TOYOTA

Technical Review

Special Feature

Toyota's Full Lineup Strategy for Carbon Neutrality

2023/4 Vol.68

TOYOTA Technical Review
Apr. 2023 Vol.68

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Toward Achieving Carbon Neutrality

Masahiko Maeda,
Member of the Board Directors

We are currently facing and searching for solutions to a range of social issues such as economic instability and an energy crisis caused by factors including global warming, climate change, natural disasters, and the COVID-19 pandemic. The elements that make up these social issues are intertwined with each other in complex ways. As we speak, no one has been able to sketch out a clear road toward their resolution.

In particular, since the concept of carbon neutrality is closely associated with social issues involving all aspects of the environment, countries and regions around the world have started to pursue a wide range of carbon-neutral initiatives. With Japan pledging to achieve carbon neutrality by 2050, this has become a major social issue for every sector of industry. Carbon neutrality is defined as a state of net-zero carbon dioxide (CO_2) emissions, which can achieved by balancing the emissions of greenhouse gases with their removal. For the automotive industry, this means eliminating CO_2 from the whole vehicle life cycle, including the CO_2 generated in the manufacturing of materials and parts, power generation, driving, fuel production, as well as scrapping and recycling. In addition to new vehicles, it is also important to include vehicles already on the road when considering the concept of carbon neutrality.

As often stated by Akio Toyoda, the President of Toyota, our mission is to provide goods and services that make people throughout the world happy through the development and manufacture of vehicles or, in other words, to "mass produce" happiness. We regard social issues related to preserving the environment as one of the highest priorities of our business, and we have a long history of pursuing a wide range of initiatives to this end.

Since the debut of the first-generation Prius in 1997, Toyota has worked to reduce CO_2 emissions through the development of different types of electrified vehicles, including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs). An important step toward achieving carbon neutrality is correctly understanding its fundamental meaning. More specifically, this understanding must begin from the awareness that the enemy of carbon neutrality is carbon, not the internal combustion engine. Although reducing the consumption of fossil fuels through wider adoption of electrified vehicles is important, vehicles powered by engines that use carbon-neutral fuels such as hydrogen, e-fuels, and biofuels have also been proposed in recent years as possible solutions. These fuels can be applied to means of transportation other than vehicles, such as trains, boats, and the like, as well as a wide range of other industries, including power generation, energy, and steel. We are also undertaking joint research to accelerate development and to commercialize cutting edge technologies in the energy and environmental fields, particularly solar cells, through tie-ups with relevant external organizations and companies. Some of our other initiatives include developing efficient household storage batteries capable of supplying power using BEVs even after a natural disaster, a project to develop new future cities that use low carbon fuel (LCF) or hydrogen in Fukushima Prefecture, activities to reduce CO_2 during vehicle manufacturing, and research into CO_2 absorption using nature or industrial technologies. As well as the development of vehicles and carbon-neutral fuels, we think that it is important to implement a multi-dimensional strategy for both achieving carbon neutrality and absorbing CO_2, including energy management using household storage batteries, reducing CO_2 during vehicle manufacturing and scrapping, and so on.

In recent years, Europe and the U.S. in particular have started to focus on BEVs as the solution for achieving carbon neutrality. Although both BEVs and FCEVs have zero tailpipe CO_2 emissions, the method by which the electricity or hydrogen fuel is produced affects the scale of CO_2 emissions over the whole vehicle life cycle. The popularization of electrified vehicles must be considered hand-in-hand with how the fuel is produced. In other words, to realize carbon neutrality, it is important to select methods that can realize the appropriate reduction of CO_2 across every aspect of energy production, transportation, and use. We also believe that environmental technology can only be truly regarded as good for the environment when it is used by a large number of people. For this reason, we think customers should be given the option of selecting vehicles equipped with various types of environmental technologies as well as just comparatively expensive BEVs.

The introduction of BEVs is making progress in Europe where the utilization of renewable energy is growing. In China, compact BEVs are rapidly becoming popular in rural areas and hydrogen buses are being adopted in cities. In Brazil, bioethanol has been practically adopted. In addition, in the U.S., there is rising demand for various forms of mobility, including BEVs, PHEVs, and FCEVs. The diversity in the energy situation depending on the region demonstrates the fact that there is not a single solution for reducing CO_2 emissions. We believe that, just as there is more than one way to climb a mountain, there is more than one route to reach carbon neutrality, and regulations should not limit our choice of technologies. Of the world's many automakers, Toyota is distinguished by the wide lineup of vehicles we sell to customers in various regions around the world, from compact cars to sedans, SUVs, premium models, and commercial vehicles. Therefore, we need to offer a full lineup of choices to provide mobility that properly supports the convenience of our global customer base.

This edition of the *Toyota Technical Review* describes BEVs, FCEVs, new applications for fuel cells (FCs), hydrogen engines, and infrastructure technologies that support these products as part of our full lineup strategy to help achieve carbon neutrality. It describes our multi-dimensional approach to carbon reduction and the development of carbon-neutral vehicles in line with the energy situation and customer preferences in every region as an automaker that offers a full lineup of products around the world.

First, BEVs. We intend to create a full lineup of BEVs to expand the available choices of electrified vehicles. Of these, the Toyota bZ series of BEVs is aiming to win the acceptance of as many customers as possible around the world. The name "bZ" stands for "beyond zero," and expresses our desire to provide customer value that goes beyond zero emissions.

In China, we are working to help protect the environment by accelerating our mobility-related efforts to achieve carbon neutrality. For this purpose, to help realize people-centered and highly convenient sustainable mobility, Toyota has developed the bZ3 as the second model in its bZ series of battery electric vehicles (BEVs) after the bZ4X. The bZ3 was developed locally in China as a product specifically for Chinese customers.

At the same time, in Japan, we are introducing ultra-compact BEVs and walking area BEVs that closely meet the needs of a wide range of customers to help realize the concept of mobility for all. First, in addition to short-distance daily use, the C$^+$pod was specifically developed for corporate users visiting customers on a regular basis, and users in urban or mountainous communities. The new C$^+$walk walking area mobility series is smaller than conventional mobility and includes a standing type BEV that was launched on October 1, 2021, as well as seated type and wheelchair-linked type BEVs (launch date yet to be decided). Our aim is to offer mobility that delivers peace of mind and safety to everyone at all stages of life, including people capable of driving a normal vehicle, elderly drivers, people that have returned their driving license, and people in wheelchairs.

The next type of mobility is FCEVs powered by hydrogen energy. Among carbon-neutral fuels, hydrogen can also play an extremely important role as an energy carrier. The inconveniences of electricity can be offset by converting it into hydrogen. In the form of hydrogen, energy can be stored for extended periods of time and even transported easily in accordance with demand. In addition, ammonia and e-fuels, which are regarded as promising sources of energy for the future, can be produced by reacting hydrogen with nitrogen and CO_2. Toyota is also aiming to further contribute to the realization of a hydrogen energy-based society. Initiatives include the modularization of FC components to facilitate the application of FCs to a wider range of products. It is also working to create new value for FCEVs by taking advantage of the abundant power generation capacity of FCs to raise the performance and effectiveness of FCEVs in non-driving situations. The transportation sector is also studying hydrogen engines in addition to FCEVs. Hydrogen is easier to ignite than gasoline and is therefore more susceptible to abnormal combustion. This edition of the *Toyota Technical Review* also analyzes the particular abnormal combustion mechanism of hydrogen engines and examines technologies capable of controlling this phenomenon.

The final articles of this edition's special feature cover power charging and supply technologies, which will play an indispensable role in popularizing the electrified vehicles described above. Toyota has adopted a multi-dimensional strategy to help achieve carbon neutrality while increasing the choices available to customers. As part of this strategy, the expansion of charging infrastructure will play a key role in encouraging the widespread adoption of BEVs. Various issues that affect automakers are being examined, such as the ideal form of charging infrastructure for carbon neutrality, eliminating customer concerns and complaints, ensuring convenience, and so on. Power supply technologies are also entering wider use as part of next-generation power systems, such as local power generation systems for local consumption coordinated with renewable energy sources to help achieve carbon neutrality.

We are faced with extremely difficult issues to overcome before we can realize a sustainable society. In 2018, Toyota declared its intention to change its business model from a company that builds cars to a mobility company. This is rooted in the idea that technology must contribute to people's happiness and wellbeing. Precisely because we live in such an age, we must be a company that is needed by people and society. Our mission of mass producing happiness stems from this idea.

Finally, the concept behind the planning of this edition of the *Toyota Technical Review* can be summarized in the key words "beyond zero." These words illustrate our determination to pass our beautiful home planet onto the next generation, In addition to resolving the issues that we are facing as individuals and communities (i.e., turning the negative impacts of these issues to zeroes), we are also looking beyond zero to create and provide new value by continuing to diligently seek ways to improve lives and society for the future. We believe that, hand-in-hand with the 5.5 million people involved in Japan's automotive industry, we can make steady progress to resolve the issues of our society and help to realize our aim of mass producing happiness.

The Toyota bZ4X

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Abstract

Toyota is aiming to help achieve carbon neutrality by preparing a wide range of product options in line with local conditions and customer needs around the world. The recently launched bZ4X is a no-compromise battery electric vehicle (BEV) and the first model in the bZ series, which is based on a dedicated BEV platform. This article outlines the objectives of the bZ4X and the technologies to realize these objectives.

Keywords: *bZ4X, BEV, e-TNGA, eAxle, thermal management, regeneration boost, solar charging system*

1. Introduction

Battery electric vehicles (BEVs) are attracting increasing attention amid worsening global warming and growing calls for reductions in CO_2 emissions. Although BEV sales have previously shown slight growth in some regions in reaction to favorable regulations and financial incentives, the last few years have seen major changes in the market, enough to suggest that the era of BEVs has finally arrived both inside and outside Japan. Unlike the BEV booms of the past, the market today seems poised on the verge of a period of full-scale BEV popularization.

In response to these conditions, Toyota has developed its first dedicated BEV platform and used it to create the bZ4X. This article outlines the development objectives of the bZ4X and its main technologies.

2. Development Aims

2.1 Meaning of bZ

The name of the bZ4X has the following significance. “bZ” stands for “beyond zero,” representing Toyota’s aim to create and provide greater value beyond minimizing the negative impacts of vehicles. “4” represents the size of the vehicle, and “X” indicates the vehicle type (i.e., a sport utility vehicle (SUV)).

The vehicles that Toyota plans to develop using the BEV platform are called the bZ series, and share the following common values.

*1 ZEV B&D Lab., Toyota ZEV Factory
*2 Vision Design Div., Vehicle Development Center
*3 Electric Powertrain Development Management Div., Powertrain Company
*4 E/E Architecture Development Div., Vehicle Development Center

2.2 The four values of the bZ series

Toyota has established the following four people-centric values for the bZ series.

2.2.1 You and Others

In addition to a comfortable cabin, the bZ series offers new lifestyles and the opportunity to spend precious time with family and friends.

2.2.2 You and Your Car

The bZ series delivers the unique joy of driving that can only be provided by a BEV and the excitement of anticipated possibilities.

2.2.3 You and the Environment

The bZ series will contribute positively to the environment in addition to helping to reduce the negative impacts of vehicles, such as CO_2 and other emissions.

2.2.4 You and Society

The bZ series creates an even safer society where everyone can enjoy greater peace of mind.

2.3 Vehicle concept

With the bZ4X, Toyota wanted to create a vehicle that customers would choose based on the value it provides, not because of the novelty of a BEV. The bZ4X was designed with the aim of creating not just a simple means of transportation, but an exciting car in which all passengers can share an enjoyable time and space. Reflecting these objectives, “Activity Hub” was set as the development concept of the bZ4X.

3. Design

In the coming era, it will be necessary to widely and flexibly meet the diversifying needs of users. Instead of product-first development determined based on the convenience of the manufacturer, this era demands user-oriented ideas focused on the requirements of people's actual lifestyles. For styling, the first step in the development of the bZ series was to freely create ideas for user experiences. Next, experimental interior and exterior design studies were carried out to verify whether these experiences could be realized using the BEV platform. Since it was necessary to sketch a wide range of future user lifestyles to create such experience-based values, a global team was formed (a BEV taskforce comprising members from all Toyota's satellite design centers, including those outside Japan), and several concepts were created that reflected those values. Departing from the restrictions of conventional models, people-centric user-based concepts that bring changes to interior spaces and shape unique exterior silhouettes were created. Using concept models created through this process, the design team studied the direction for the interior and exterior design of the bZ series, and demonstrated just how far the BEV platform could be expanded (these concept models included the six in the EV lineup announced in June 2019 (**Fig. 1**)).

Fig. 1 Design Studies Using the BEV Platform

The bZ4X is the first model in the bZ series and its development commenced based on one of these concept models.

As mentioned above, the vehicle concept was "Activity Hub."

Rather than seeing the vehicle as a simple means of transportation, the development team wanted to realize a design capable of achieving value proposition through its capability to bring friends and companions together, and act as a central hub for journeys through the city and suburbs.

3.1 Exterior design

The exterior design aims to project an image combining novelty that stands out in the big city and SUV-like toughness capable of taking on the great outdoors.

Based on a concept model fabricated at a European design studio (**Fig. 2**), the vehicle aims to realize an advanced and emotional feel ideal for a dedicated EV.

Fig. 2 Sketches and Full-Size Model Created at European Design Studio

(1) From the side, the vehicle creates an advanced impression through a sleek silhouette that projects the feeling of a low center of gravity to evoke the typical smooth and sporty performance of an EV. The front and rear fenders combine large moldings that emphasize the power of an SUV (**Fig. 3**).

Fig. 3 Side View Expressing both Sleekness and Power

(2) For the front, the designers took on the challenge of creating a unique BEV face to distinguish it from a conventional vehicle. The front expresses the identity of the vehicle through the following three elements.
   1) Hammerhead design theme: the sharp three-dimensional shape that runs from the low hood to the headlamps emphasizes the width of the tip of the nose and appears to push the vehicle forward, creating a unique and iconic design

(**Fig. 4**).
The hammerhead design combines with the headlamps to create a vigorous expression of piercing eyes (**Fig. 4**).

2) Emphasized corner portions: since a BEV does not need a grille, the bZ series takes advantage of this feature to simplify the styling of the center of the vehicle face. With attention drawn away from the center, the corners form new eye-catching consolidations of functional parts such as fender moldings, headlamps, sensors, aerodynamic air curtains, and the like.

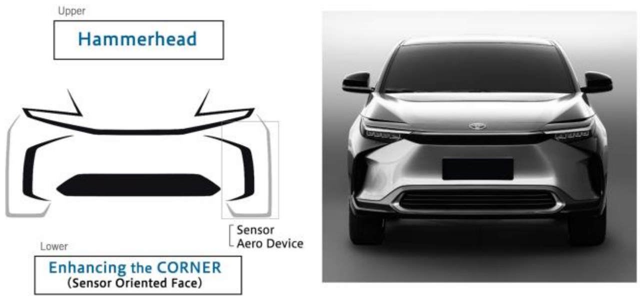


Fig. 4 Front Identity of the bZ Series

3) Symbolism of battery module: the front features a thin lower grille to represent the underfloor battery module and express the nature of the vehicle as an EV.

(3) At the rear end of the cabin, the tail lamps form a horizontal single-character line. Combined with component parts arranged in a trapezoidal motif, this emphasizes the wide and firmly planted stance of the vehicle rear.

(4) The qualities of the surfaces and lines over the whole body were designed under a theme called "Hi-tech & Warmth," which aims to express the beauty of advanced technology combined with the warmth that comes from a human's hands (**Fig. 5**).

Fig. 5 Expression of Textures Combining an Advanced Technological Feeling and Human Warmth

(5) The wheels unobtrusively emphasize size, while projecting novelty through a contrast between machine finishing and black paint, and resin accents (**Fig. 6**).

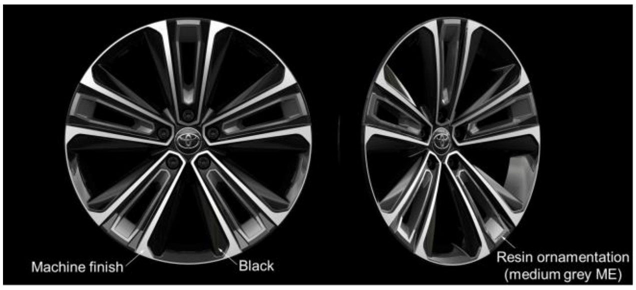


Fig. 6 20-Inch Wheels Designed to Project an Advanced Impression (Machine Finishing and Black Gloss Paint + Resin Ornamentation)

(6) The color chosen to symbolize the bZ series is called Precious Metal. The metallic impression created by this color helps to create a distinctive surface texture that imbues the futuristic nature of the bZ series with warmth (**Fig. 7**).

Fig. 7 Precious Metal: Symbolic Color of the bZ Series

3.2 Interior design

The aim of the interior is to create a comfortable space in which anyone can share the enjoyment of traveling while enabling their loved ones to relax. The resulting interior makes full use of the packaging that only a BEV can provide.

(1) Thanks to the long wheelbase enabled by the BEV platform, the rear seats have the foot room of a luxury sedan. Every seat feels roomy and open under the concept of "equivalent value for all seats" to enable the occupants to relax comfortably (**Fig. 8**).

Fig. 8 Open and Relaxing "Equivalent Value for All Seats" Interior Concept

(2) The sense of openness is further emphasized by the thin instrument panel set low down in the interior space that expands toward the front and rear. The dashboard is wrapped in a soft-looking tactile fabric, which projects a comfortable home-like appearance (**Fig. 9**).

Fig. 9 Interior Image Sketch and Fabric Material

(3) The ease of accessibility to digital devices is of fundamental interest to many people. The center console is positioned to function as a shared table accessible by anyone from any seat as an information station. It consolidates a multimedia display, a wireless charging spot for smart phones, and USB ports. This console has an iconic appearance designed to resemble a single plate surface (**Fig. 10**).

Fig. 10 Function-Consolidating Center Console

(4) The intuitively user-friendly cockpit advances the concept by which items that must be looked at are positioned further away from the driver, and items that must be operated are positioned closer at hand. This layout is designed to make it even easier to concentrate on driving. Top mounted meters that are visible above the steering wheel were adopted to minimize eye movement. The switches are positioned close to the driver to enable rapid operation even while driving (**Fig. 11**).

Fig. 11 Functional Driver-Focused Layout

(5) Driving controls such as the steering wheel, steering column, and meters are grouped together in a driver's module. These modularized driving controls are integrated along wing-shaped arms to lead the line of sight from the hands to the meters. The angle of the meter visor is also aligned to the driving lane to help the driver obtain a more intuitive understanding of the position of the vehicle on the road. This measure aims to create a new fun-to-drive experience in which the driver can obtain information from the road and the vehicle at the same time. **Fig. 12** shows a model equipped with the "one-motion grip" system that combines the steer-by-wire system with a uniquely shaped steering wheel.

Fig. 12 Model Equipped with Steer-by-Wire System and Uniquely Shaped Steering Wheel

The bZ4X will be launched in markets around the world with the hope that it will encourage small positive changes as a hub for the daily life of its users and deepen the ties between loved ones.

4. BEV Platform

4.1 Development concept

The e-TNGA platform is a newly developed dedicated platform for BEVs created based on the Toyota New Global Architecture (TNGA) design architecture. The plan was created featuring a product group with multiple variations. Each structural component was defined as either fixed or flexible. Aspects of the platform such as the layout of the front and rear motors, and the position of the driver with respect to the front wheels, and the battery width are fixed. In contrast, the wheelbase, battery capacity, front and rear overhangs, and other aspects can all be changed in accordance with the product requirements (**Fig. 13**).

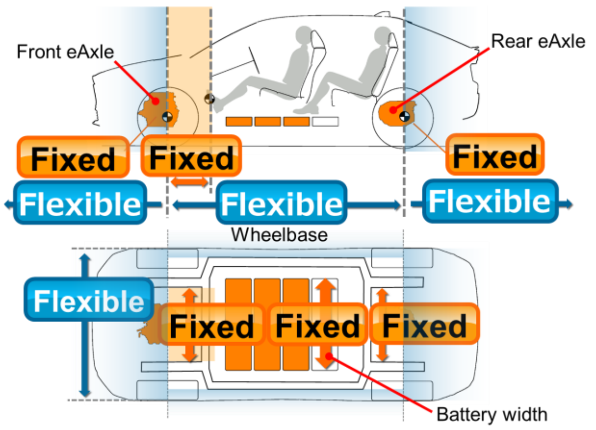


Fig. 13 Approach for Fixed and Flexible Platform Components

This platform was jointly developed with Subaru Corporation and combines the strengths of both companies to create new value. The assets of the TNGA are paired with the strengths of Subaru, such as Subaru's passive safety and all-wheel drive (AWD) technologies, resulting in a wholly new type of BEV.

4.2 Main electric components

The following major components were newly developed for the e-TNGA platform (**Fig. 14**).

- A high-capacity flat battery pack placed under the floor
- The eAxle, which integrates a motor, transaxle, and inverter (a first for Toyota)
- An electricity supply unit (ESU) that consolidates the charging and power distribution functions (a first for Toyota)

A highly rigid body structure with a low center of gravity was achieved by placing the battery pack under the floor. This realizes the fun-to-drive performance and excitement that people expect of a BEV. In addition, combining front and rear motors helps to deliver standout driving performance by enabling flexible drive systems and dynamic characteristics suitable for each vehicle in the product group.

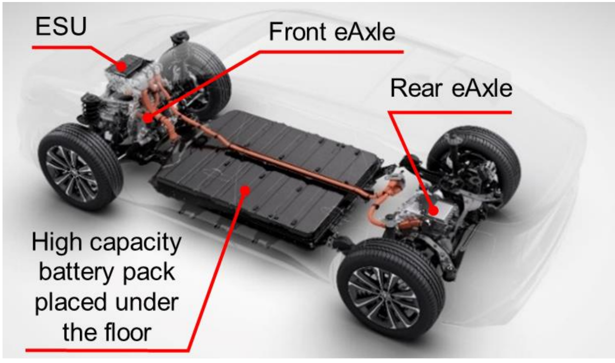


Fig. 14 Major Components of the e-TNGA Platform

4.3 Body, suspension, and motor mounting system

4.3.1 Omni-directional collision-response body structure designed to protect occupants and high-voltage components

The e-TNGA body structure is designed to protect occupants, high-voltage components, and pedestrians in the event of a collision (**Fig. 15**).

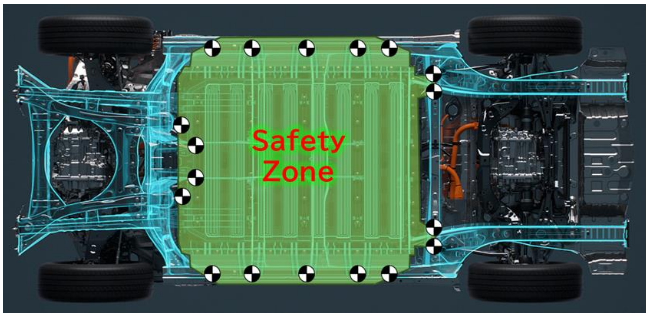


Fig. 15 Omni-Directional Collision-Response Body Structure

A highly rigid body is realized by installing the battery pack under the floor and connecting it to the robust surrounding frame structure.

4.3.2 Suspension and motor mounting system

The suspension developed for the TNGA was further refined for BEVs. Based on a concept assuming that the bZ series will be used by a wide range of people, the development focused on comfort and natural driving performance in everyday use.

Although BEVs tend to be heavier than conventional vehicles in the same category due to the need for a high-capacity battery pack, the quality of dynamic performance was enhanced by realizing a low center of gravity and low inertia moment, and by optimizing the front and rear compliance steering characteristics.

