electrolytes in order to search for solvents to apply in a wet process for an all solid state battery. This yielded clarification of the mechanism of reaction between solvent and solid electrolyte.

- (1) The oxygen atoms and nitrogen atoms in polar groups form complexes with the lithium ions in the solid electrolyte. The dissolution of those complexes in the solvent causes a degradation reaction in the solid electrolyte.
- (2) Simultaneously with these reactions, the residual moisture content of less than 30 ppm in the solvent causes hydrolysis to occur in the esters, and the hydrolysis product reacts with the solid electrolyte.
- (3) With ketones, an aldol condensation reaction occurs that takes the solid electrolyte as a base catalyst. The H₂O that is a by-product of this reaction also undergoes a

reaction that causes degradation of the solid electrolyte.

It became clear that in order to inhibit the series of reactions caused by the mechanisms of these reactions, effective candidate solvents would be hydrocarbons that do not contain polar groups and ethers, esters, and nitriles that have alkyl groups with carbon numbers of four or higher that act as a steric hindrance. Together with recognition that the residual moisture content of the solvent needs to be limited to an extremely small amount, the research yielded directions to pursue toward the practical application of wet processes.

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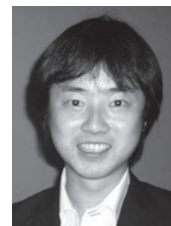
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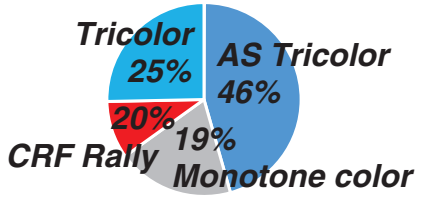
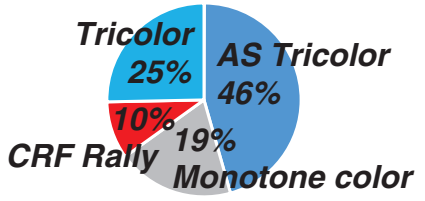


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Correction of errors

No.	Vol. No.	pdf No.	Title of the paper	Page	Corrected part	Details	
1	Vol.33 No.1	33-1_04e	Coloring Design for 2020 CRF1100L Africa Twin	p. 29	Fig. 5, pie chart of color lineup for 2019	Error	 Tricolor 25% AS Tricolor 46% CRF Rally 20% Monotone color 19%
						Correct	 Tricolor 25% AS Tricolor 46% CRF Rally 10% Monotone color 19%

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Editorial Afterword

The first issue of the Technical Review was published in 1989. Since then, it has continued for 32 years, and is now up to Vol. 33. I want to express my heartfelt gratitude to all authors and contributors, and to all those involved in the publication, for your understanding and cooperation.

From my experience working in the field of crash safety, I came to understand the great social influence of these papers. At the same time, I felt very strongly how important such influence is. Safety devices of any kind, as well as related regulations and assessments, are all created from evidence, and an accumulation of evidence, that is backed up by these papers. To express this figuratively, the individual papers have a novel quality, each like a fresh sheet of paper. They accumulate one by one, however, with all the care of people who place their weight on an unfamiliar bridge, checking thoroughly each step of the way. The vision that then emerges can make things happen in the world. I say this with full confidence because I have seen real-world results of reductions in accident-related deaths and injuries.

People have started to explore different modes of expression for papers in different fields, but there are fields for which it is necessary to preserve the paper in written form. I sense a growing diversification in the kind of presence that technical results may have. At the same time, however, I intend to continue insisting on the importance of the written paper as I handle manuscripts that arrive to me.

I have been engaged in editing for about two years now, so I am just getting started. As each submitted manuscript crosses the hurdles of passing from the first draft to the final version, I can sense how the young authors grow as they refine the substance of their papers. It is my hope that I will be of assistance in making this happen.

Shigeo TOBARU

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