In addition, ride comfort was enhanced by incorporating the battery pack into the body frame to increase body rigidity and arranging the resonant frequencies of the newly developed eAxles and mounting system.

Since the brake system helps to improve the power consumption efficiency and cruising range of a BEV, a new AHB-G brake system was adopted that realizes cooperative hydraulic and regenerative braking over two channels at the front and rear. The balance between braking effectiveness and stiffness was optimized to realize easy-to-control braking performance.

The eAxles are designed to instantly produce high torque from low speeds. The motor mounting system minimizes displacement of the eAxles and maintains stability (**Figs. 16** and **17**).

To realize excellent driveability, the development ensured that the driver does not feel uncomfortable vibration due to motor torque fluctuations caused by accelerator operation. These measures help to ensure low noise, ride comfort, stability, and driveability.

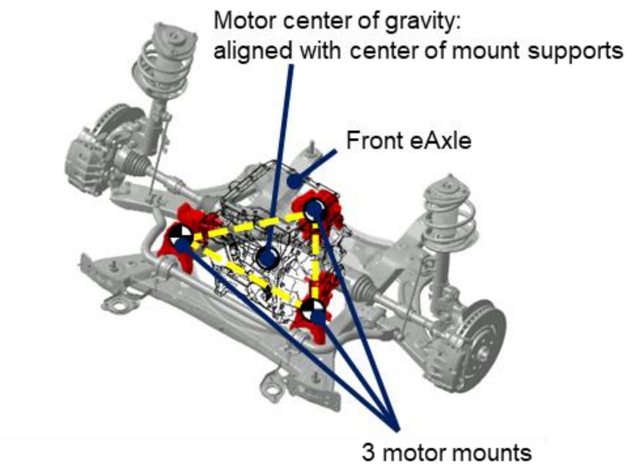


Fig. 16 Front Suspension and Motor Mounting System

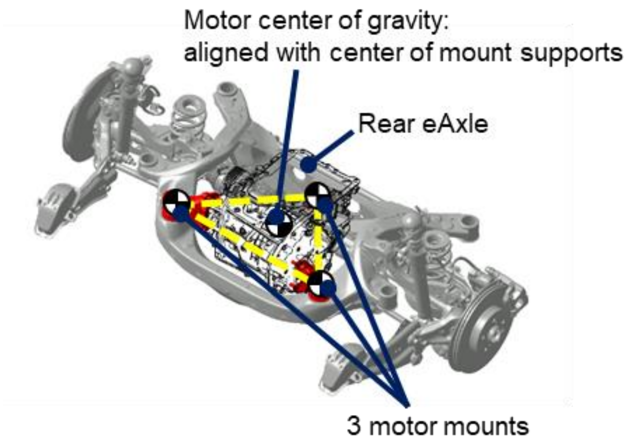


Fig. 17 Rear Suspension and Motor Mounting System

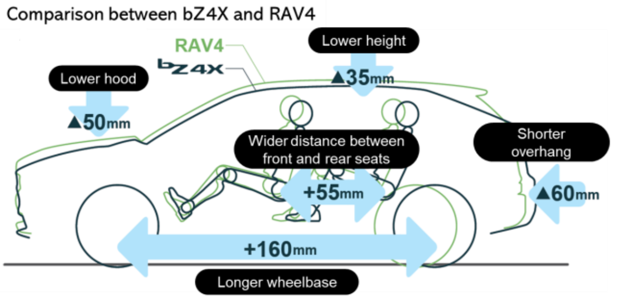
5. Body Design

5.1 Packaging

The body of the bZ4X realizes the following characteristics thanks to its distinctive packaging based on the BEV platform.

- Distinctive styling with large tires placed at the four corners, in addition to the low center of gravity and sleek silhouette.
- Comfortable and roomy interior space due to the long wheelbase.

More specifically, the wheelbase is 160 mm longer, the distance between the front and rear seats 55 mm wider, the rear overhang 65 mm shorter, the height 60 mm lower, and the hood 50 mm lower than the similar RAV4 (**Fig. 18**).



Vehicle dimensions	bZ4X	RAV4 *1	(Difference)
Length	**4,690**	4,600	+90
Height	**1,650**	1,685	-35
Width	**1,860**	1,855	+5
Wheelbase	**2,850**	2,690	+160
Front overhang*2	**915**	925	-10
Rear overhang*2	**925**	985	-60

Interior cabin dimensions	bZ4X	RAV4 *1	(Difference)
Front seat heel step*2	**275**	330	-55
Rear seat heel step*2	**290**	322	-32
Couple distance*2	**750**	750	±0
Tandem distance (between front and rear seats)*2	**1,000**	945	+55
Head clearance*3	**45**	43	+2

(mm)

*1 G and X grades.
*2 As measured by Toyota.
*3 Model with normal roof specifications, as measured by Toyota

Fig. 18 Packaging Comparison

Although the longer wheelbase is useful for creating a comfortable and roomy interior by enabling a wider distance between the front and rear seats, maintaining the same front wheel angle will increase the minimum turning radius and have a negative impact on handling. For this reason, the front wheel angle of the bZ4X is approximately 2 degrees larger than the RAV4 to maintain the same minimum turning radius as the RAV4 with a longer wheelbase. This larger front wheel angle was realized due to the characteristics of the BEV platform, which eliminates various large engine components and shifts the front body frame toward the inside of the vehicle (**Fig. 19**).

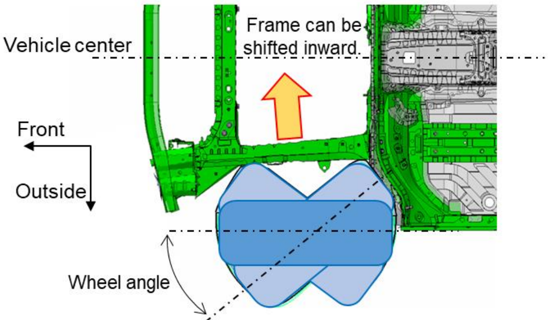


Fig. 19 Front Body Frame and Front Wheel Angle

The lower vehicle height helps to realize a lower center of gravity, sleek silhouette, and improved aerodynamic performance, which has the effect of extending cruising range. However, the lower height is disadvantageous for creating a comfortable and roomy interior because the lower roof reduces the clearance between the heads of the occupants and the headliner. In response, a thinner roof was developed for the bZ4X by revising the structure of the panorama roof, and the head positions of the occupants were lowered by changing the occupant sitting posture. As a result, although the height of the bZ4X is 60 mm lower than the RAV4, the head clearance is only 15 mm less.

In general terms, a lower head position restricts the forward field of vision. Therefore, since the eye point of the bZ4X is 36.5 mm lower than the RAV4, the distance of distinct vision (i.e., the blind spot in front of the vehicle) was reduced by lowering the hood by 50 mm. As a result, the field of vision of the bZ4X is 0.7 m wider than the RAV4 (**Fig. 20**).

Reducing the height of the hood helps to lower the center of gravity, realize a sleek silhouette, and improve the field of vision. These advantages are only possible using the BEV platform that does not have to incorporate large engine components under the hood.

	Distance of distinct vision
bZ4X	7.7 m (-0.7 m compared to RAV4)
RAV4	8.4 m

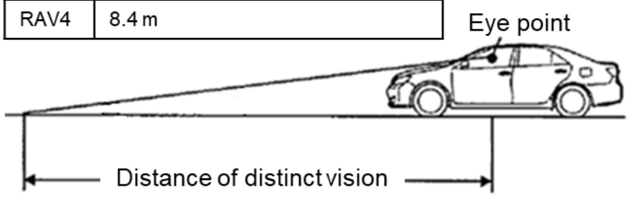


Fig. 20 Distance of Distinct Vision

The short rear overhang helps to realize the distinctive style of the bZ4X by pushing the tires out to the four corners. This feature was realized while protecting collision performance by, for example, adopting high-strength materials such as hot stamped steel in the rear floor frame. In the event of a rear collision, these materials restrict deformation within a short stroke, protecting the high-voltage components.

5.2 Top mounted meters

A new cockpit was adopted that creates a closer connection between the driver and vehicle by helping the driver to immediately identify the driving conditions just by looking straight ahead.

The layout was changed so that the meters are visible through the upper portion of the steering wheel. This was realized by positioning the meters higher and further away than in a conventional vehicle. This reduces the amount of eye movement required by the driver to look between the front of the vehicle and the meters while driving (**Fig. 21**).

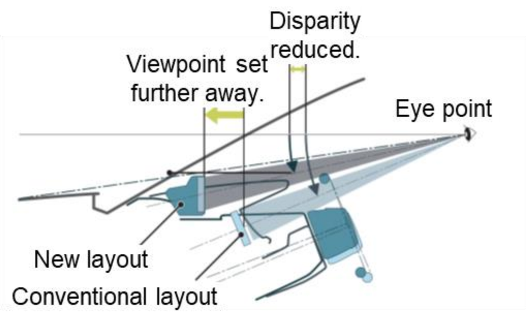


Fig. 21 Meter Layout Comparison

In addition, a wing-shaped layout that guides the driver's vision from the hands to the meters was adopted to create a cockpit with a futuristic feel. The edges of the wings on either side are closely aligned with the driving lane as a measure to make driving easier (**Figs. 22** and **23**).

Fig. 22 Wing-Shaped Layout

Fig. 23 Alignment with Driving Lane

Creating a good balance between the following two objectives is an issue when the meters are moved upward and further away.

- Ensuring the forward field of vision
- Ensuring the visible meter area

The forward field of vision was secured by eliminating the meter hood and adopting a thinner bezel around the edges to reduce the meter height and enable the meters to be located as low as possible (**Fig. 24**).

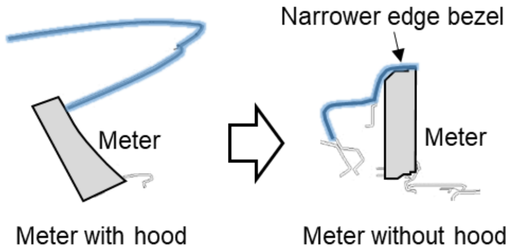


Fig. 24 Meter Geometry

The visible meter area was secured by concentrating the information necessary for driving in the upper part of the screen around the ring. As a result, this information is not blocked by the steering wheel (**Fig. 25**).

Fig. 25 Visible Meter Area

Although it was decided to adopt hoodless meters to widen the forward field of vision and create a futuristic design, issues such as sunlight shining on the meters (glare) and the reflection of the meters in the windshield needed to be addressed. Anti-reflection (AR) and anti-glare (AG) measures were implemented to prevent sunlight shining on the meters and windshield reflection was prevented by adopting a light-control film and increasing the brightness range.

5.3 Thin instrument panel

To help realize a more comfortable cabin for users, the top surface of the instrument panel was lowered and foot room expanded to create a more open and pleasant interior space.

The top surface of the instrument panel is lower and the foot room of the front passenger seat is larger than the similar RAV4 (**Figs. 26** and **27**).

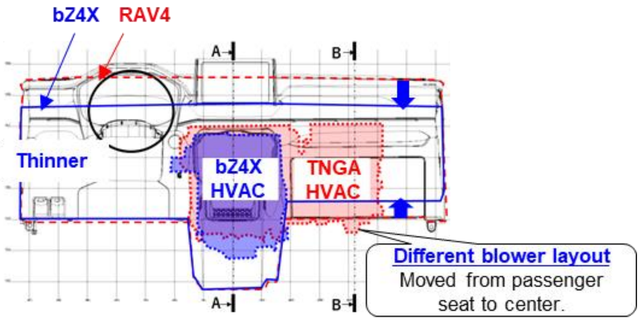


Fig. 26 Rear View Comparison

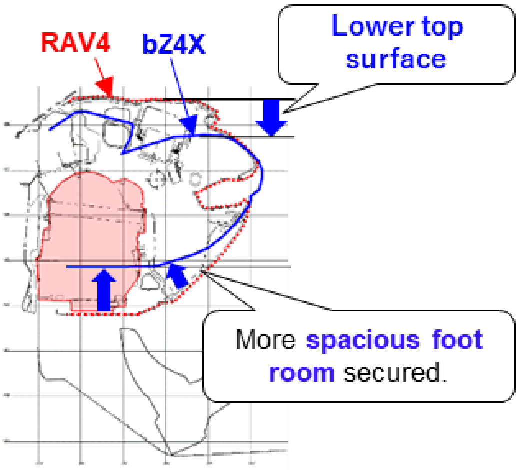


Fig. 27 Cross-Section of Passenger Seat (B-B)

A conventional instrument panel contains a large number of structural parts, including the heating, ventilation, and air-conditioning (HVAC) system, ducts, and reinforcing members. To realize these structural parts with a thinner instrument panel, it was necessary to completely revise the conventional structure, internal device layout, and duct routing.

Therefore, to increase the space available in the interior, a newly developed HVAC system was adopted that is 30% smaller than the TNGA system with the same output. The size of the HVAC system was reduced by moving the blowers from the passenger seat side to the center of the instrument panel, replacing the blow type mechanism with a suction type mechanism, and adopting a more efficient turbo fan (**Fig. 28**). These measures also reduced the power consumption of the HVAC system by 30%.

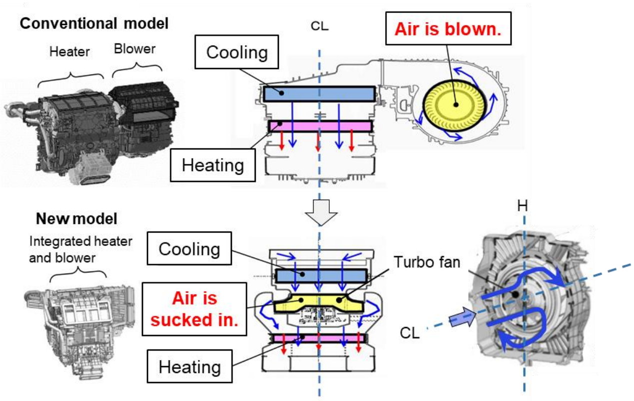


Fig. 28 HVAC System Layout Comparison

In addition, the outlet to the register at the top of the HVAC system in the RAV4 was replaced by a rear outlet. This allowed the top surface of the instrument panel to be lowered (**Fig. 29**).

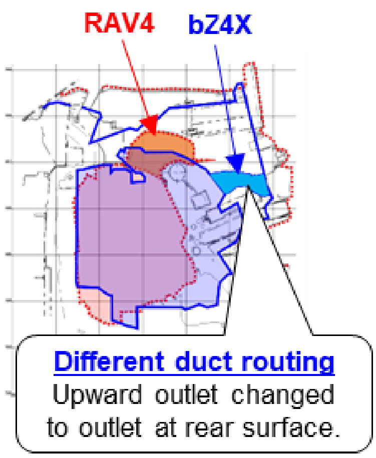


Fig. 29 Center Cross-Section (A-A)

The duct routings from the HVAC system to the driver and passenger seat registers were also revised. Conventionally, these routings pass over the instrument panel reinforcement. However, the positions of this reinforcement and the airbag were revised so that the routing to the driver's seat register passes to the rear of the reinforcement and the routing to the passenger's seat passes to the rear and below the register. As a result, the register routings no longer pass above the reinforcement and the height of the instrument panel top surface could be lowered (**Fig. 30**).

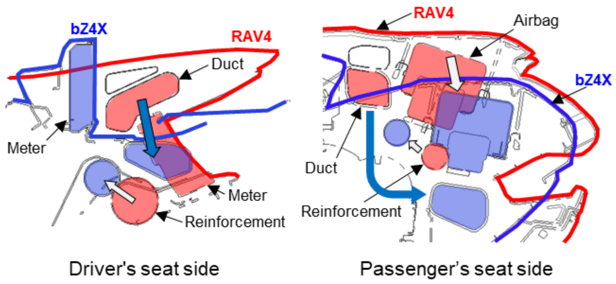


Fig. 30 Duct Routing Comparison

6. Powertrain

6.1 eAxles

6.1.1 Aims and outline of eAxle development

Compact and lightweight integrated eAxles were developed to realize a longer cruising distance and a more spacious interior (**Fig. 31** and **Table 1**).

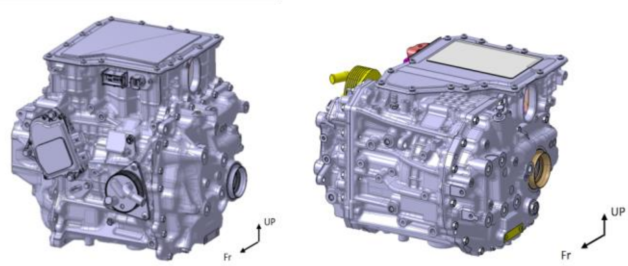


Fig. 31 eAxles (Left: Front eAxle, Right: Rear eAxle)

Table 1 Main eAxle Specifications

		Front eAxle		Rear eAxle
Maximum motor output	(kW)	150	80	80
Maximum motor torque	(Nm)	266.3	168.5	168.5
Transaxle type		3-axis 2-stage deceleration type		
Total gear ratio		13.786		

The following power consumption efficiency improvements were adopted based on the environmentally friendly and power-saving technologies developed through Toyota's experience with hybrid electric vehicles (HEVs).

- Low-viscosity e-transaxle fluid (TE) (**Fig. 32**)
- Twin cooling routes for the highly efficient stator using an electrical oil pump and oil cooler
- Newly developed low-loss inverter devices

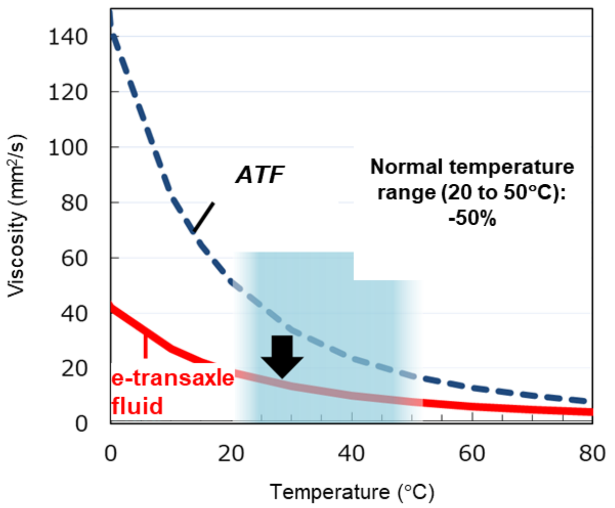


Fig. 32 Comparison of Transaxle Fluid and Automatic Transmission Fluid (ATF) Viscosity

A compact structure was adopted that completely incorporates the motor, transaxle, and inverter, reducing the eAxle size. The length of the front eAxle was shortened to help expand the interior space (by widening the tandem distance) and the height of the rear eAxle was lowered to help create a larger cargo space (**Fig. 33**).

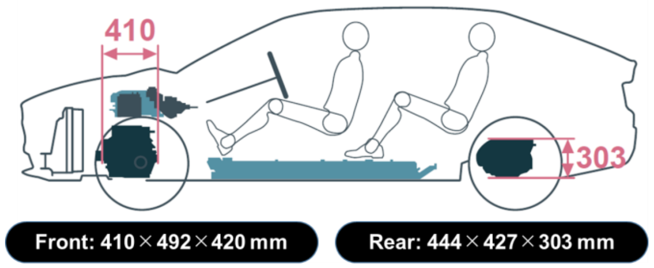


Fig. 33 eAxle Installation Layout

A pre-loaded differential was adopted in addition to equal-length left and right drive shafts to ensure excellent straight-line stability.

6.2 ESU

6.2.1 Aims and outline of ESU development

A compact ESU was adopted with an integrated structure capable of carrying out the power conversion, charging, and power distribution functions in a single unit. The high-voltage wiring branch function, devices such as the DC relay, and electromagnetic compatibility (EMC) measures such as ferrite components, which are usually included inside the battery pack of conventional BEVs, were all integrated into the ESU and installed in the motor compartment. This allowed a higher capacity battery pack to be mounted under the floor to increase cruising range and simplified the structure of the battery pack to help realize a flat floor. The ESU is compatible with DC charging stations up to a maximum of 150 kW and AC charging up to a maximum of 7 kW, which helps to shorten charging times.

6.2.2 Main ESU specifications and component parts

Table 2 lists the main specifications of the ESU and **Fig. 34** shows its component parts. As shown in the figure, the ESU is divided into upper and lower structures.

Table 2 Main ECU Specifications

Market		China	North America	Europe	Japan
Charging standard		GB/T	CCS1	CCS2	CHAdeMO
DC fast charging		Compatible with 150 kW charging stations			
AC charging	Rated input	7 kW			
Main DC-DC	Output current	150 A			
Sub DC-DC	Power	150 W			
High-voltage branching connections		High-voltage battery pack, front eAxle, Rear eAxle, DC and AC charging port lids, and auxiliary functions (electric air conditioning, water heater, AC 1,500 W inverter)			

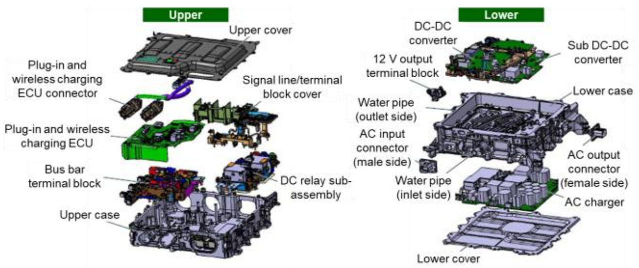


Fig. 34 Component Parts of ESU

7. Battery Pack

7.1 Aims of Battery Pack Development

With BEVs beginning to gain popularity around the world, a battery pack was developed that realizes appealing cruising range while ensuring safety and peace of mind.

7.2 Characteristics

7.2.1 Battery type

Table 3 and **Fig. 35** describe the specifications and components of the battery pack. Newly developed high-capacity lithium-ion battery cells were adopted to realize a long cruising range and high power.

Table 3 Main Specifications

Battery type	Lithium-ion
Number of battery cells	96
Rated voltage	355.2 V
Battery capacity	201 Ah
Total battery power	71.4 kWh
Operating temperature range	-30 to 60°C

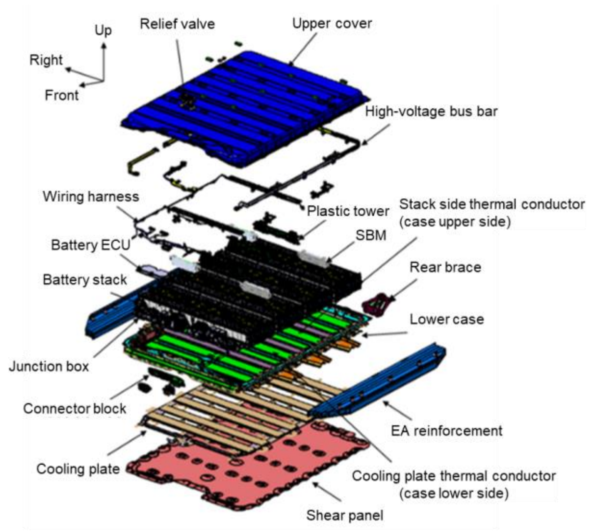


Fig. 35 Battery Pack Components

7.2.2 Mounting structure

A spacious interior was realized by lowering the height of the flat high-capacity battery pack and mounting it under the floor. The flat floor around the feet of the second row seats is a particular feature of the vehicle. This layout also helps to enhance dynamic performance by lowering the vehicle center of gravity (**Fig. 36**).

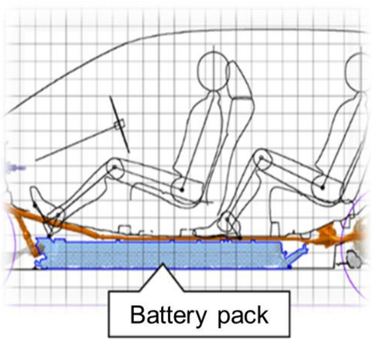


Fig. 36 Location of Battery Pack

7.3 Safety

A safe battery design was adopted that incorporates measures to help prevent self-heating and short circuits and to realize an excellent level of safety and peace of mind.

7.3.1 Cooling structure

A separate cooling structure was adopted as a measure to help prevent coolant leakages coming into contact with the battery. However, a highly resistive specialized coolant was adopted in the event that contact occurs (**Fig. 37**).

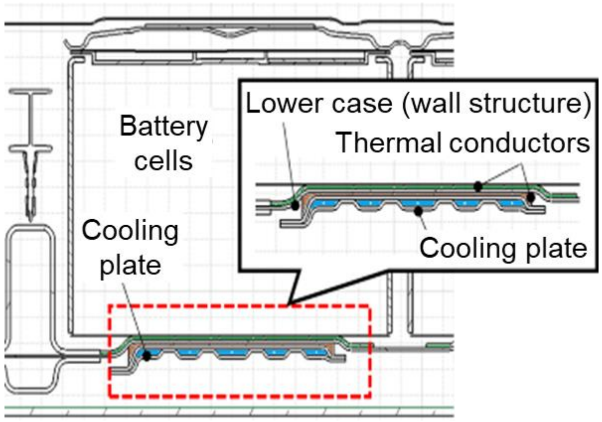


Fig. 37 Cooling Plate Structure

7.3.2 Protection from external inputs

The case structure was designed to avoid battery damage due to external inputs. Internal cross members, front and rear frames, and EA reinforcements were adopted to help protect the battery against collisions and maintain its mechanical integrity. A shear panel (aluminum bottom plate) was adopted to help protect the battery against road surface contact (**Fig. 38**).

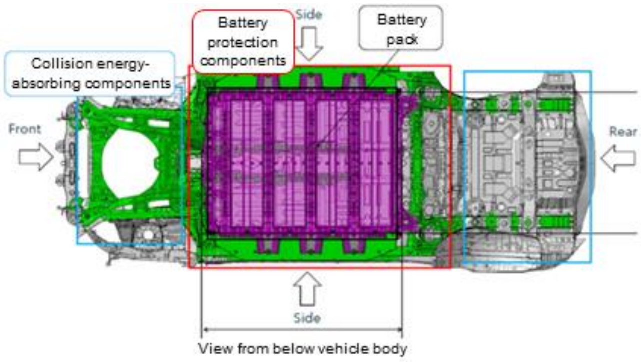


Fig. 38 Protective Structures against External Inputs

7.4 Battery lifetime

Using the technologies obtained from the development of HEVs, battery deterioration was minimized by adopting various approaches involving the materials, pack structure, control systems, and the like. The development targeted world-leading battery capacity retention after 10 years (**Fig. 39**).

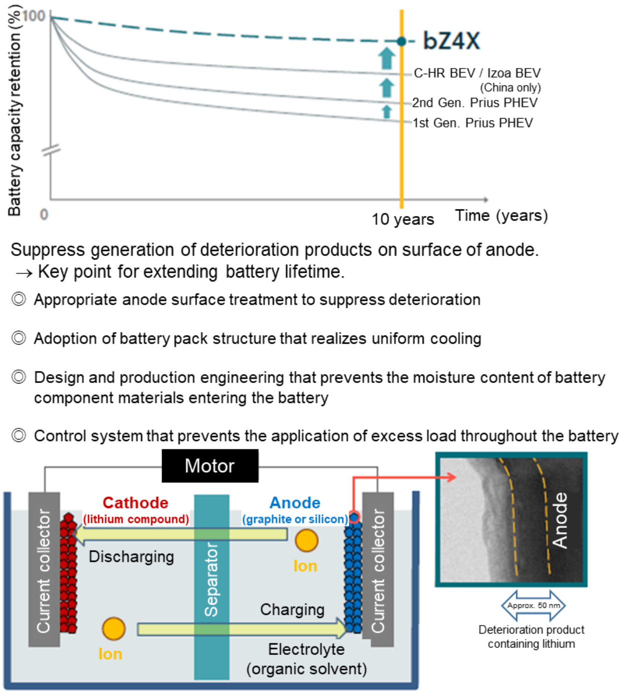


Fig. 39 Development to Enhance Battery Capacity Retention

8. Thermal Management System

8.1 System concepts

Issues of BEVs include the shortening of battery lifetime due to high-temperature operation, and cruising range deterioration in cold weather. An innovative thermal management system was developed to help address these two issues. More specifically, the following technologies were adopted: (1) optimum heat control technology connected to the heat circuit of the HVAC system (**Fig. 40**) and (2) effective heating and cooling technology for the occupants. Technology (1) increased the heating efficiency of the heat pump by adopting a simple refrigeration cycle while maintaining the optimum battery temperature.* Technology (2) was realized by radiant heaters that efficiently heat the legs of the occupants* and a new technology called ALL AUTO (ECO) for the air conditioning environment of the occupant compartment.

* A first for Toyota

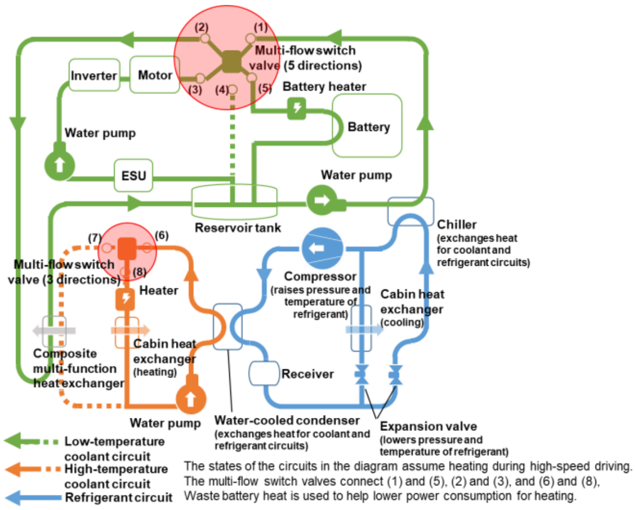


Fig. 40 Heat Control Technology

8.2 Battery temperature adjustment

8.2.1 Outline

A cooling method capable of efficient temperature adjustment was adopted. This method maximizes the battery power while suppressing decreases in battery capacity. **Fig. 41** shows the circuit states and refrigerant flows during battery cooling. The temperature of the battery is lowered using coolant, which has been cooled to below the ambient temperature via a chiller that utilizes air conditioning refrigerant.

Fig. 42 shows the circuit states and refrigerant flow during battery warming. The temperature of the battery is raised by a battery heater incorporated into the battery coolant circuit.

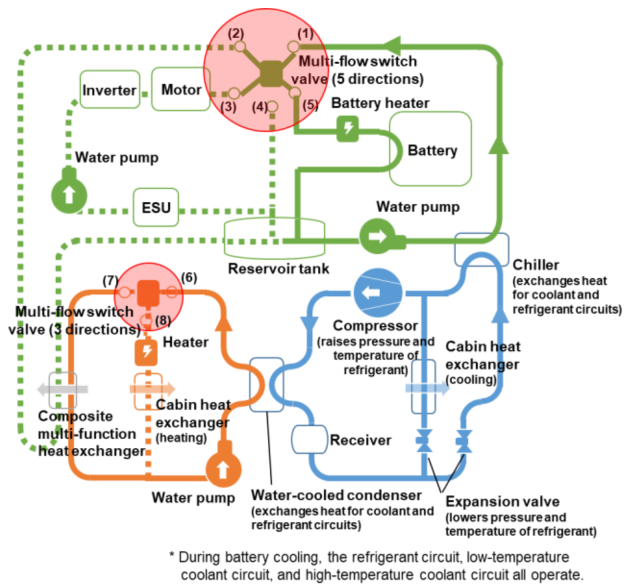


Fig. 41 Circuit States and Refrigerant Flows during Battery Cooling

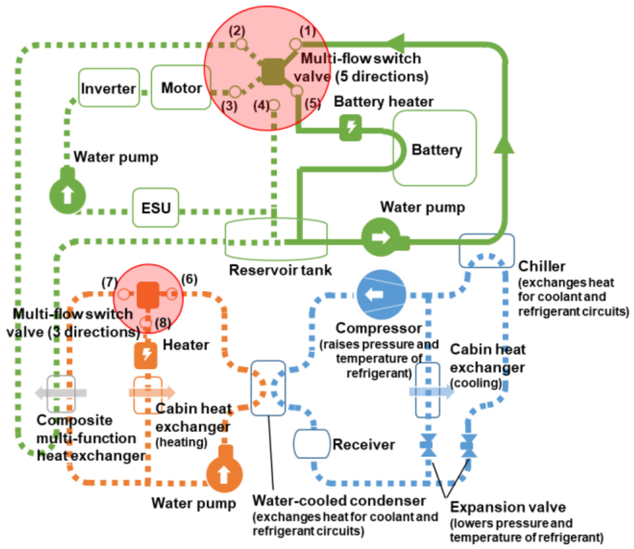


Fig. 42 Circuit States and Refrigerant Flows during Battery Warming

8.2.2 Variable performance cooling

A control that varies the cooling performance was adopted to vary the amount of battery cooling in accordance with the generated heat. The amount of heat generated by the battery is calculated from the input and output power values, and the level of cooling is adjusted accordingly. **Fig. 43** shows an outline of this control.

The control has the following three advantages.

- It reduces the operating load of cooling components when the vehicle is being driven under low loads and increases lifetime.
- It raises power consumption efficiency by reducing power consumption when the vehicle is being driven under low loads.
- It enables stronger cooling performance when the vehicle is being driven under high loads, thereby helping to prevent battery temperature rise and suppressing battery capacity deterioration

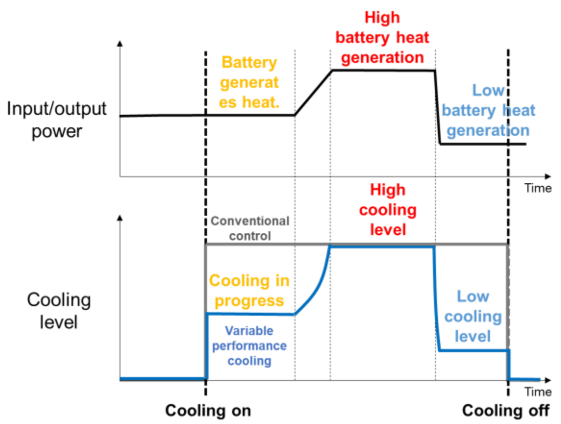


Fig. 43 Outline of Variable Performance Cooling

8.2.3 Cooperative control with air conditioning

A cooperative control that coordinates the air-conditioning and cooling systems was constructed. **Fig. 44** shows an outline of the coordination between these systems. The cooling level is increased in accordance with the battery temperature. At a high level, battery cooling is prioritized. At a low level, the air conditioning is prioritized. This control ensures the optimum balance between the cooling performance of the battery and occupant compartment.

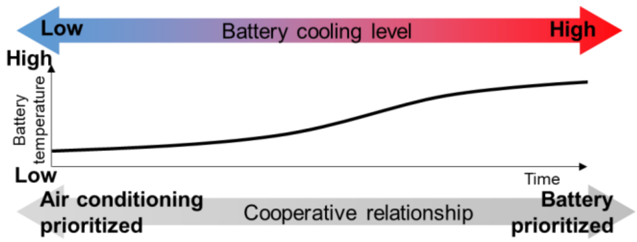


Fig. 44 Coordination with Air Conditioning

8.3 Highly efficient heat pump

Heating energy is saved by directing waste heat from the powertrain and battery to a heat pump.

Heat can be exchanged between the circuits using the chiller that cools the battery, the multi-flow switch valves, and the composite multi-function heat exchanger. A control instructs the multi-flow switch valve circuits to direct waste battery heat to the heat pump. However, if the heat pump is operated continuously, the amount of heat that is absorbed from the air decreases due to the frost generated on the composite multi-function heat exchanger, which acts as an external compressor unit. This has an adverse effect on heating efficiency. This issue was addressed by using the accumulated waste heat from the powertrain to melt the frost and extend the operation time of the heat pump, thereby substantially increasing heating efficiency.

8.4 Radiant heaters

People are more likely to feel warm when the area around the knees is heated. Therefore, as an efficient way of warming the occupants, radiant heaters that prioritize this area were adopted. These radiant heaters were designed to maximize instantaneous heating performance, and the heater surface temperature is raised to 100°C or higher within a minute of activation. In addition, the radiant heaters realize a warm space using the far-infrared radiation effect (**Fig. 45**). At the same time, safety was ensured using an in-built sensor that stops heat generation when contact with the human body is detected.

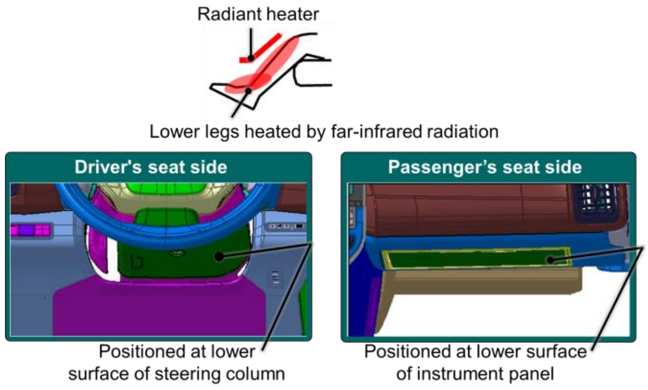


Fig. 45 Radiant Heaters

8.5 ALL AUTO (ECO) control

To extend the cruising range of the vehicle in cold temperatures while ensuring a comfortable occupant compartment, the ALL AUTO (ECO) integrated control technology was developed and applied to the air conditioning environment. This technology closely coordinates the operation of devices that perform direct temperature control (such as the seat heaters, steering wheel heater, and the like) with the air flows from the HVAC system.

In addition, an ALL AUTO (ECO) button was added to the air conditioning control panel. This button can be used to create a comfortable interior space for all users (**Fig. 46**).

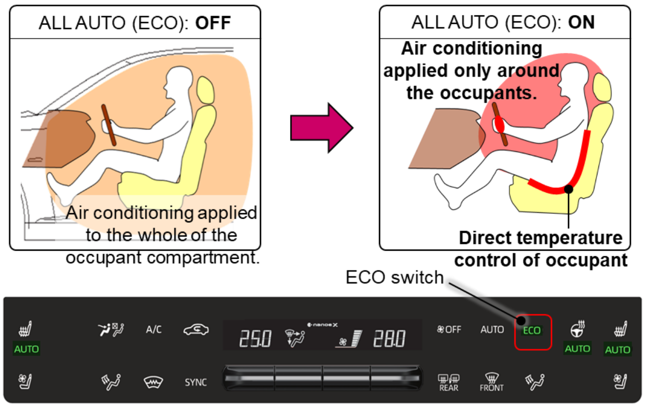


Fig. 46 ALL AUTO (ECO) Control

9. Dynamic Performance and Inertia Characteristics

9.1 Concept

Inertia characteristics are an important part of realizing linear vehicle response to steering inputs, anti-rollover performance and other aspects of vehicle stability, and excellent ride comfort. The development of the bZ4X aimed to design the inertia characteristics of the vehicle taking maximum advantage of the under-floor battery layout, which is one of the distinguishing features of the e-TNGA.

9.2 Inertia characteristics design

The basic concept for creating inertia characteristics capable of enhancing handling and stability is the application of uniform vertical loads to each of the four tires while driving. This requires the forces generated at the tires to be as uniform as possible. In the e-TNGA, the high-capacity battery pack was located under the floor at the center of the vehicle with the aim of creating uniform vertical loads at the tires. The inertia characteristics were then designed so that the center of gravity of the vehicle is located close to the driver's hips when viewed from the side and located at the vehicle center when viewed from the rear (**Fig. 47**). The positioning of the battery pack also helps the tires to be pushed out to the four corners of the vehicle. The battery pack lowers the height of the vehicle center of gravity, reduces the amount of load shift during driving, and stabilizes fluctuations in the vertical load at the four wheels.

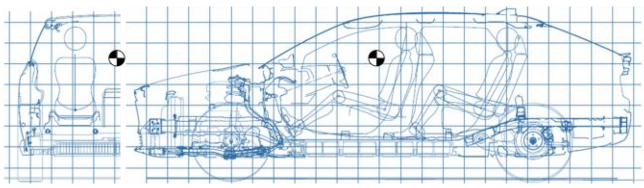


Fig. 47 Position of Vehicle Center of Gravity

9.3 Body rigidity

This development focused on the relationship between vehicle roll behavior and static torsional stiffness to create a natural roll sensation during cornering. The e-TNGA is designed to ensure that static torsional stiffness is higher than a certain level of roll stiffness, which is determined by the specifications of the coil springs and stabilizers. As shown in **Fig. 48**, the battery case is used to contribute to body rigidity. This gives the vehicle higher torsional stiffness than a vehicle equipped with an internal combustion engine (ICE) or an HEV, and ensures a rigidity ratio equivalent to competing models (**Fig. 49**).

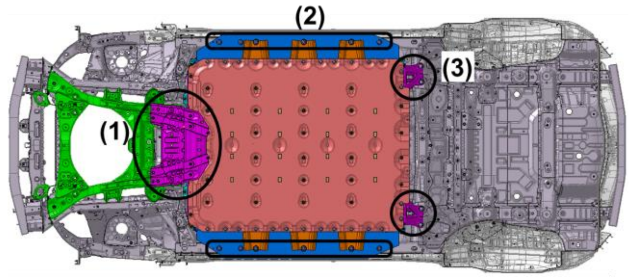


Fig. 48 Structural Elements Designed to Enhance Body Rigidity ((1) to (3))

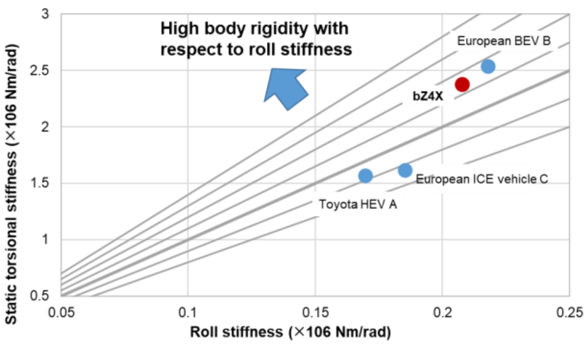


Fig. 49 Roll Stiffness and Static Torsional Stiffness

10. Regeneration Boost

10.1 Development concepts

To help provide the new values inherent in a BEV, regeneration boost control was newly developed for the bZ4X as a function that helps to ensure a fun-to-drive experience and reduces driver workload. This function regenerates energy to enhance longitudinal acceleration while the vehicle is coasting. A newly developed motor torque design technology was used to realize fun-to-drive BEV performance, while strong regenerative deceleration and creep functions were developed to reduce driver workload.

10.2 Strong regenerative deceleration function

The development aimed to reduce driver workload by decreasing the number of times that the driver has to move from the brake pedal to the accelerator pedal. The maximum longitudinal acceleration using regenerated energy during coasting was set to 1.5 m/s^2. This covers approximately 80% of the longitudinal acceleration in a speed range up to approximately 80 km/h in actual driving. Therefore, since the driver does not have to switch pedals in these acceleration ranges, the frequency of pedal operation can be reduced (**Fig. 50**).

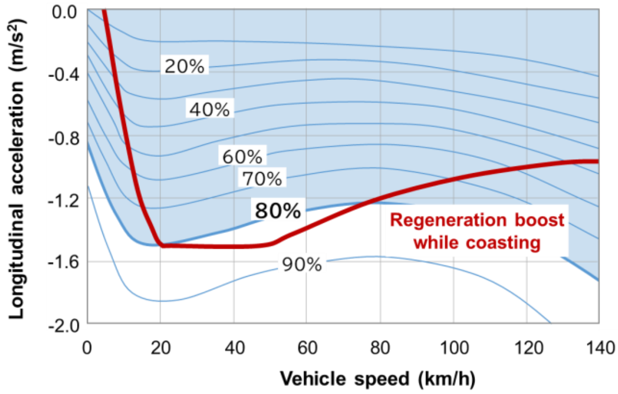


Fig. 50 Deceleration Frequency Distribution and Regeneration Boost Characteristics under Real World Driving Conditions

10.3 Creep function

The creep function was designed to maintain controllability when parking the vehicle. The change in acceleration from the strong regenerative deceleration function to the creep function was set to be gradual enough to allow simple controllability by giving the driver ample time to switch pedals immediately before the vehicle stops. The creeping speed was also set to be lower than in a conventional vehicle (**Fig. 51**).

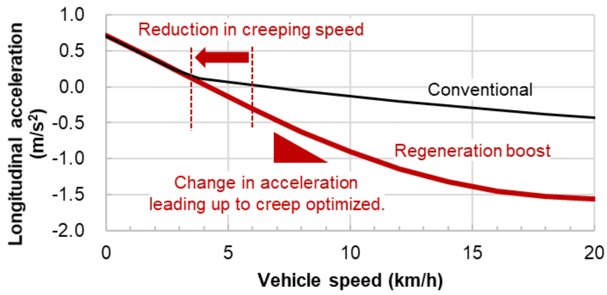


Fig. 51 Comparison of Conventional and Regeneration Boost Creep Functions

10.4 Motor torque design technology

To realize a fun-to-drive experience, the acceleration and deceleration feeling was formularized based on human perceptual characteristics. **Fig. 52** shows the motor torque design procedure.

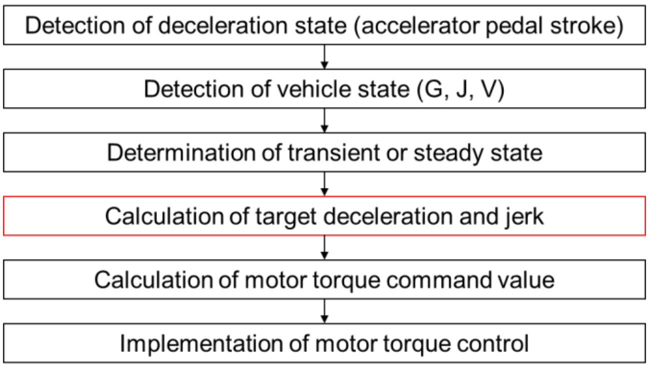


Fig. 52 Torque Design Procedure based on Human Perceptual Characteristics

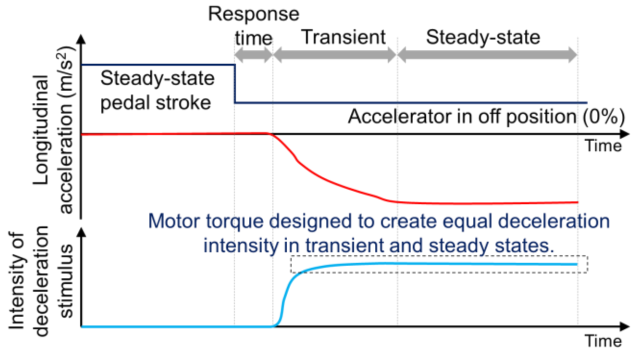


Fig. 54 Relationship between Transient and Steady-State Characteristics of Deceleration

The motor torque of the bZ4X was defined based on this torque design procedure to produce a linear acceleration and deceleration feeling in response to accelerator pedal operation (**Fig. 53**).

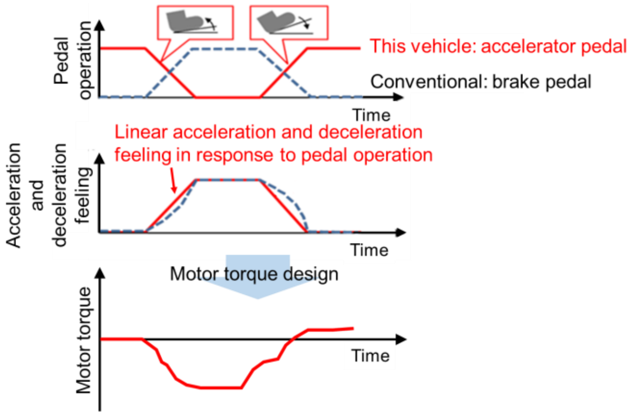


Fig. 53 Acceleration and Deceleration Feeling and Motor Torque in Response to Pedal Operation

However, there was the concern that the powerful deceleration feeling created by the new strong regenerative deceleration function might cause driver or passenger discomfort after a sudden operation. Therefore, under the concept of creating a seamless deceleration feeling even when the accelerator pedal is operated rapidly, discomfort was reduced by controlling transient motor torque to maintain an equal deceleration stimulus in both transient and steady states (**Fig. 54**).

11. Solar Charging System

11.1 Introduction

A solar charging system was developed for the bZ4X as part of global efforts to realize a sustainable society and Toyota's objective of achieving carbon neutrality by 2050.

11.2 System outline

The solar charging system of the bZ4X consists of a solar roof with two solar panels, and a solar ECU that controls the generated electricity. The solar DC/DC converter (DDC) in this ECU identifies the maximum power generated by the solar panels under maximum power point tracking (MPPT) control. Then, depending on the vehicle state, the boost DDC converts the voltage to the voltage of the EV supply battery, or the step-down DDC converts the voltage to 12 V and supplies it to the vehicle systems (**Fig. 55**).

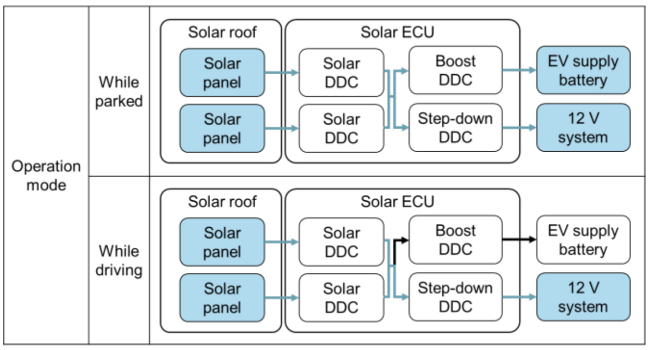


Fig. 55 System Operation in each Operation Mode

While the vehicle is parked, the EV supply battery can be charged to extend the cruising range or to supply electricity in an emergency. During driving, electricity can be supplied to the 12 V battery systems to reduce the power consumption of the EV supply battery, thereby also helping to extend cruising range.

The solar panels are able to generate power of approximately 224 kW/h per year (based on the sunload data in Nagoya, Japan, and calculated from the average daily data between 1990 and 2009 provided by the New Energy and Industrial Technology Development Organization (NEDO)). Under a power consumption efficiency of 7.81 km/kWh as defined by the Worldwide Harmonized Light Vehicles Test Cycle (WLTC), this amount of power generation corresponds to an annual distance of 1,750 km for the bZ4X.

11.3 Solar roof

The new bZ4X solar roof adopts back-contact solar cells to improve performance. The area filled by the solar cells was increased by adjusting the string length using half-cutting and shingling technology. (**Fig. 56**).

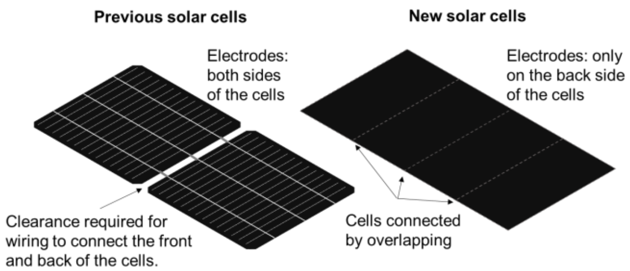


Fig. 56 Connection Method for Solar Cells

As a result, the specific power density of the bZ4X solar roof is 8.4% higher than that of the Prius PHEV (**Table 4**).

Table 4 Specific Power Density of Solar Roofs

Item	Prius PHEV	bZ4X
Generated power (W)*	180	225
Power generation area (m^2)	0.919	1.06
Specific power density (W/m^2)	196	212

* Measured in accordance with IEC 61215 and Toyota's own method.

In addition, by adopting back-contact solar cells, all the electrodes and wiring are invisible from above and the color uniformity of the roof is improved. These improvements enable greater coherence between the design of the system and the vehicle. (**Fig. 57**).

Fig. 57 Styling of Solar Roof

11.4 End notes

The solar charging system of the bZ4X helps to enhance both the economic and environmental performance of the vehicle by reducing the frequency of plug-in charging and CO_2 emissions, respectively. Development will be continued to improve the performance of the solar charging system by expanding the mounting area of the solar panels and adopting new solar cell materials.

12. Conclusion

The bZ4X is the first model developed using the BEV platform. The aim was to develop a user-friendly vehicle for everyday scenarios that would showcase the excellent response and comfort of a BEV with the objective of popularizing the whole concept of environmentally friendly vehicles. In addition to the technologies described in this article, the development team took on a wide range of new challenges ranging from production engineering to sales measures. There are various roads toward carbon neutrality, and adding another choice for customers in the form of the bZ4X should help to bring that goal one step closer. The authors would like to take this opportunity to express their sincere gratitude for the invaluable contribution of Subaru Corporation and everyone in the Toyota group who participated in this joint development.

Toyota intends to continue tirelessly working toward achieving carbon neutrality.

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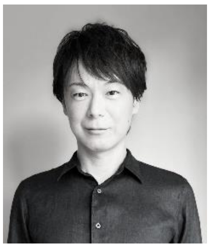

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The Toyota bZ3

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Abstract

The Toyota bZ3 is a battery electric sedan that was jointly developed by BYD Toyota EV Technology Co., Ltd. (BTET: a joint venture established by Toyota and BYD Company Ltd. (BYD)) and FAW Toyota Motor Co., Ltd. (FAW Toyota). The bZ3 was developed by a team of engineers from Toyota, BYD, and FAW Toyota, who worked in unison to combine the strength of each company and offer a completely new experience to customers in China. This article describes the results of the development, which aimed to realize a vehicle that embodies the tastes of Chinese customers. These results were obtained through mutual and respectful collaboration between Chinese and Japanese engineers in China.

Keywords: *Family Lounge, BEV, developed in China, intelligent technology, heat management, voice control, collaborative development*

1. Introduction

Toyota is working to help protect the environment in China by accelerating efforts to achieve carbon neutrality. At the same time, to help realize people-centered and highly convenient sustainable mobility, Toyota has developed the bZ3 as the second model in its bZ series of battery electric vehicles (BEVs) after the bZ4X. The bZ3 was developed locally in China as a product specifically for Chinese customers.

1.1 Local development in China for Chinese customers

The development concept of the bZ3 was the Family Lounge.

This concept reflects the idea that vehicles can provide a comfortable space to enjoy a relaxing time with family and friends, rather than merely being a means of transportation. This concept forms part of the objectives of the bZ series, which aims to provide new values through new experiences in keeping with the meaning of "bZ" (beyond zero).

The first of these new experiences is that of a calming and relaxing space.

Each of the rear seats is designed to feel like a restful living room sofa that provides plush seating comfort for everyone. In addition, a class-leading spacious floor area allows the occupants to relax free from constraints.

The second new experience is that of a space that helps family and friends to meet and share time together.

The interior is designed around the Digital Island area, which forms the central feature of the lounge by drawing in the eyes and creating a coherent focal point for conversation. This Digital Island features a large vertical center display clearly visible from both front seats. It includes a cutting-edge infotainment system that can be enjoyed by all the occupants of the vehicle within a supremely comfortable and quiet interior space.

The third new experience is that of a fun-to-drive mobile space that reduces fatigue over long distances.

The driving position draws on the lessons of the Toyota New Global Architecture (TNGA) design philosophy and is configured to minimize muscle strain. Wide use of voice controls helps to reduce fatigue due to switch operation.

To make it easier for the driver to concentrate and enjoy the driving experience, the cockpit has a driver-oriented design that positions items that must be looked at further away from the driver, and items that must be operated closer at hand.

The top-mounted meters are located in a position that sets the driver's viewpoint further away than in a conventional vehicle to minimize eye movement. The uniquely shaped steering wheel helps to create a racing-driver-like experience. The lamp and the washer functions are activated using paddle switches and the turn signals are located on the steering wheel switches. This objective of this design is to minimize necessary hand and finger movements.

Other notable features of the bZ3 include elegant and futuristic styling, a high-quality and reliable EV battery that delivers peace of mind and safety, a highly efficient EV system with low power consumption, cruising range a class above other vehicles due to world-leading aerodynamic performance, and the latest infotainment

*1 BYD Toyota EV Technology Co., Ltd.

system. The result is a vehicle that provides a full range of new experiences.

1.2 Collaborative development between Toyota, BYD, and FAW Toyota in China and Japan

Toyota's engineers in Japan recognized that the experience and sensibilities of the engineers at BYD Company Ltd. (BYD), who are pioneers in the field of BEVs, would be an indispensable part of building a vehicle that fits the lifestyles and tastes of customers in China. At the same time, it was also appreciated that collaboration with FAW Toyota Motor Co., Ltd. (FAW Toyota) would be essential in recognition of that company's excellent reputation with customers in China due to its broad lineup and extensive production, sales, and service systems.

From the beginning of this collaborative development project in 2020, the three companies worked to overcome daily challenges related to language, experience, technology, and work practices. The development progressed and finally succeeded thanks to the mutual support between the project members who found common ground as representatives of companies from the same continent of Asia.

This common ground included the shared desire to provide new people-centered experiences and values, and to help preserve the environment in China.

This collaborative project between China and Japan combined the strengths and technologies of Toyota, BYD, and FAW Toyota to satisfy the expectations of customers in China and, together with the bZ4X, to help create a new era of BEVs.

2. Vehicle Packaging

The unique packaging of the bZ3 is realized by the special characteristics of Toyota's dedicated BEV platform. Distinctive styling is achieved by a low center of gravity, sleek silhouette, and tires pushed out to the four corners. In addition, a long wheelbase enables a comfortable and roomy interior space (**Fig. 1** and **Table 1**).

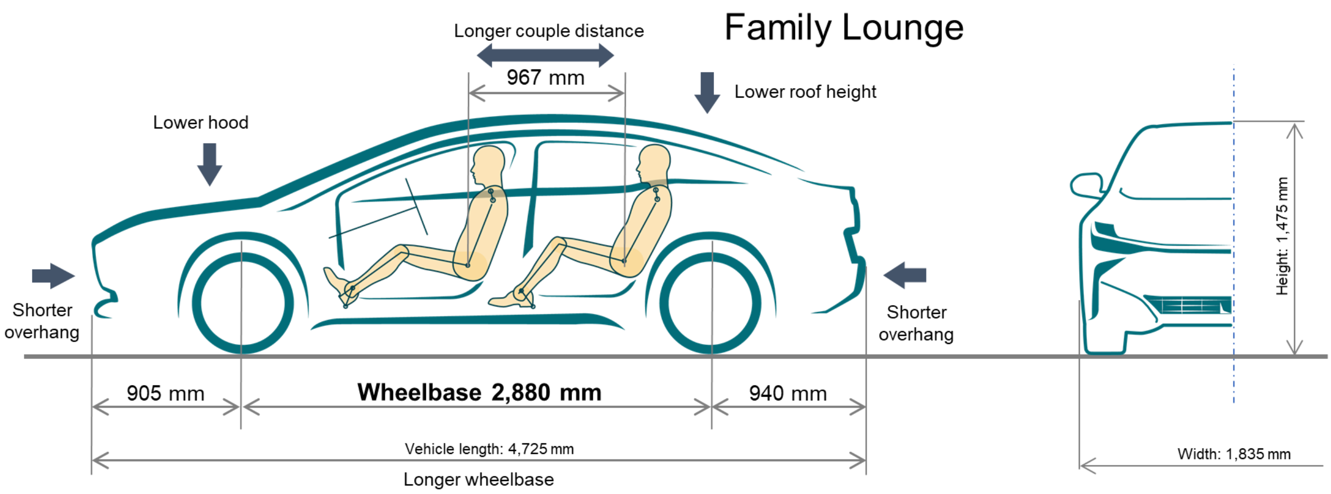


Fig. 1 Vehicle Packaging

Table 1 Vehicle Specifications

	bZ3	vs Allion	vs Camry
Length	4,725 mm	-5 mm	+160 mm
Height	1,475 mm	-40 mm	+5 mm
Width	1,835 mm	-55 mm	-20 mm
Wheelbase	**2,880 mm**	**-130 mm**	**-55 mm**
Overhangs (front/rear)	905/940 mm	+39/+86 mm	+72/+117 mm
Couple distance	967 mm	-49 mm	+4 mm

The e-TNGA platform is a newly developed dedicated platform for BEVs created based on the TNGA. For the bZ3, the e-TNGA platform was combined with a refined version of the BYD platform to create a low-floor platform specifically for BEVs. The vehicle packaging incorporates the short front and rear overhangs that only a BEV can realize with the Family Lounge concept to create a spacious cabin (**Fig. 2**).

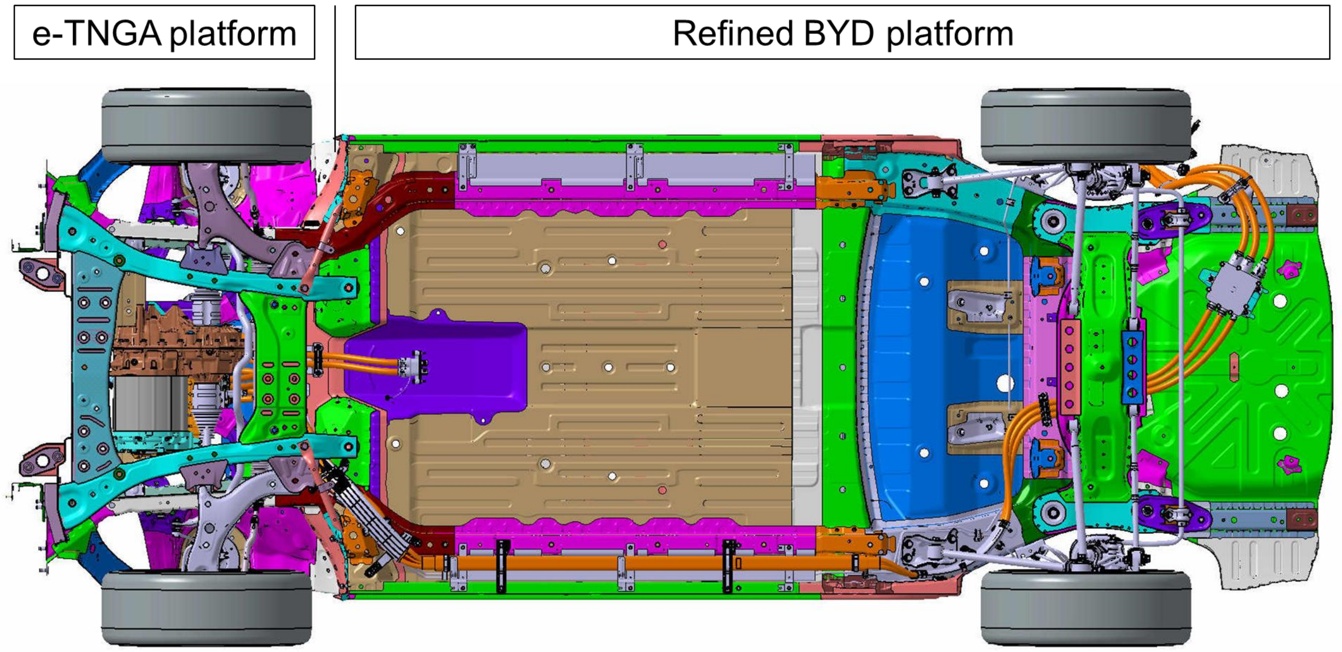


Fig. 2 Platforms (Underbody View)

3. Design

In China, the sedan remains the mainstream type of vehicle on the market for a number of reasons. The idea of vehicle ownership has only been embedded in China for a comparatively short period of time. As a result, sedans have remained popular with customers as a trusted and beloved symbol of transportation in daily life. Sedans have retained this position even as SUVs have come to the forefront. Manufacturers from both inside and outside China provide a diverse lineup of sedans, which remain a strong presence in the market. In China, BEVs are rapidly gaining customer support, helped by government-led measures to popularize new energy vehicles. Under these circumstances and taking advantage of its late arrival on the market, it was understood that the styling of the bZ3 would play a major role in harnessing brand power as a weapon for lowering barriers to market entry and for creating a unique appeal.

The styling of the bZ3 was planned assuming young first-time buyers (new families) and ride hailing services as the target markets. The development team took on the challenge of realizing the Family Lounge concept (**Fig. 3**) within normal C segment dimensions. This concept takes advantage of the spacious interior and, in particular, the roomy rear seats created by the long wheelbase of the BEV platform.

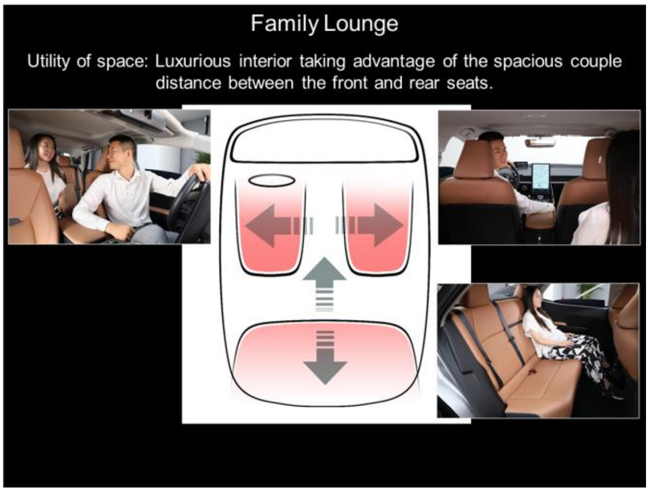


Fig. 3 Family Lounge

3.1 Exterior design

In the minds of Chinese customers, the expected image for a sedan is nothing less than elegance. This was one of the valuable lessons learned in the process of local development in China. Sharing the attributes of the bZ series with the previously released bZ4X, the exterior design of the bZ3 is futuristic and recognizable at a glance as that of a BEV, while incorporating the essential authentic elements of a sedan (**Fig. 4**).

Fig. 4 Sketch Aiming to Combine an Advanced Impression and Elegance

(1) From the side, the bZ3 combines a long wheelbase with the long cabin of a fastback to create a sleek silhouette.
In profile, the form combines a linear sense of speed and a flowing elegance by integrating an impression of solid power and richly changing convex/concave surfaces (**Fig. 5**).

Fig. 5 Sleek Side Profile Combining Powerful and Convex/Concave Surfaces with Rich Cross Sections

(2) The upper frontal area adopts the hammerhead design theme that takes advantage of the low hood as the common identity of the bZ series.
Daytime running lights (DRLs) that run through the left and right sides serve to emphasize this theme and underline the impression of width. Below the DRLs, the low set headlamps (consisting of four LED lenses) affirm the impression of a low center of gravity and aggressive face of the vehicle (**Fig. 6**).

(3) The exterior form emphasizes the corner elements that are a commonality of the bZ series.
The functionality and attractive stance of the bZ3 is highlighted by the consolidation of the thin lower front grille, the drag-reducing air curtains at the corners, the headlamps, and the sensors (**Fig. 6**).

Fig. 6 Front Identity of the bZ Series

(4) The body of the bZ3 expresses the unique lines and surfaces common to the bZ series.
Particular attention was paid to creating textures that combine edgy elements and sensual beauty based on a theme called Hi-tech & Warmth.

(5) Finally, a body color called Silky Brown that directly communicates the elegance of a sedan was selected as the signature color of the bZ3 (**Fig. 7**).

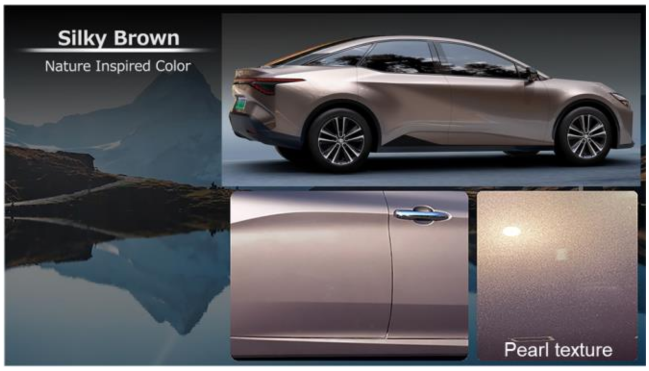


Fig. 7 Examples of Silky Brown, the Signature Color of the bZ3

3.2 Interior design

Customers in China are reacting to a rapid increase in social stress through thoughtfulness to family and friends, giving rise to the desire to place their family and friends in the most comfortable interior vehicle space. The development of the bZ3 focused on taking advantage of the available space in a BEV to create an open and comfortable area, while also ensuring driving enjoyment, and usability for all (**Fig. 8**).

Fig. 8 Interior Image Sketch

(1) The interior space has a simple structure that combines a low instrument panel with reassuringly solid surrounding elements that cocoon the occupants like a bathtub, with the aim of creating a relaxing sense of openness and an excellent range of visibility (**Fig. 9-1**). In particular, the center air conditioning register positioned at the top surface of the instrument panel was designed to enhance comfort by gently enveloping the whole of the interior space with cooling or warming air, and to greatly simplify the normally cluttered center cluster area. The door trim combines a simple window switch structure with an armrest that incorporates the inside door handle on the back of the assist grip, realizing both a streamlined appearance and greater user-friendliness (**Fig. 9-2**).

Fig. 9-1 Simple and Open Interior Layout

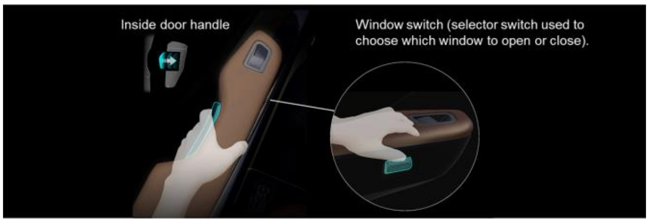


Fig. 9-2 Simple Armrest with Integrated Functions

(2) In the same way as the bZ4X, the driver module that combines top mounted meters with a uniquely shaped steering wheel symbolizes the driver-oriented cockpit of the bZ3. The bridge between the steering wheel and the meters facilitates natural eye movements and makes it easier to concentrate on driving (**Fig. 10**).

Fig. 10 Driver Module

(3) The tray-shaped console around the shifter is called the Digital Island. Smart phones and other devices can be placed freely in this area and charged wirelessly. The styling of the Digital Island is integrated with a vertical center display to enhance user-friendliness for customers belonging to the digital age (**Fig. 11**).

Fig. 11 Convenient Tray-Shaped Digital Island Console (Smart Phone Usability)

(4) The design motif of the rear seats is a living room sofa. The distinguishing feature of the seats is a flat cushion that can seat three people with ease. Combined with the spacious foot room created by the long wheelbase, the rear provides a comfortable and relaxing space (**Fig. 12-1**). The center seat of a sedan can feel cramped. However, extra foot room was created by cutting out the bottom part of the rear of the center console. In combination with the flat floor, this design creates a comfortable seating area even in the center seat (**Fig. 12-2**).

Fig. 12-1 Rear Seats Inspired by a Living Room Sofa

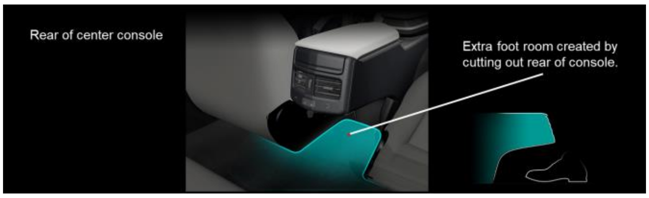


Fig. 12-2 Extra Foot Room Created by Rear Shape of Center Console

The bZ3 is distinguished by eye-catching individuality and an open interior layout. The development team hopes that it will be loved by customers as a car that brings positive changes to the lifestyles of a new generation without being constrained by the conventional boundaries of a sedan.

4. Multimedia and Intelligent Mobility Technology

Vehicle infotainment systems have to be, at the very least, as functional and user friendly as smart phones, tablets, and other rapidly advancing personal mobile devices. At the same time, since vehicles are a part of people's living space, onboard systems have to be optimized for in-vehicle use while providing personalized and highly usable services. In the Chinese market in particular, key points for realizing a next-generation cockpit include accurately identifying customer needs, as well as tracking and providing leadership for rapidly evolving market trends.

This development aimed to provide services that facilitate information liaison with other mobile devices in a highly functional and open ecosystem through extensive use of the third-party apps that are common feature on smart phones and other mobile devices. In addition to the pre-installed online map app, online music app, as well as weather and other information-based apps, a wide range of apps can be downloaded from the app store to cover a wide range of customer needs (**Fig. 13**).

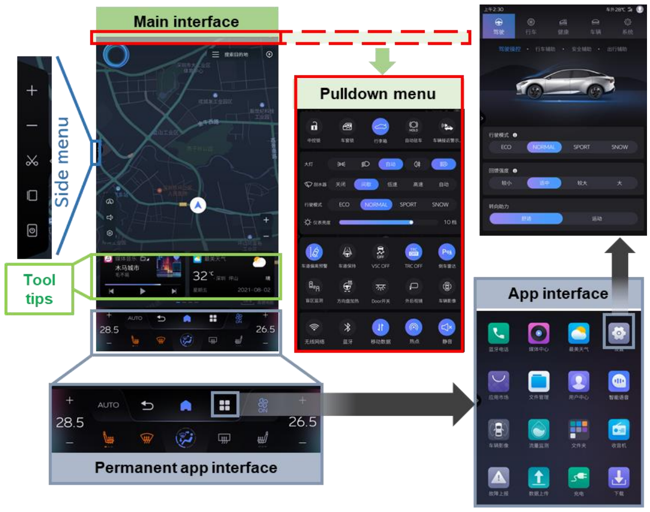


Fig. 13 Multimedia Operation Interfaces

The bZ3 is also provided with an interface to realize voice controls, which are extremely important in the Chinese market. This interface is implemented by a virtual agent character to more closely respond to the needs of customers. This is achieved by a people-centered functional design that uses image data from the driver monitor camera, external information from pre-installed third-party apps, and the like, while displaying expressions and speech patterns for different scenarios and situations. It can also actively propose certain functions based on the situation. The agent is also capable of personal growth depending on how the car is used (i.e., the frequency that the agent is activated, total driving distance, and so on). The appearance of the agent's character also changes as it grows, adding new functions and the like so that the user can appreciate the growth as it occurs, thereby creating an even more friendly experience (**Fig. 14**).

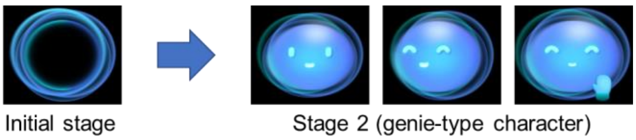
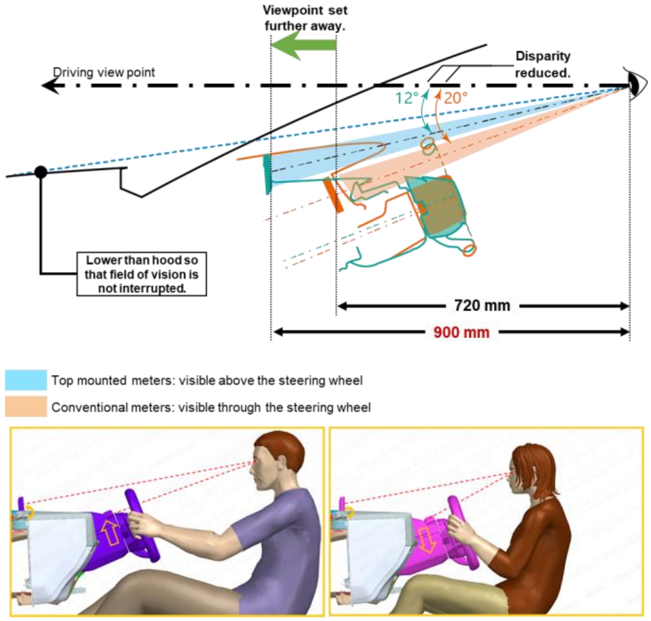


Fig. 14 Personal Growth of Agent Character

The cockpit also features top mounted meters that minimize the driver's eye movement and enable excellent visibility. The height of the meters is set below the height of the hood on the driver's eye line so that the forward field of vision is not interrupted. Combined with the unique shape of the steering wheel, this design reduces the size of the display area that the steering wheel conceals from view. The meters also move flexibly with the steering column, which allows drivers with different physiques to comfortably adjust the driving position. The minimalistic display only shows items necessary for driving, such as the speed and battery charge, creating an ideal meter design dedicated to the needs of the driver (**Fig. 15**).



Top mounted meters	Left screen	Right screen
	ADAS peripheral monitoring system	Speed
	TPMS	Gear
	Door opening/closing	Power meter
	Turn-by-turn guidance (left turn)	Battery charge
	ADAS telltales	Turn-by-turn guidance (right turn)
	Power window selection	Odometer
	Warning lights	Lamp system telltales
	Turn signal (left)	Speed limit indication (RSA)
		Driving mode
		Turn signal (right)
	LED indicators	
	The driver can judge the operational state of the vehicle from the LED indicators.	

Fig. 15　Top Mounted Meters

The turn signal and wiper switches are consolidated on the steering wheel. This means that, unlike with conventional switches, the driver can operate the vehicle while holding the steering wheel at all times.

Around the cockpit, user-friendly hardware switches are used for functions that must be operated immediately as well as frequently used functions. In contrast, the design takes advantage of the large display to increase the number of touch panel switches for functions related to comfort, amusement, and convenience. Consolidating the switches on a single screen, making the switches clearly available, and the use of voice controls both enhances the user-friendliness of the vehicle and helps to create an uncluttered, futuristic-looking cockpit (**Fig. 16**).

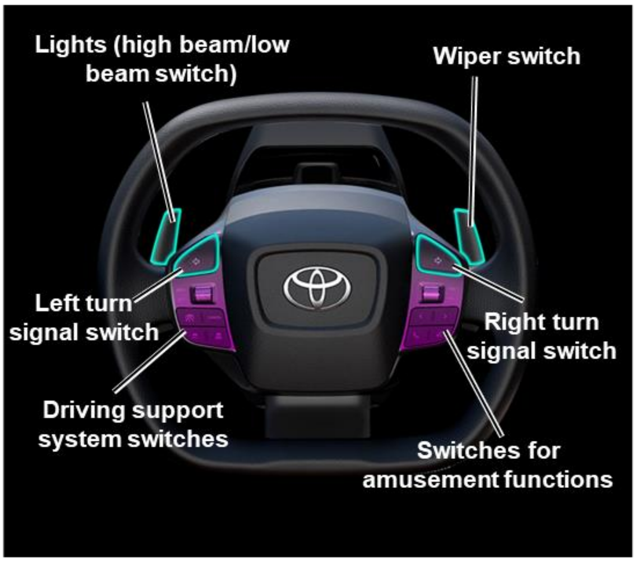


Fig. 16　Steering Wheel Switches

The bZ3 supports over-the-air (OTA) updates of onboard computer software to reduce waiting times at dealers. Via OTA updates, the user can upgrade the navigation system map and entertainment functions, enhancing convenience and enjoyment. OTA updates can also be used to add new functions to cockpit products such as the interior lighting and air conditioning, creating a more rewarding user experience. This OTA update function is available as standard equipment on all models. Rapid vehicle upgrades help to ensure that the vehicle is kept constantly updated and provides a sophisticated experience to enhance the customer's interaction with the vehicle.

5. Introduction of Individual Vehicle Technologies

5.1　EV system

A new EV system was developed by refining the functions and reliability of the base BYD EV system. **Table 2** shows an outline of the EV system.

Table 2 Basic Specifications of EV System

	500 km range version	600 km range version
EV range (CLTC)	517 km	616 km
Vehicle weight	1,720 kg	1,830 kg
Battery capacity	49.9 kWh	65.3 kWh
Rated voltage	333 V	435 V
Motor output	135 kW	180 kW
Motor torque	303 Nm	303 Nm
AC charging output	6.6 kW	6.6 kW
DC charging time (from 30 to 80%)	27 minutes	28 minutes

5.1.1 EV battery

A new highly durable and reliable EV battery system was developed based on BYD's Blade battery (**Fig. 17**). The Blade battery is a low-cost battery with good safety performance that uses lithium iron phosphate (LFP) for the cathode material. Generally speaking, the advantages of LFP is its extremely high thermal stability and resistance to smoke generation. In contrast, one disadvantage is low energy density. This development realized a high energy density of approximately 150 Wh/kg using a cell-to-pack structure in which the cells are directly fixed to the battery pack. A space-saving aluminum tray integrated with the cooling plate was also developed. The thermal management system cools or warms the battery as appropriate, which helps to extend battery lifetime and optimize charging times at low or high temperatures. A special high-resistance long-life coolant (LLC) was adopted as a safety measure in the event of coolant leakage.

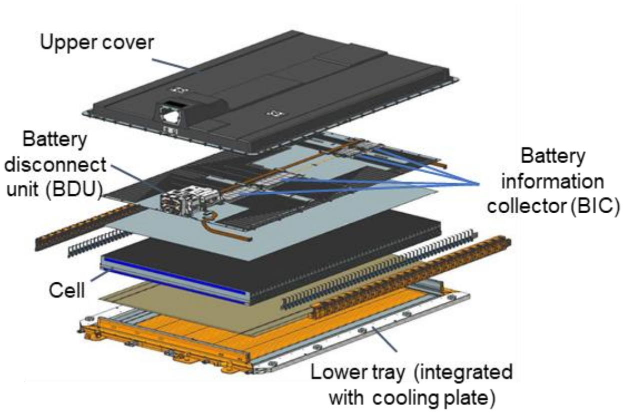


Fig. 17 EV Battery

5.1.2 eAxle

A newly developed eAxle was adopted that combines a transaxle, motor, and inverter (**Fig. 18**). The motor uses rectangular winding to help reduce size and weight and to increase efficiency. Motor noise was also reduced by measures such as arranging the resonant frequencies to disperse the natural frequencies of each component, adopting a rotor with a skewed structure, and suppressing torque ripple by harmonic injection.

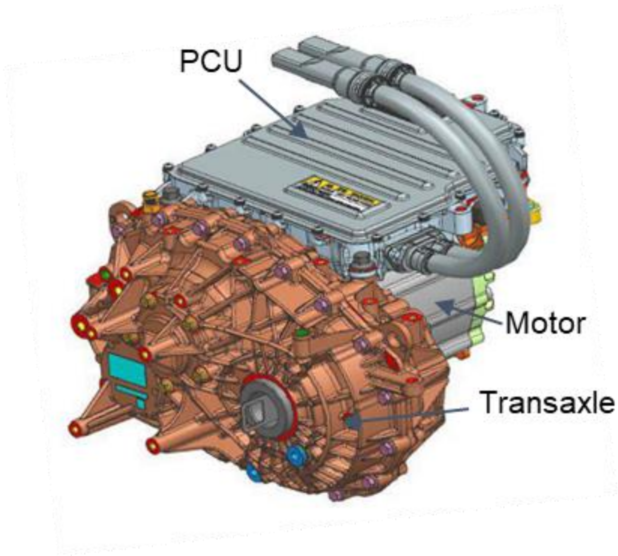


Fig. 18 eAxle

5.1.3 Electricity supply unit (ESU)

The ESU integrates the functions of a 6.6 kW onboard charger, DC-DC converter, and high-voltage wiring into the same component, helping to reduce the size and weight of the electrical parts. The ESU also features a built-in 3.3 kW vehicle-to-load (V2L) discharge function. The charging port incorporates the AC and DC charging inlets, and is mounted at the rear-left of the vehicle for ease-of-use by customers in China (**Fig. 19**).

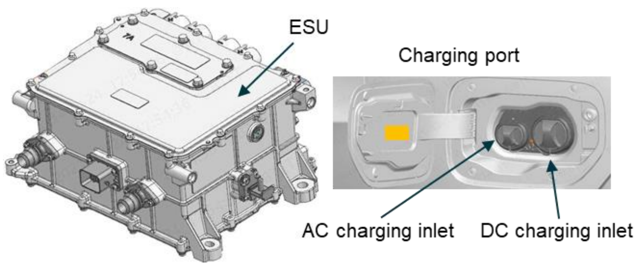


Fig. 19 ESU and Charging Port

5.2 Thermal management system

One major issue of BEVs is the substantial drop in cruising range that occurs in cold temperatures. This issue was addressed by adopting a highly efficient heat pump-based heating system. In addition, a condenser was installed inside the heating, ventilation, and air-conditioning (HVAC) system to apply direct overheating using high-temperature refrigerant. This configuration helps to further raise system efficiency. When the heat pump cannot operate at extremely low temperatures, a 6 kW high-voltage positive temperature coefficient (PTC) heater is used to ensure the performance of the heater system.

To cool the battery, low-temperature refrigerant distributed by an electrical expansion valve is passed through a chiller to reduce the coolant temperature. This electrical expansion valve is capable of precisely distributing the coolant to keep the occupant compartment at a comfortable temperature while controlling the temperature of the battery. To overheat the battery at cold temperatures, the battery and occupant compartment are heated by switching the circuit using a coolant flow control valve. These controls provide safe thermal management for both interior comfort and the battery (**Fig. 20**).

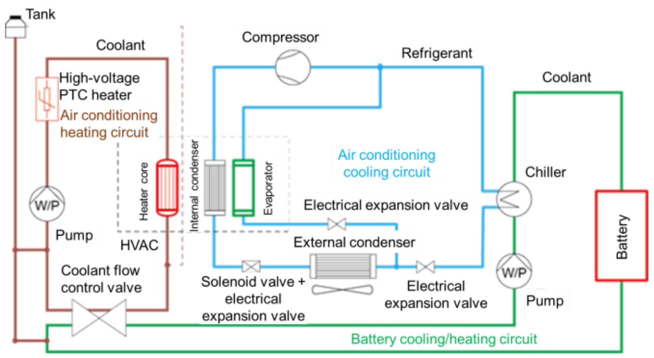


Fig. 20 Thermal Management System

6. Vehicle Performance

6.1 Passive safety performance

Fig. 21 shows Toyota's safety concept. In addition to compliance with regulations and assessments such as the China New Car Assessment Programme (C-NCAP) and the China Insurance Automotive Safety Index (C-IASI), the bZ3 also complies with the following two internal targets focused on occupant protection: (1) a 90-degree pole side impact collision test for high-voltage battery protection and (2) an 88 km/h moving deformable barrier (MBD) test to ensure safety in the event of a rear-end collision.

Compliance with the 90-degree pole side impact collision test is achieved by a structure that disperses force inputs along multiple ultra-high strength steel paths. This structure ensures good safety performance while also reducing vehicle weight (**Fig. 22**).

Toyota's internal targets for rear-end collision tests involve a higher impact energy than specified in regulations. The purpose of these targets is to ensure the safety of the high-voltage system and rear seat passengers. Force inputs are dispersed by a high-strength bumper reinforcement and side members on the left and right. This structure satisfies the requirements of 80 km/h offset crash tests (and the Chinese 50 km/h full lap test) (**Fig. 23**) as well as Toyota's internal Global Outstanding Assessment (GOA) targets.

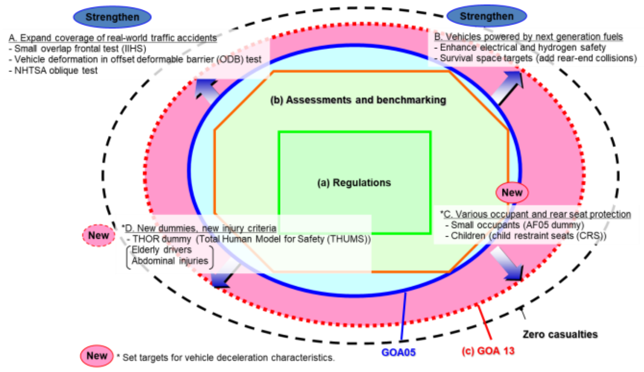


Fig. 21 Toyota's Safety Concept

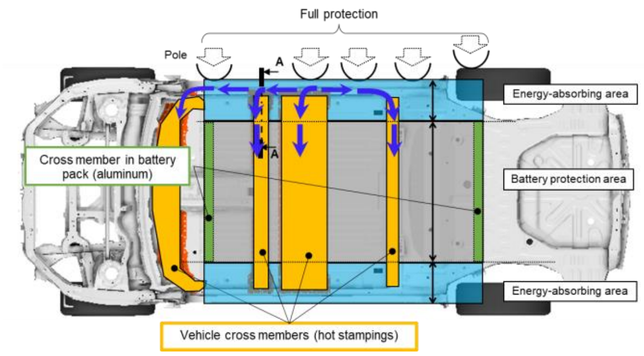


Fig. 22 90-Degree Pole Side Impact Collision Test

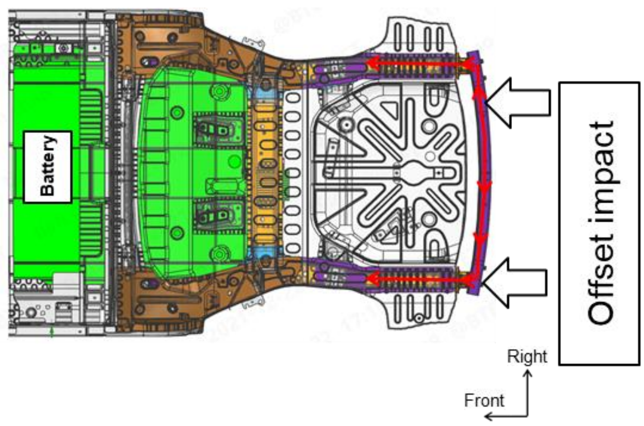


Fig. 23 Rear-End Collision Test: 88 km/h MDB

6.2 Power consumption efficiency and cruising range

The power consumption efficiency and cruising range of a BEV are extremely important aspects of performance for customers when choosing a vehicle.

This project combined the controls nurtured by Toyota during its long history of hybrid electric vehicle (HEV) development with BYD's component loss-reduction technologies to maximize the specific power density of the battery. These measures helped to realize class-leading low power consumption and extend the cruising range of the vehicle (**Fig. 24**).

In addition, an air-heating heat pump system was adopted to improve the cruising range of the vehicle at low temperatures, which is a key issue of BEVs. As a result, the bZ3 realizes a cruising range of at least 300 km/h (under the China light-duty vehicle test cycle (CLTC)) even at an outside temperature of 0°C (**Fig. 25**).

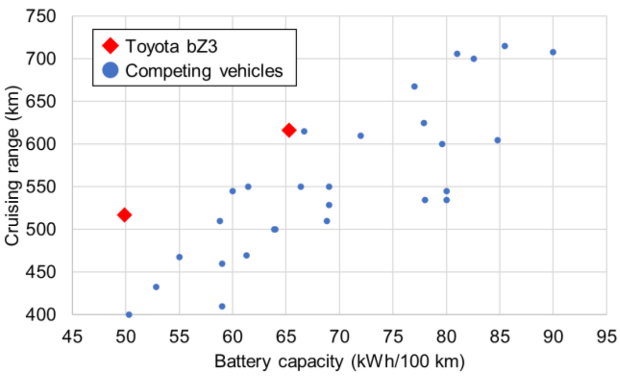


Fig. 24 Cruising Range

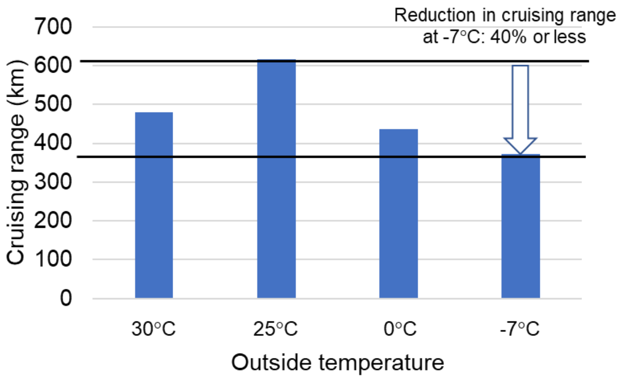


Fig. 25 Practical Cruising Range at Different Temperatures

6.3 Aerodynamic performance

Running resistance (i.e., aerodynamic drag and rolling resistance) must be minimized to extend cruising range. Decreasing the drag coefficient (CD) is an extremely important part of improving aerodynamic performance. Lowering the CD by just 0.005 points equates to a distance of 3.5 km.

This development realized a class- and world-leading CD of 0.218 by adopting a body with a smooth and cohesive surfaces extending from the front grille, aerodynamic stream lines by adopting a sharp rear structure, low CD wheels, and a fully covered under floor (**Fig. 26**).

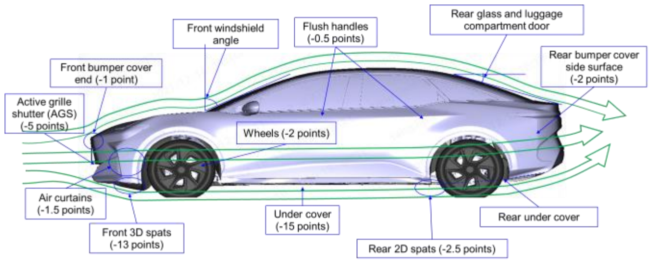


Fig. 26 Aerodynamic Improvements

6.4 Noise, vibration, and harshness (NVH) performance

Since it is impossible to block all sounds, the development aimed to reduce vehicle noise to a level unlikely to be perceived as discomforting, and to realize a balanced level of quietness.

First, the overall level of road noise due to road surface roughness was reduced since this is likely to cause fatigue in long-distance driving (**Fig, 27**).

Second, wind noise and harsh tire noise that directly impact conversations when driving at high speeds were also reduced (**Fig. 28**). These measures helped to ensure top-class levels of quietness and to realize an interior space ideal for close family conversations.

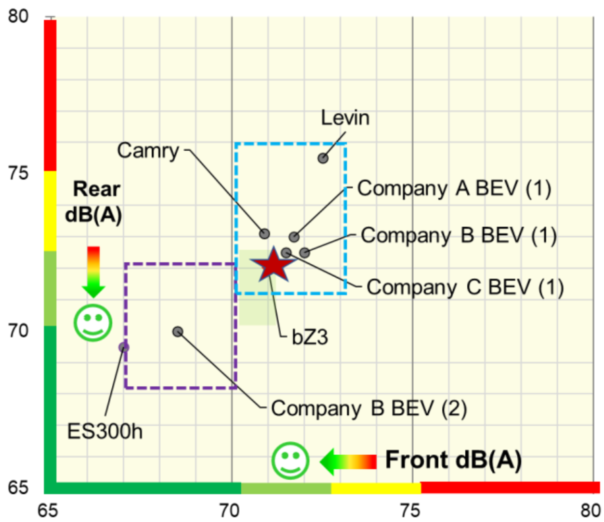


Fig. 27 Road Noise

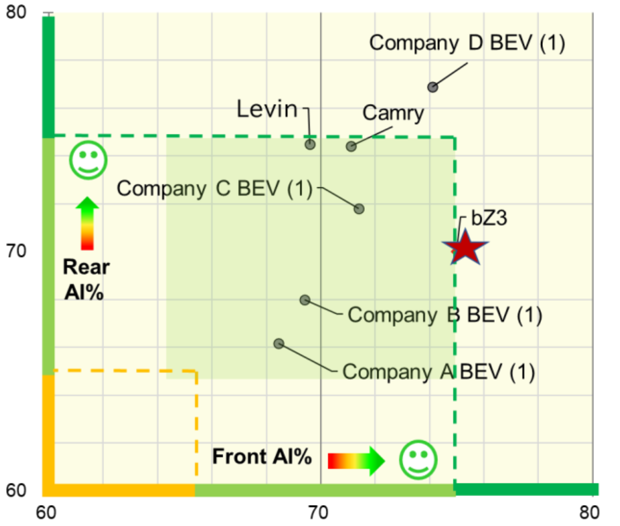


Fig. 28 Steady-State Articulation Index (AI)

6.5 Dynamic performance

One common characteristic of the bZ series is smooth driving performance that follows the intention of the driver. The bZ3 aimed to combine this characteristic with the unique acceleration feeling of a BEV and an appropriate driving feel for the Family Lounge concept that can be enjoyed by all occupants.

Taking advantage of the special torque-full characteristics of a BEV, acceleration performance with the accelerator pedal half depressed (1/2 stroke), which is equivalent to the normal driving range (usage frequency: 1σ), was enhanced while maintaining the basic driving performance of the vehicle (**Fig. 29**).

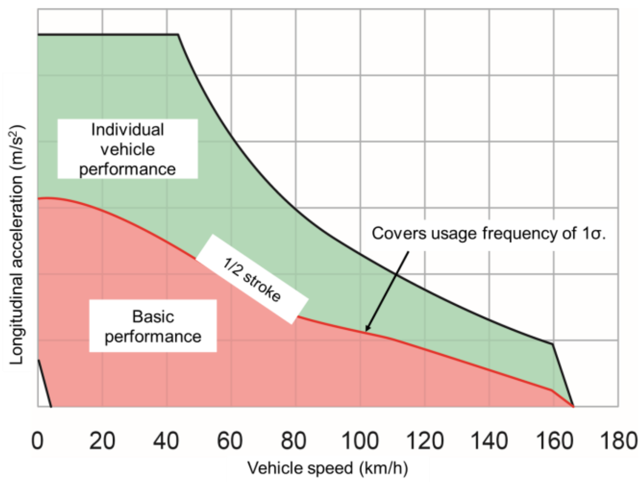


Fig. 29 Agile BEV Acceleration Characteristics

As a result, the 0 to 100 km/h acceleration performance of the bZ3, which is often used to judge the product appeal of vehicles, is faster than the published values for most other competing vehicles (**Fig. 30** and **Table 3**).

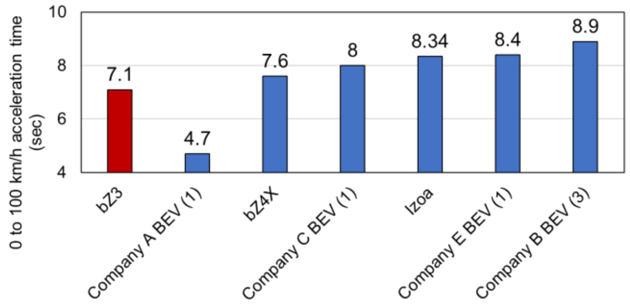


Fig. 30 0 to 100km/h Acceleration Performance

Table 3 Acceleration Times (Reference)

	Acceleration time (sec)		
	0 to 100 km/h	0 to 50 km/h	50 to 80 km/h
bZ3 500 km range version	7.8	3.1	2.6
bZ3 600 km range version	7.1	3.2	2.3

6.6 Ride comfort

To realize the Family Lounge concept, the development aimed to achieve equivalent ride comfort to the next highest class of vehicles (i.e., the Camry class). **Fig. 31** shows the vibration level when driving over bumps, which is one index used to judge ride comfort. As the graph shows, a value close to the Camry was achieved by tuning the suspension characteristics.

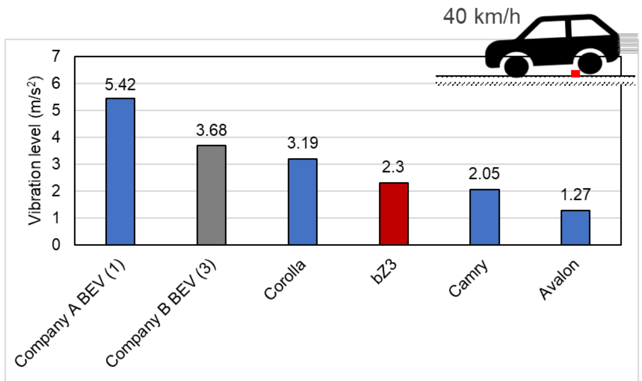


Fig. 31 Vibration Level when Driving Over Bumps

7. Conclusion

The development of the Toyota bZ3 was accomplished thanks to the invaluable cooperation of a wide range of partner companies, including BYD and FAW Toyota. The authors would like to take this opportunity to express their sincere gratitude. Toyota intends to continue taking

on the challenge of developing BEVs that will delight customers in China, the world's most developed BEV market.

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The C⁺pod Ultra-Compact BEV

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Abstract

This article describes the C⁺pod ultra-compact BEV. This model was developed with the aim of providing confident and natural mobility to people at all stages of life under the concept of mobility for all. It is primarily intended to be used within an aging society as a way of contributing to the diversification of transportation options in urban areas and the suburbs, and to help address environmental issues.

Keywords: *mobility for all, ultra-compact, BEV, motor vehicle type designation*

1. Introduction

As Toyota transforms itself into a mobility company, its objectives are to provide confident, natural, and safe mobility that meets the needs of the widest range of people under the concept of mobility for all, while at the same time, expanding the popularity of environmentally friendly vehicles to achieve carbon neutrality based on the appreciation of the Earth as our home planet.

This article describes the C⁺pod ultra-compact BEV that was developed to help meet these two objectives.

2. Significance of the C⁺pod

With age, deterioration of physical capabilities and concerns about either causing or becoming involved in an accident results in people giving up existing forms of mobility, as typified by older people returning their driving licenses. This has the effect of constricting people's individual range of movement and means that it may become more difficult to satisfy people's desire for mobility in the future. Therefore, it is necessary to provide more confident, natural, and even safer forms of mobility to enable freedom of movement for all later in people's lives. Another responsibility of a mobility company is to help popularize environmentally friendly vehicles from the perspective of improving the global environment and contributing to people's happiness. Consequently, Toyota has decided to take on the challenge of developing and launching its first ultra-compact and walking area BEVs to help provide mobility to people at all stages of life (**Fig. 1**). Therefore, the significance of the C⁺pod is its contribution to Toyota's mission to mass-produce happiness.

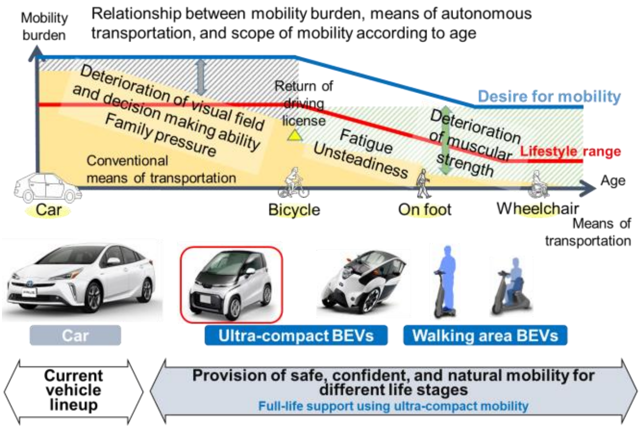


Fig. 1 Launch Concept for Ultra-Compact BEVs

3. Ultra-Compact Mobility (Vehicles with Motor Vehicle Type Designation)

In this development, after verifying the vehicle size and conditions such as the average number of occupants in daily usage, it was presumed that the C⁺pod would mainly be used for short distance journeys of two people. Although ultra-compact vehicles have the same dimensions as minicars (motorized bicycles) and can be classified in the mini-vehicle category that does not limit where the vehicle can be driven or the type of user, it was decided to obtain motor vehicle type designation as a vehicle with a top speed of 60 km/h unable to be driven on national expressways (**Fig. 2**). In addition, this certification enables the application of the following passive safety standards, which are slightly less stringent than those applied mainly to mini-vehicles.

- Lower collision velocity in full overlap frontal impact tests (50 ⇒ 40 km/h)
- Lower collision velocity in offset frontal impact tests (56 ⇒ 40 km/h)
- Non-application of pole side impact test

*1 Toyota ZEV Factory
*2 ZEV B&D Lab., Toyota ZEV Factory

	Class 1 motorized bicycles (minicars)	Mini-vehicles		
		Ultra-compact mobility		
		Vehicles with motor vehicle type designation	Certification vehicles	
Top speed	60 km/h	60 km/h	Individual restriction	No structural restrictions
Rated power	≤ 0.6 kW	> 0.6 kW	0.6 to 8.0 kW	> 0.6 kW
Maximum occupant capacity	1 person	4 people	2 people	4 people
Size: Length	≤ 2.5 m	≤ 2.5 m	≤ 3.4 m	≤ 3.4 m
Size: Width	≤ 1.3 m	≤ 1.3 m	≤ 1.48 m	≤ 1.48 m
Size: Height	≤ 2.0 m			
Passive safety standards	None	Applicable (destructive test) Reduction or exemption of some test velocities	Applicable (dimensional requirements)	Applicable (destructive test)
Eligible applicants for registration	No restrictions	No restrictions	Leaders of local public bodies Or, leaders of consortiums organized by local public bodies	No restrictions
Permitted driving areas	Nationwide	Nationwide	Permitted areas only	No restrictions
Permitted roads	Ordinary roads only			Ordinary roads, expressways, and controlled-access highways
Driving license	Ordinary motor vehicle license			

Fig. 2 Motor Vehicle Type Designation for Ultra-Compact Mobility

4. Styling Development

The exterior includes a black upper body that integrates seamlessly with the headlights and taillights to create a sense of cohesion and futuristic BEV styling. The firmly planted stance of the tires within the minimal vehicle packaging and advanced body styling results in a friendly and warm design that creates a simple and accessible impression for users across a wide range of ages. The interior presents a contrast between black and white to create an impression of size that exceeds its actual dimensions. Switches are also consolidated in a single area to realize a simple and user-friendly design for all driving scenarios (**Fig. 3**).

Fig. 3 Styling (Exterior and Interior)

5. Vehicle Outline

5.1 Packaging

Aiming to achieve a vehicle size capable of realizing superb handling and the capability to park in the smallest space, the packaging was designed to seat two adults side-by-side within the smallest possible width. The vehicle length satisfies the maximum of 2,500 mm required by the regulatory passive safety standards. Assuming that the vehicle would be used by people from a wide range of ages, the size of the door openings and seat heights were set prioritizing accessibility (**Fig. 4**).

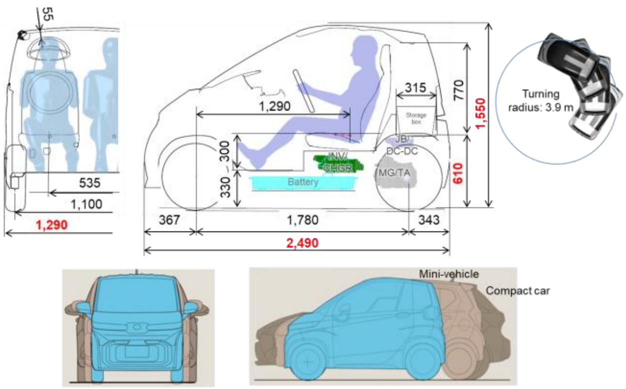


Fig. 4 C⁺pod Packaging and Size Comparison

5.2 Body structure

5.2.1 Underframe

A new underframe was developed for motor vehicle type designation (i.e., a dedicated C⁺pod platform). Because of the compact size of the C⁺pod, it was necessary to develop an underframe capable of properly absorbing impact forces. Technologies from existing models were applied and high-strength steel members selected to efficiently distribute the forces applied in a collision (**Fig. 5**).

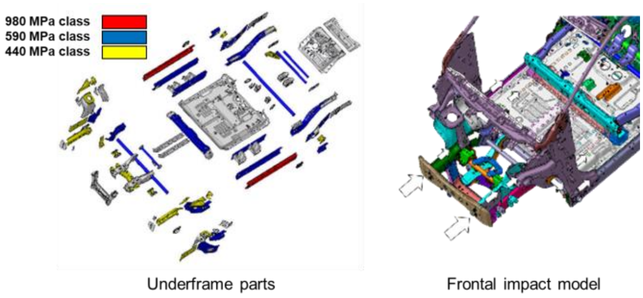


Fig. 5 Underframe Members and Frontal Impact Model

5.2.2 Upper pipe frame

With the impact forces controlled using the underframe as described above, it was decided to adopt a pipe frame for the upper body (**Fig. 6**). The objectives of this approach were as follows.

- To facilitate the addition of derived model variations (i.e., the capability to adopt different upper bodies over a common underframe).
- To reduce weight.
- To reduce investment by eliminating tooling costs.

Challenges of pipe frames include ensuring the positional accuracy of the rivets used to fasten the pipe frame to the body, the pipe frame fitting sequence, and outer panel quality requirements such as water sealing for the doors. These challenges were met by adopting an integrated three-sector approach involving design, production engineering, and manufacturing to build-in quality. This approach succeeded in adopting and mass-producing Toyota's first ever pipe frame.

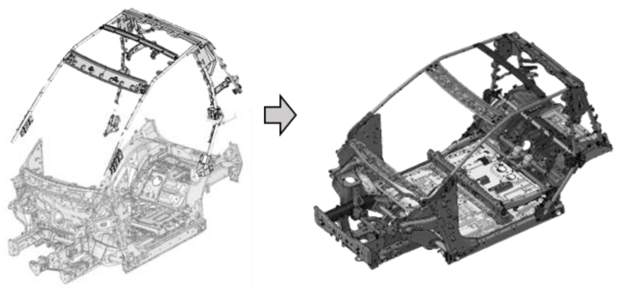


Fig. 6 Outline of Upper and Underframes

5.3 Plastic outer panels

In combination with the pipe frame, the C$^+$pod also uses plastic outer panels (**Fig. 7**). The objectives of these panels were as follows.

- To reduce weight.
- To enable a wide variation of styles (flexible color tones and the like).
- To expand into the outer panel swap business.
- To enhance repairability by enabling the replacement of individual panels.

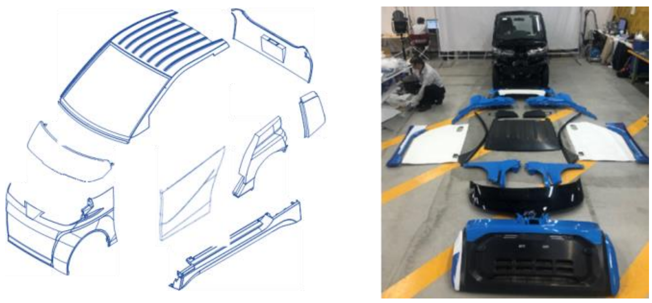


Fig. 7 Plastic Outer Panels of the C$^+$pod

The use of plastic outer panels enables the adoption of individually painted plastic parts. This allows users to select from a wide range of outer panel styles at a reasonable price. A good example of this is the option of selecting flexible color tones (**Fig. 8**). Furthermore, instead of a conventional painting process that coats the entire body, this approach also allows the adoption of more compact painting processes that help to reduce the environmental impact of the vehicle over the whole production process from a life cycle assessment (LCA) perspective.

Fig. 8 Flexible Color Tones of the C$^+$pod

5.4 BEV system

5.4.1 Battery pack

Despite its compact size, it was still necessary to ensure a driving range that would appeal to the customer as a viable form of mobility. Therefore, a highly reliable high-capacity lithium ion battery was adopted. To secure both cabin space and sufficient space for the battery, a new flat type of battery pack was developed for installation under the floor outside the occupant compartment (**Fig. 9**).

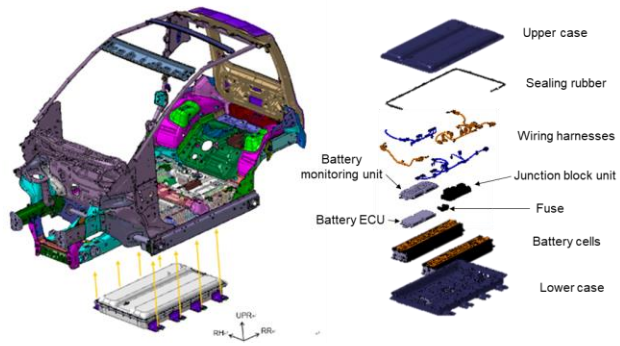


Fig. 9 Battery Pack Installation and Component Parts

The battery pack has a capacity of 9.06 kWh and was developed assuming use in the future as a storage battery for industrial or household uses. Each battery is equipped with control functions (a battery monitoring unit and battery ECU) to facilitate battery usage. The design also minimizes the work hours required to convert the battery for reuse.

5.4.2 BEV transaxle

The rear motor from the Prius e-Four was adopted to realize sufficient dynamic performance while restricting cost. However, a new high-voltage permanent magnet synchronous rotor was developed to match the target power of the C$^+$pod (**Fig. 10**).

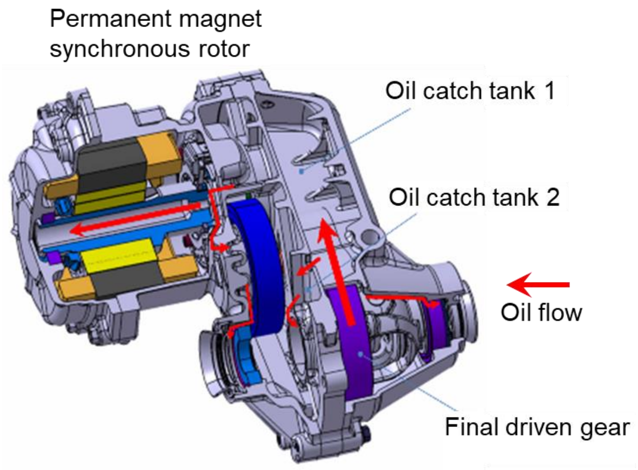


Fig. 10 C+pod Transaxle and Oil Lubrication System

The C+pod uses a gear train with a high reduction ratio. A three-axis design was adopted to reduce size so that the transaxle could be mounted in the extremely limited available lateral space of a compact BEV. In addition, a lubrication system was adopted that throws up oil onto the gears using gear rotation. The lubricating oil collects in the catch tanks and is supplied to the bearings and oil seals to help improve durability, driving range, and power consumption efficiency.

5.5 Safety systems

It was assumed that the C+pod would be used by people of all ages and at all stages of life. For this reason, the C+pod is equipped with active and passive safety systems to help ensure peace of mind and safety. In particular, the following passive safety systems are provided to help the vehicle avoid collisions (**Fig. 11**).

- Pre-collision safety system (collision avoidance type with pedestrian (day and nighttime) and bicycle (daytime) detection functions)
- Parking support brake system (rear static object detection)

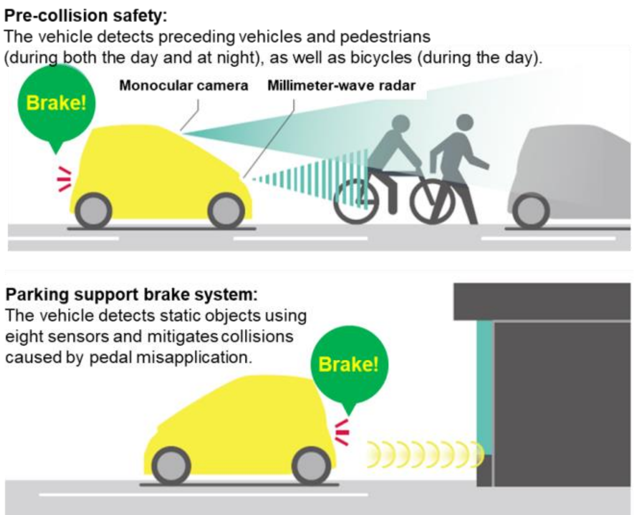


Fig. 11 Outline of Active Safety Functions: Pre-Collision Safety and Parking Support Brake Systems

In addition, the main passive safety systems are as follows.

- SRS airbags (driver and passenger seats)
- Seatbelts with pretensioner and force limiter
- Body designed to mitigate pedestrian collisions (plastic outer panels)

With a top speed of 60 km/h and the safety systems described above, the C+pod was assessed by Aioi Nissay Dowa Insurance Co., Ltd. as having excellent damageability and repairability (D&R) performance. As such, the C+pod was the first BEV to qualify for a discount on insurance premiums offered by that company.

5.6 Electricity supply system

With vehicle usage diversifying, it was decided to equip the C+pod with a system capable of supplying electricity for outdoor activities or in emergencies such as during a blackout or after a natural disaster. In addition to a 100 V accessory outlet below the passenger seat, a manufacturer's option is available that allows a vehicle power connector to be inserted into the front charging inlet, which gives the vehicle the capability to supply electricity rated at 1,500 W/AC 100 V (**Fig. 12**). It is probably unlikely that people will have the time to read the manual before using the electricity supply system in an emergency. Since using this system on a regular basis might help to reduce panic when an emergency occurs, the ample capacity of the battery (equivalent to approximately 10 hours of electricity supply for an ordinary household) was designed to encourage active daily use of the system.

AC 100 V outlet
(below passenger seat)

Vehicle power connector

Fig. 12 Electricity Supply System

6. Production

The C$^+$pod is produced at Toyota's Motomachi Plant. One of the notable characteristics of this plant is its role in contributing to the reduction of CO_2 emissions. For example, the Motomachi Plant is engaged in the verification of next-generation fuel cells and uses a fleet of fuel cell forklifts fueled by hydrogen produced by solar power.

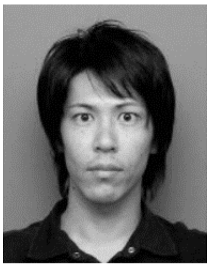
The C$^+$pod is assembled using dedicated processes, including in-house molding and painting of the plastic outer panels and battery pack assembly. To retain flexibility against production fluctuations, only a minimum amount of fixed equipment is used in an easily reorganized layout. In addition, by enhancing the skills and proficiency of the assembly line workers and teaching skills for multiple processes (i.e., greater skill versatility), this assembly process is highly robust against production fluctuations and is capable of assembling a C$^+$pod using as few as four workers.

7. Conclusion

The ultra-compact C$^+$pod BEV is a core product in the C$^+$ series that includes the C$^+$walk $_T$ walking area BEV. With the aim of realizing mobility for all, Toyota is taking on the responsibility of developing new types of mobility. Toyota is aiming to help create a society in which everyone can live active and rewarding lifestyles and to popularize environmentally friendly vehicles by listening carefully to users and adopting a process of continuous improvement.

Finally, the authors would like to use this opportunity to express their sincere gratitude to all the suppliers and relevant people that contributed to the development of the C$^+$pod.

Authors



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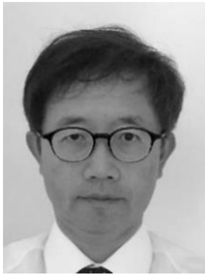

A. Yanaka

Supporting the Development of a Hydrogen-Energy Based Society by Expanding Fuel Cell Application

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Abstract

Hydrogen energy and the realization of a hydrogen energy-based society are regarded as increasingly promising ways of achieving carbon neutrality. Toyota is working to develop more advanced fuel cell (FC) technologies, and launched the first-generation Mirai fuel cell electric vehicle (FCEV) in 2014, followed by the second-generation in 2020. Toyota is also aiming to further contribute to the realization of a hydrogen energy-based society. Initiatives include the modularization of FC components to facilitate the application of FCs to a wider range of products. It is also working to create new value for FCEVs by taking advantage of the abundant power generation capacity of FCs to raise the performance and effectiveness of FCEVs in non-driving situations.

Keywords: *carbon neutrality, hydrogen energy based society, fuel cell (FC), modularization, FC system module, hydrogen storage module, new value creation, FCreation*

1. Introduction

1.1 Trends toward carbon neutrality

With countries and regions around the world recognizing global warming as a common issue, concrete and challenging messages about the achievement of carbon neutrality are being sent out (**Fig. 1**).

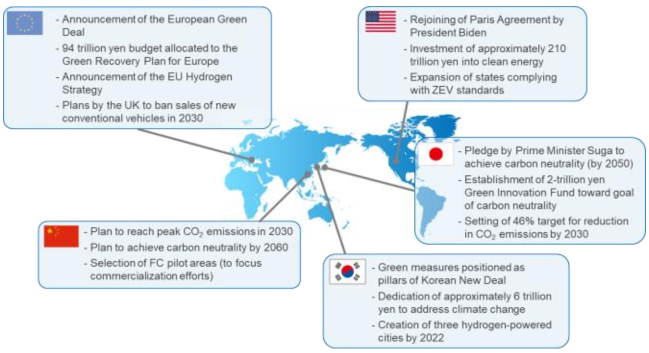

Fig. 1 National and Regional Trends toward Carbon Neutrality

In 2020, then Japanese Prime Minister Suga issued a pledge to achieve carbon neutrality by 2050. In April 2021, this was followed by the announcement of a 46% target for reducing new greenhouse gas emissions in fiscal 2030 compared with fiscal 2013. Faced with these trends and commitments, there is global demand for stable supplies of clean and reasonably priced energy to enable further economic growth.

1.2 Roles of hydrogen energy in society

With the use of electricity derived from solar, wind, and other renewable sources on the rise, energy storage and transportation is becoming an increasingly important part of maintaining the balance between energy supply and demand. As a result, there are growing expectations around hydrogen since it can be produced using a wide variety of methods and is suitable for both long-distance transportation and storage. In addition, since the energy density of hydrogen is higher than batteries, it has several advantages. These include the capability to store larger amounts of energy and shorter refueling times, which can reduce the downtime of applications (**Fig. 2**). Considering these advantages, hydrogen can be used as a buffer when managing the balance between renewable energy supply and demand. As such, it has the potential to play a vital role in future efforts to realize carbon neutrality.

[*1] Commercial ZEV System Products Development Div., Toyota ZEV Factory

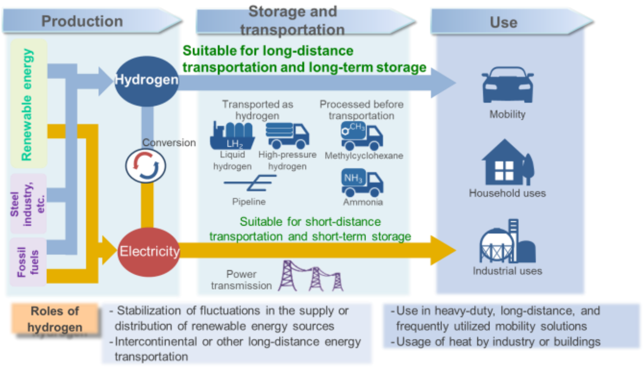

Fig. 2 Roles of Hydrogen Energy in Society

1.3 Contribution to society and initiatives to expand the application of fuel cells

1.3.1 Steps for social implementation

This section describes the steps for implementing fuel cell (FC) technologies in society as an indispensable part of expanding the use of hydrogen (**Fig. 3**). Starting with electrochemical technologies, the aim is to contribute to society by expanding the product lineup in accordance with the usage environments of customers and improving the applicability of hydrogen for various purposes.

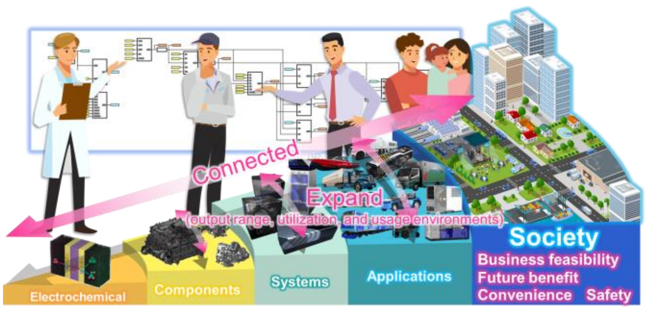

Fig. 3 Steps for Implementing Hydrogen FCs in Society

Specific examples of how hydrogen can contribute to society include the development of more livable cities (such as cities that are better prepared for natural disasters), the improvement of logistics and delivery services, the modeling of low-carbon factories, and so on (**Fig. 4**).

Fig. 4 Hydrogen-Related Initiatives for Social Contribution

1.3.2 Advances in FC technologies and initiatives to expand applicability

Toyota started developing FC technologies in 1992. Since then, it has improved power density and fuel efficiency while reducing system cost (**Fig. 5**). The first-generation Mirai debuted in 2014, followed by the second generation in 2020.

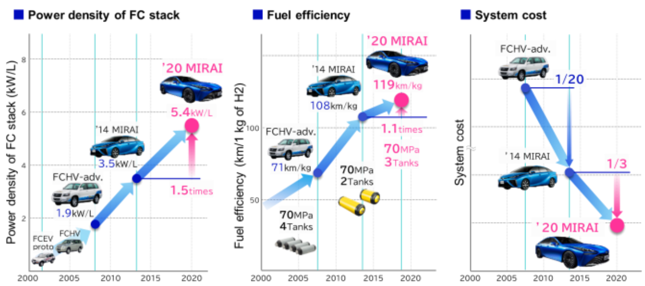

Fig. 5 Advances in FC Technologies

To help expand the range of hydrogen applications, Toyota has started sales of FC system modules. The aim is to provide a wide range of users with the opportunity to experience the FC system technology developed for the Mirai.

In addition, Toyota is also in the process of developing hydrogen storage modules capable of transporting and storing hydrogen safely and conveniently using the hydrogen storage technology from the Mirai.

Toyota is also engaged in new value creation projects involving the development of fuel cell electric vehicles (FCEVs) with benefits over and above basic driving functions. The aim of these projects is to create new value by taking advantage of the power generation capabilities and quiet interior of an FCEV.

This article describes these FC module, hydrogen storage module, and new value creation initiatives in more detail.

2. FC System Modularization

The use of hydrogen is regarded as an effective way of achieving carbon neutrality. For this reason, there is growing demand for the adoption of FC and hydrogen storage systems in electric propulsion applications. The existing FC system from the Mirai is difficult to utilize in other applications due to the specific installation requirements of components in the Mirai. Modularization by consolidating FC system components is seen as an effective way of addressing this issue.

Modularization has two purposes: to package components together and to improve the usability of the FC system in new applications. This was achieved through user-friendly design of all interfaces.

In this project, FC module variants with different power outputs were designed to facilitate utilization in a wide range of applications.

2.1 Objectives and concepts of FC system modularization

This section describes the modularization of the power generation components of the FC system. Modularization has the following two objectives.

The first objective is the adaptation of the FC system for commercial applications. The term “commercial applications” refers to non-passenger vehicle uses (such as buses and trucks), marine vessels, trains, and other forms of mobility. It also refers to non-mobility applications such as construction machinery, stationary generators, and so on. There are various commercial applications requiring different power outputs, ranging from several kW to several MW (**Fig. 6**). Durability is also a key factor for commercial applications. For example, heavy-duty trucks are driven for extended periods of time, several times longer than passenger vehicles. Before the system can be applied to commercial vehicles, it was necessary to re-design the FC stack and other components to achieve quality products at competitive prices. Therefore, the proven system of the Mirai was refined to realize a highly durable system for commercial applications.

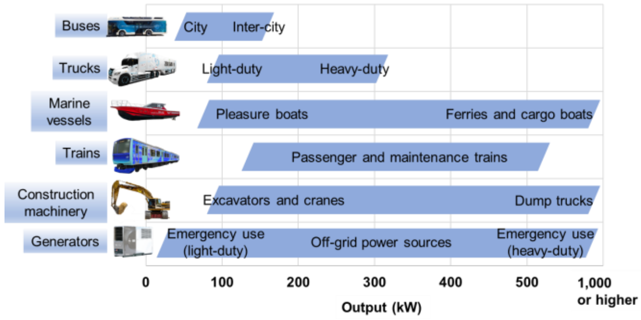

Fig. 6 Power Range of Commercial Applications

The second objective is to reduce the development period of customers adopting the FC system. Toyota started external sales of the FC system from the first-generation Mirai to selected users to encourage its adoption in commercial applications. This system required a large amount of time and resources before power could be generated safely, which created a major workload for users. Therefore, one of the objectives of modularization is to reduce this burden.

Modules have been developed under the following concepts to accomplish these two objectives.

(1) Development of all-in-one modules that can be used to generate power simply by connecting the necessary interfaces
(2) Preparation of a full module lineup, ranging from low to high power
(3) Development of vertical and horizontal type modules to increase installation flexibility
(4) Enhancement of Mirai FC system components to realize high power and durability
(5) Enabling power scale-up through an interface that allows easy connection of multiple modules
(6) Achieving greater applicability to various commercial systems through, for example, compatibility with low-pressure hydrogen supplies

2.2 All-in-one modules

To enable adoption in various commercial applications and realize short set-up times, the FC system of the second-generation Mirai (outlined in **Fig. 7**) was modularized. The FC module contains the FC stack (the heart of the system), the hydrogen injectors, and the hydrogen pump, the air system that includes the air compressor and intercooler, the cooling system for the FC stack and high-voltage components, and the FC boost converter (FDC) that controls the output voltage.

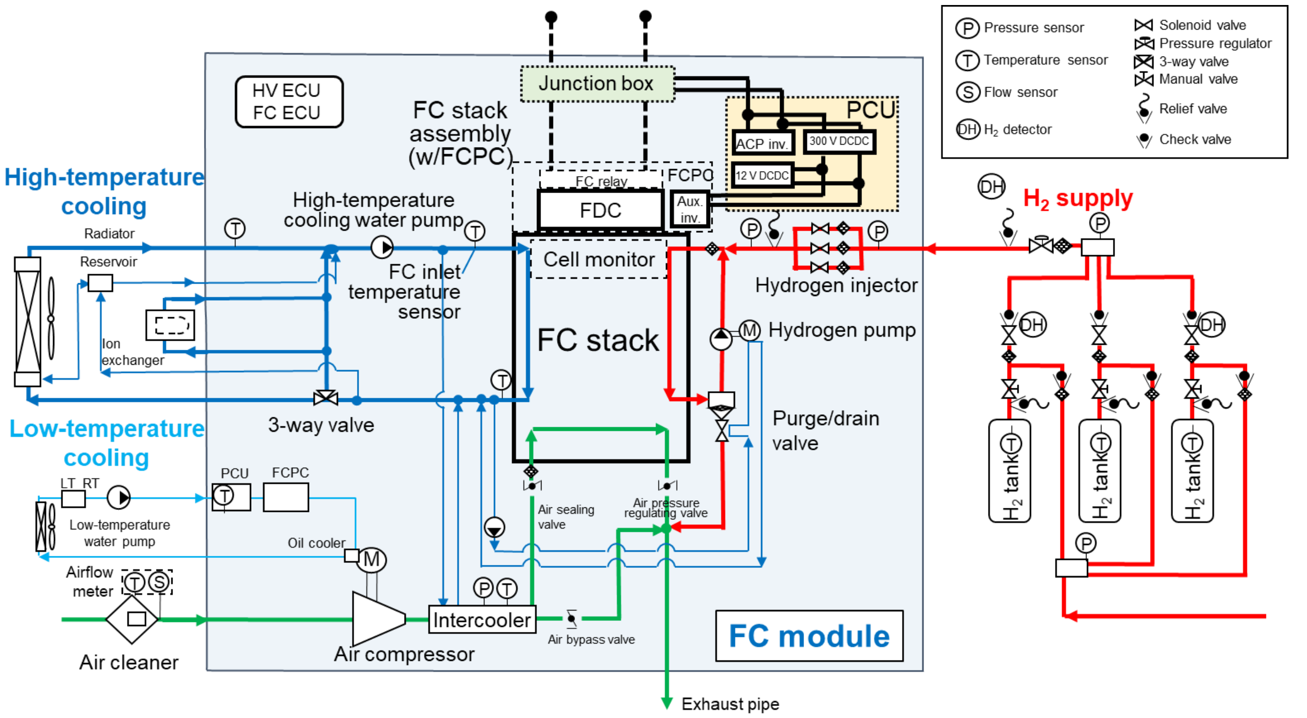

Fig. 7　Systems in FC Module

After the cooling system is filled, hydrogen and air can be supplied through predetermined routes, enabling power generation (**Fig. 8**). In many systems offered by competitors, the FC current is an operational variable controlled by monitoring the voltage. As a result, it is difficult to respond quickly to power requests. In contrast, because the developed FC module is equipped with an FDC that carries out the power control function, the user only needs to provide a power request.

In addition, the switching devices in the FDC use the silicon carbide (SiC) power semiconductors newly developed for the Mirai, which have 80% lower loss than conventional devices.[1]

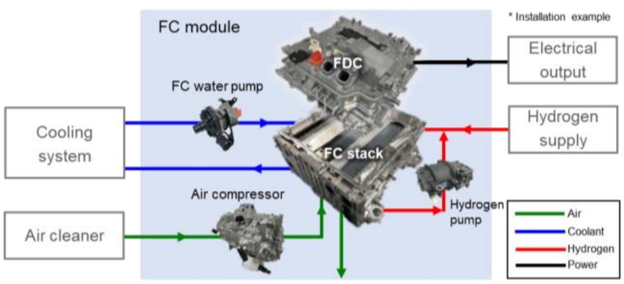

Fig. 8　Configuration of FC Module

The FDC also carries out the role of adjusting the FC voltage to the voltage of the user's system. Many commercial applications are hybrid systems that combine an FC system with a high-voltage battery. The FDC automatically adjusts the FC voltage in accordance with the system voltage, which changes depending on the battery state of charge (SOC) (**Fig. 9**).

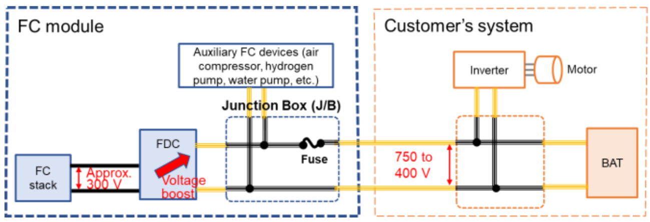

Fig. 9　High-Voltage System

In addition, the FDC is equipped with a function that enables autonomous start ups of the FC system under sub-zero conditions without using a heater or other external device. This function utilizes rapid FC warm-up control to prevent the freezing of generated water).[2] An onboard control that measures the FC impedance and maintains the optimal power generation state (electrolyte membrane lubrication) at all times is also included.[3]

In contrast, many FC modules offered by competitors do not have a built-in FDC. The customer must prepare its own FDC and develop the aforementioned controls independently. As this requires precise knowledge of the characteristics of the FC stack and FDC, control development can be burdensome for the customer.

2.3　FC module lineup

There are multiple power versions of the FC module. In addition to the standard type with a continuous power rating of 60 kW, a light-duty 8 kW module for applications such as forklifts requiring lower power (24 and 50 kW variations are also under development), and 80 kW modules for applications requiring slightly higher power are under development or already on sale (**Table 1**). Multiple units of these modules can be used to meet the large power requirements of heavy-duty trucks and the like.

The power and installation space requirements of commercial applications differ widely. As a result, the number and installation position of the FC modules will vary. Therefore, in addition to the different power variations, vertical and horizontal type modules have also been developed (**Fig. 10**).

Table 1　FC Module Lineup

Product specifications		Light-duty module (Toyota Industries Corporation)			Vertical module	Horizontal module
External appearance						
Performance	Rated power (kW)	8	24	50	2 types (60/80)	2 types (60/80)
	Durability	20,000 hours (using typical forklift operation pattern)	Under development		15,000 hours (using typical truck operation pattern)	
	Voltage (V)	48	80	300 to 400	400 to 750	
	Current (A)	166	300	166	0 to 133	
External shape	Size (L×W×H mm)	542×610×440	Under development		890×630×690	1,270×630×410
	Weight (kg)	Approx. 113			Approx. 250	Approx. 240
Operational environment	Stack temperature (°C)	0 to 75 (max.: 80)			-30 to 75 (max. 90)	
	Minimum starting temperature (°C)	0			-30	
	Storage temperature (°C)	-10 to 80			-40 to 90	
	Elevation (m)	Up to 1,000			Up to 3,400	
Supply	Fuel type	Hydrogen	Hydrogen	Hydrogen	Hydrogen	
	Hydrogen quality	SAE J2719	SAE J2719	SAE J2719	SAE J2719	
	Supply pressure (MPa, abs)	0.18 to 1.6	Under development		0.5 to 1.6	
Safety	Hydrogen	IEC 62282-4-101 compliant			UNR-134, ISO 26262	
	High voltage	IEC 62282-4-101 compliant			UNR-100, UNR-118	
Environment resistance	Dust and water protection	IP54	Under development	IP55	IP67 (excluding air compressor breather)	
	Vibration	JIS C 60068-2-27		JIS D 1601 level 45	ISO 19453-6	
	EMC	EN 12895		EN 12895	IEC 61000-4-2.3	
Status		Under development (specifications may change)			On sale	

Fig. 10　FC Modules (Left: Vertical Type, Right: Horizontal Type)

As application examples of the vertical and horizontal modules, the vertical type is designed for trucks with the module installed in the engine compartment, whereas the horizontal type is designed for city buses with the module installed on the roof. In addition, two or three modules can be connected in series for heavy-duty tractors, highway buses, and other applications requiring high power output. Multiple modules can also be connected for trains and stationary generators that require even higher power. As a result, a wide range of commercial applications can be covered using the vertical, horizontal, or combinations of multiple modules (**Fig. 11**)

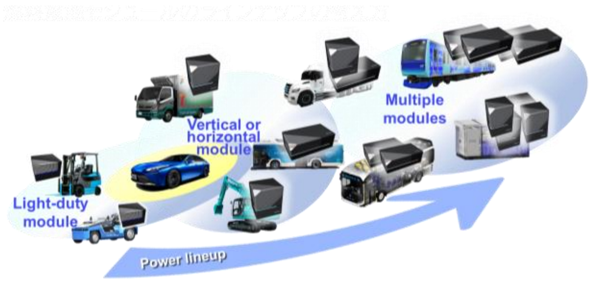

Fig. 11　Examples of Module Use with Commercial Applications

2.4　Easy-to-install dimensions for commercial applications

The available space for module installation in commercial applications was investigated before the dimensions of the vertical and horizontal type modules were fixed. The width (W dimension) of the FC module was determined by the distance between the beams of a truck frame (**Fig. 12**). The height (H dimension) was selected to allow installation on the roof or under the floor of a bus.

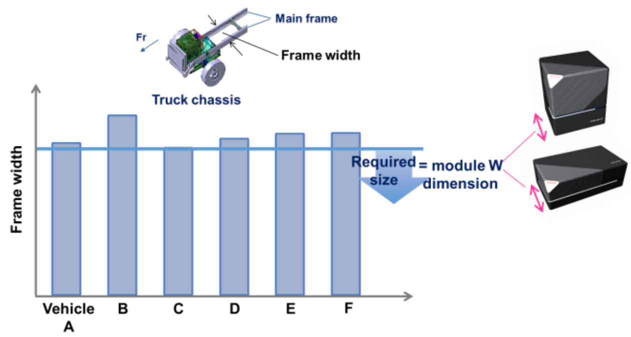

Fig. 12　Frame Width and W Dimension of FC Module

When the FC stack generates electricity, some of the water that forms in the cathode passes through the electrolyte membrane to the anode. This water is collected by the hydrogen system gas-liquid separator and drained. Since the Mirai uses gravity to collect this water, the gas-liquid separator is installed at the bottom of the system (**Fig. 13**). In contrast, to shorten the H dimension of the FC module, some of the piping is oriented upward, which means that the water cannot collect in the gas-liquid separator by gravity alone. Therefore, the whole hydrogen circulation line including the gas-liquid separator was visualized and analyzed. The routing of piping was revised and the performance of the gas-liquid separator enhanced to enable collection of waste water. This allowed the important H dimension to be reduced (**Fig. 14**).

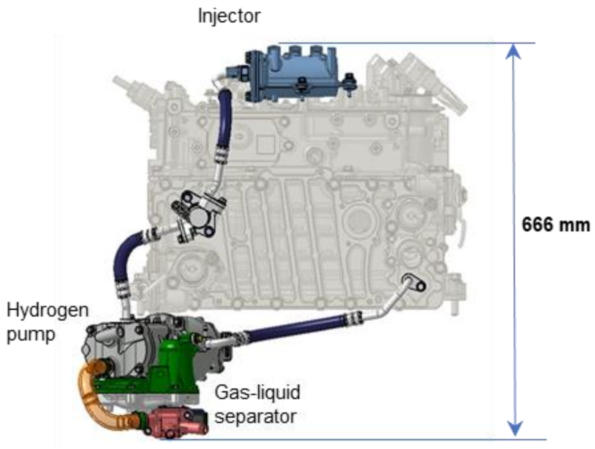

Fig. 13 Side View of Mirai FC System

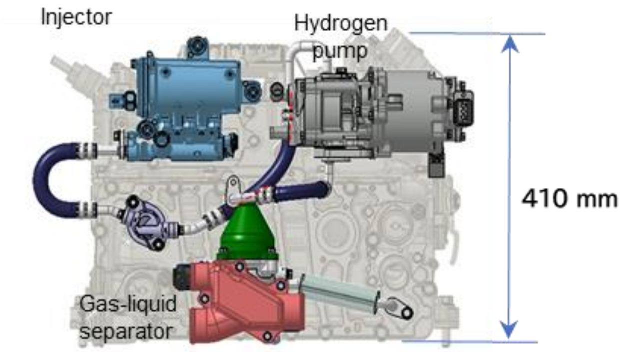

Fig. 14 Side View of FC Module

2.5 Increasing the power and durability of the FC module

Commercial applications require a higher continuous power rating and greater durability than passenger vehicles. Therefore, a comprehensive inspection of the FC system components was carried out to identify those requiring additional development. The performance of these FC components was then enhanced without changing the external dimensions. The FDC and air compressor are described below as representative examples.

The FDC is a chopper type boost converter. If the continuous power application is increased, higher current will flow in the switching devices, reactor, and filter capacitors. As a result, more heat will be generated and durability will decrease. A liquid-cooling structure was developed for the FC module to replace the air-cooled filter capacitors used in the Mirai. In this structure, the surface below the capacitor is filled with a highly conductive heat-dissipating potting material to create contact with the surface of the cooling plate (**Figs. 15** and **16**). The heat dissipation capacity of this structure is approximately 5 times higher than that of air, which allowed the continuous power rating to be increased while maintaining high durability.

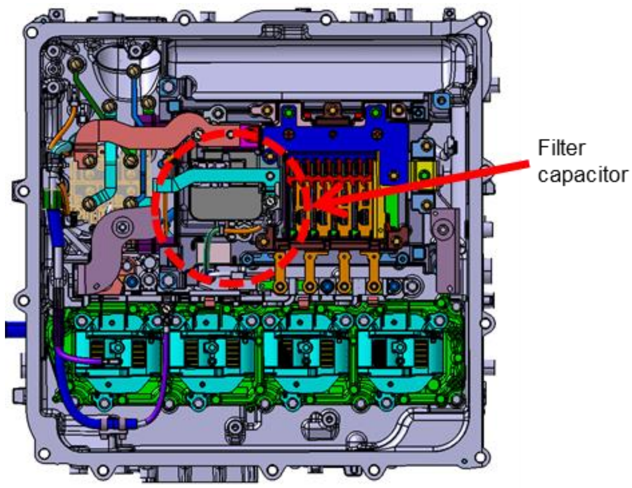

Fig. 15 FDC and Filter Capacitor

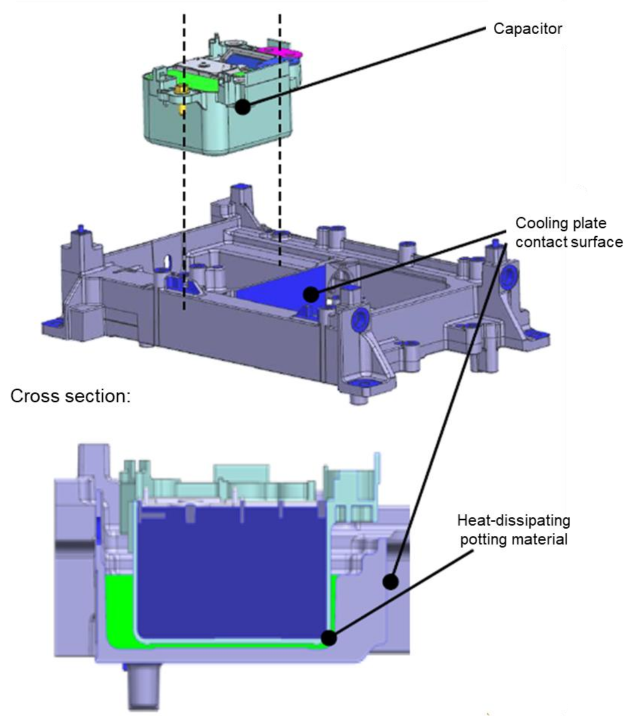

Fig. 16 Cooling Structure of Filter Capacitor

In addition, the overall operation time of commercial applications is longer than that of passenger vehicles. As a result, the total number of revolutions of rotating mechanisms increases. In particular, the durability of the air compressor needed to be improved since turbo type compressors operate at high rotational speeds. Durability several times greater than for a passenger vehicle was realized by improving parts such as the bearings built into the step-up gear box that connect the motor and impeller.

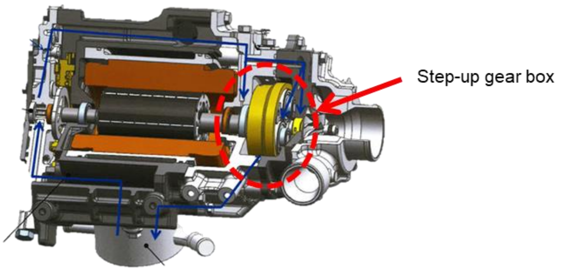

Fig. 17 Step-Up Gear Box of Air Compressor

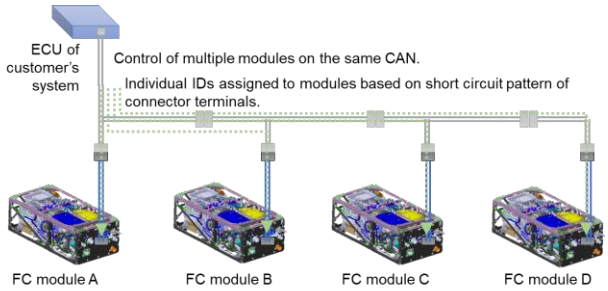

Fig 19 Connection of Multiple FC Modules

2.6 Easy-to-connect single-panel interface for commercial applications

The FC module must be easy to connect to the user's systems. In addition, since applications requiring high power will be connected to multiple FC modules, each module must have an interface that facilitates inter-module connection. The FC system installed in the engine compartment of the Mirai was specifically optimized for the Mirai. Therefore, the interface connections are oriented in various directions. The FC module increases usability while minimizing pressure drop by consolidating all the piping and wiring interfaces at a single panel (**Fig. 18**).

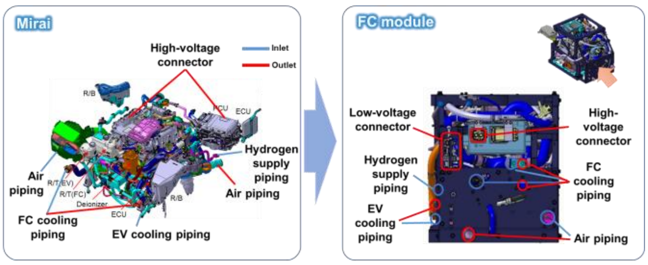

Fig. 18 Interface Consolidating Connections at Single Panel

2.7 CAN communication signals for multiple FC module connection

A controller area network (CAN) is used to communicate between the customer's ECU and the FC module ECU. When multiple FC modules are utilized, each module will have the same ID. This causes confusion during CAN communication and prevents individual module control. However, creating different software for each module to enable individual control would cause an increase in cost. Therefore, ID terminals were created using a 12 V connector, which allows individual IDs to be assigned to separate modules based on the short circuit pattern of the terminals. As a result, multiple modules can be controlled individually by the same CAN communication from the customer's ECU without having to create separate FC module software (**Fig. 19**).

2.8 Improving compatibility with various commercial application

The FC modules were developed to be compatible with a wide range of components provided by the customer, such as high-voltage batteries, as well as radiators and other cooling systems. Compliance was also ensured with product standards, which differ from those for passenger vehicles. The following sections describe these points in more detail.

2.8.1 Compatibility with various high-voltage batteries

In the Mirai, if a short circuit occurs in the high-voltage system, a fuse activates to stop the system safely. In contrast, because the specifications of the batteries and fuses on the user's side will differ depending on the application, the FC system components and cables must be protected on the FC module side. The installation of fuses that interrupt current flow in the event of a short circuit was considered. However, since there were no existing fuses designed for the necessary high voltage/high current specifications, it was decided to incorporate a newly designed junction box (**Fig. 9**).

2.8.2 Compatibility with various cooling systems

The coolant temperature at the FC stack inlet and outlet must be controlled to enable efficient power generation. In the Mirai, since the cooling properties and piping lengths of the radiator are known, this control can be performed using a temperature sensor at the outlet only. Since radiators and piping provided by the user are likely to have various cooling properties, lengths, and so on, a temperature sensor was added to the FC stack inlet (**Fig. 7**). This sensor makes the FC module compatible with a wide range of cooling systems.

2.8.3 Compliance with international commercial standards

FC modules in commercial applications are likely to be installed and operated under a wide variety of environments, some of which may be more severe than those assumed for the Mirai. Therefore, the FC modules were developed to comply with international standards for dust and water protection, vibration, and electromagnetic compatibility (EMC) (**Fig. 20**).

Fig. 20 Environmental Performance Compliant with International Standards

Dust and water protection standards require the product to be completely immersed in water. These are harsh conditions not covered by passenger vehicle standards. Countermeasures adopted for the FC modules included designing the case for the ECU. These measures enable the modules to satisfy IEC 60529: IP67 (excluding the breather of the air compressor).

For compliance with vibration standards, first, the vibration modes of the FC system components in the FC module were analyzed. Based on this analysis, the brackets were designed to offset the resonance points, while reducing stress and weight (**Fig. 21**). As a result, the FC modules comply with category 2 of ISO 19453-6.

For the EMC standards, the FC modules comply with IEC 61000-4-2 and 3, which are international industry standards related to electric and electronic components.

As a result of these efforts, the user of the FC module is not required to take any further measures for compliance, helping to shorten the customer's application development time.

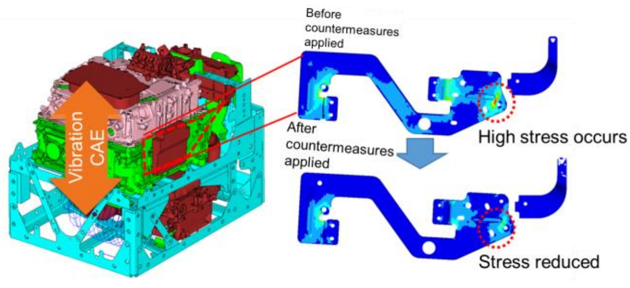

Fig. 21 Bracket Stress Analysis of Acceleration Inputs in Truck

2.9 FC module support and servicing

The FC module concept was announced in February 2021, three months after the launch of the second-generation Mirai. Sales started in March of the same year.[4][5] Inquiries were received from many parties around the world working on trucks, buses, marine vessels, trains, construction machinery, stationary generators, and so on. In addition to selling the FC modules as a product, Toyota also provides engineering support based on the experience gained during the development of the Mirai (**Fig. 22**).

When a customer is considering purchasing an FC module, Toyota provides support related to understanding the properties of FCs and FC systems, hydrogen and high-voltage safety design, safety regulations and compliance, as well as the selection of the appropriate module for the application.

For system design, Toyota uses the model-based development (MBD) and model-in-the-loop simulation (MILS) processes developed for the FC system of the Mirai.[6] These tools support studies of the power ratio of the FC module and high-voltage battery, calculate the lifetime of the FC system, provisionally calculate the hydrogen consumption of the application, and so on.

When the system is started up, Toyota will attend evaluations carried out by the customer (such as bench tests) and assist with the setup.

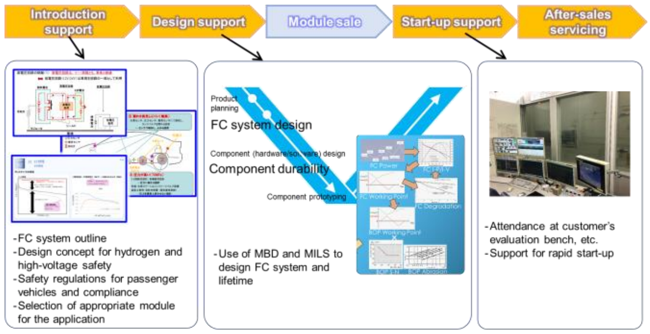

Fig. 22 Support for FC Module Introduction, Design, and Start-Up

Unlike passenger vehicles, there are no dealers or servicing organization in locations outside Japan for these FC modules. Therefore, a servicing organization is being created through the network of the Toyota group to streamline the global introduction of FCs (**Fig. 23**).

Fig. 23 Global Provision of User Services

2.10 Extent of FC module adoption

Fig. 24 shows some examples of the projects currently under way around the world in partnership with our customers. As Toyota has primarily focused on the development of passenger vehicles, many of these projects are a first for the company, and are providing important lessons almost on a daily basis. Many users are just starting to take on the challenge of working toward carbon neutrality, and Toyota hopes to grow and improve together with our partners.

Fig. 24 FC Adoption Projects by Global Users

3. Hydrogen Storage Module

As part of the trend toward carbon neutrality, Toyota has received multiple requests related to the use of hydrogen in non-automotive fields, including trains, marine vessels, stationary generators, cargo handling equipment at ports, and so on. However, a major issue impacting these potential applications is the difficulty of transporting and using hydrogen. Currently, curdles (bundles of cylinders) made of metal high-pressure hydrogen tanks are the main means of hydrogen transportation. However, apart from increased weight, the upper limit pressure of such cylinders is around 20 MPa, which lowers the transportation efficiency. In addition, to use hydrogen across a wide range of fields, tanks with specific hydrogen quantities must be provided for various commercial applications, and customers must be able to use these tanks safely and with peace of mind. Therefore, hydrogen storage modules were developed based on the following principles.

(1) Design tanks for multiple hydrogen quantities in line with the requirements of various commercial applications
(2) Enhance transportation efficiency by adopting the carbon fiber reinforced plastic (CFRP) high-pressure hydrogen tanks developed for the Mirai that use a 70 MPa resin liner (referred to below as “resin high-pressure hydrogen tanks”).
(3) Ensure autonomous safety by introducing abnormality detection and automatic stop functions

3.1 Development of high-pressure hydrogen tanks

First, this section describes the resin high-pressure hydrogen tanks used to build the hydrogen storage module. For the Mirai, tanks with a resin liner were adopted to reduce weight (**Fig. 25**). The volume of hydrogen that can be stored in these tanks is directly related to the cruising range of an FCEV and has a major impact on FCEV usability. When high-pressure hydrogen tanks are installed in a vehicle, the available space is a challenge. Therefore, various sizes of tanks have been developed to make the most efficient use of the available space (**Table 2**). To ensure quality and safety during the tank manufacturing process, the same outer tank diameter was adopted. This allows the axis center to be fixed and ensures stable quality in the process.

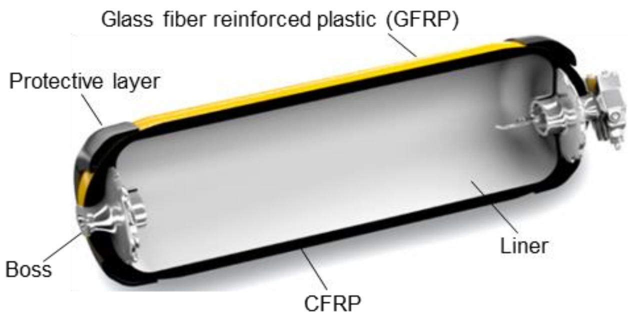

Fig. 25 High-Pressure Hydrogen Tank for the Mirai

Table 2 High-Pressure Hydrogen Tank Lineup

		G2-1	G2-2	G2-3	G2L-1	G2L-2	G2L-3	G2XL-1
Product specifications								
Nominal working pressure	mm	70						
Length	mm	1,467	1,201	684	2,060	1,850	1,650	2,060
Diameter	mm	299			486			702
Internal volume	Liters	64.9	52.0	25.3	230.0	202.0	176.0	457.0
Tank weight	kg	43.0	36.7	22.6	136.0	118.0	100.9	243.8
Hydrogen storage capacity at nominal working pressure	kg	2.6	2.1	1.0	9.4	8.2	7.2	18.7
Compliance with standards and criteria		Chinese technical standard T/CATSI 02 007-2020 UN-R134			UN-R134 (certification planned for 2022)			

3.2 Hydrogen storage module development

The hydrogen storage modules were developed based on the 70 MPa resin high-pressure hydrogen tank system adopted in the Mirai (**Fig. 26**). This system includes multiple hydrogen tanks, the high-pressure piping system connecting the tanks, pressure sensors, and the like. The system also contains a main stop valve that cuts off the hydrogen supply in an emergency, as well as an ECU that controls the action of this valve. In addition, assuming that the hydrogen storage modules might be directly connected to the FC modules, a high-pressure regulator can also be added to control the hydrogen pressure.

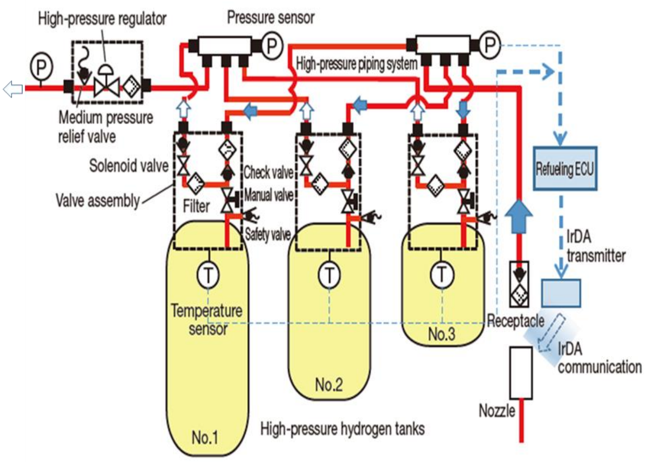

Fig. 26 High-Pressure Hydrogen Tank System for the Mirai

3.2.1 Hydrogen storage module lineup

The unveiled concept model was a module combining four resin high-pressure hydrogen tanks (**Fig. 27**).[7] The development lineup includes four module types with different internal tank volumes (**Table 3**) compatible with various applications. The TC4 module was developed assuming use with stationary generators, the TC8 and TC10 modules are designed for automotive applications such as light-duty buses and light-duty trucks, and the TC36 module is designed for marine vessels and cargo handling equipment at ports, which require large volumes of hydrogen (**Fig. 28**).

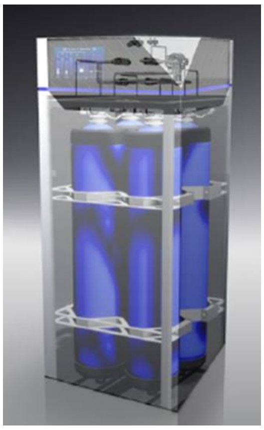

Fig. 27 Hydrogen Storage Module Concept

Table 3 Hydrogen Storage Module Lineup

Type	TC4	TC8	TC10	TC36
External appearance				
Size	769×769×1,177 mm	769×769×1,694 mm	769×769×1,960 mm	2,684×906×2,464 mm
Weight	Approx. 110 kg	Approx. 180 kg	Approx. 220 kg	Approx. 1,000 kg
Tank type	G2-3 × 4 tanks	G2-2 × 4 tanks	G2-1 × 4 tanks	G2-L1 × 4 tanks
Internal tank volume	101 L	208 L	260 L	900 L
Hydrogen storage capacity	4.0 kg	8.4 kg	10.4 kg	Approx. 36.0 kg
Tank working pressure	70 MPa			
Status	Under development			

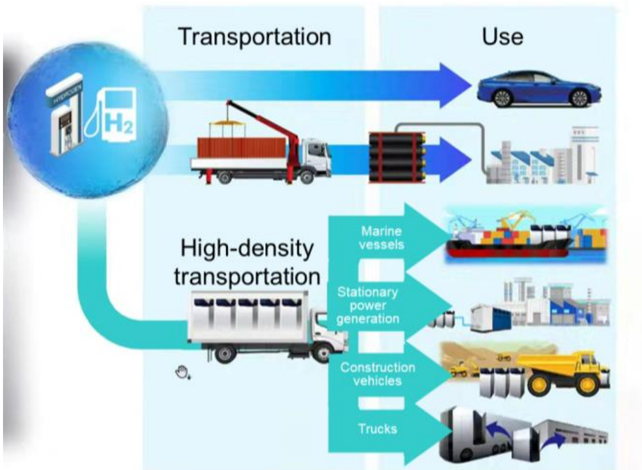

Fig. 28 Outline of Hydrogen Storage Module Usage

3.2.2 Enhancement of transportation efficiency

One of the advantages of a hydrogen storage module is a high weight effectiveness (i.e., the hydrogen capacity per unit weight). The use of lightweight resin high-pressure hydrogen tanks and a high filling pressure of 70 MPa realizes a weight effectiveness four times higher than a curdle utilizing conventional metal high-pressure hydrogen cylinders (**Fig. 29**). As a result, the number of times that hydrogen needs to be transported can be substantially reduced.

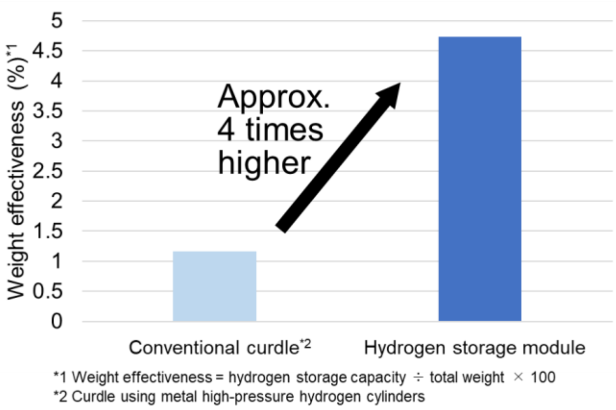

Fig. 29 Weight Effectiveness of Hydrogen Storage Module

3.2.3 Autonomous safety mechanisms

A high degree of safety is necessary to enable easy use of the hydrogen storage module. Therefore, a safety device that automatically monitors the operation state of the module was added (**Fig. 30**). This device is equipped with various safety mechanisms that, for example, immediately shut off the hydrogen supply if abnormal vibration is detected from an external source (**Fig. 31**). The level of these safety systems will be continuously improved through evaluations and field operational tests (FOTs) in real-world usage environments.

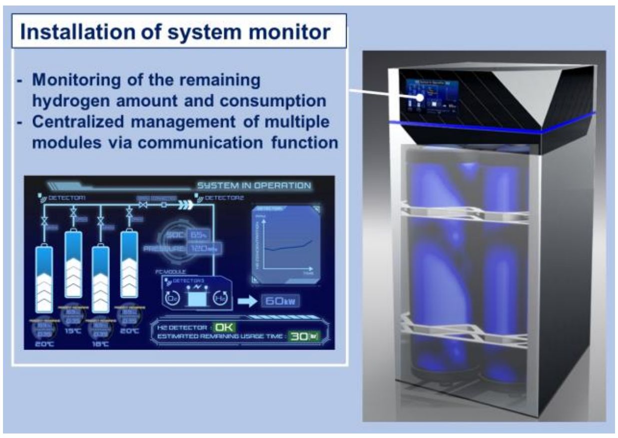

Fig. 30 System Monitoring

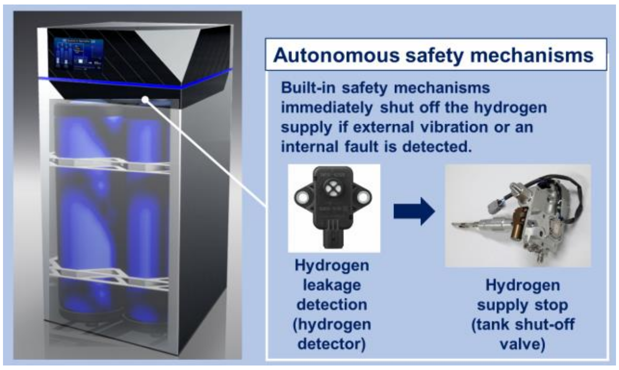

Fig. 31 Autonomous Safety Mechanisms

3.3 Examples of initiatives related to hydrogen storage module development

Permission from the Ministry of Economy, Trade and Industry and other authorities was obtained to demonstrate the transportation of hydrogen in resin high-pressure hydrogen tanks at the Super Taikyu Race Series in March 2022. The resin high-pressure hydrogen tank curdle was able to transport four times more hydrogen than a metal high-pressure hydrogen tank curdle by filling multiple high-pressure resin tanks (16 tanks × 2 sets) up to 45 MPa, and by increasing the number of curdles that can be mounted on a transportation truck due to the lower weight of the tanks (**Figs. 32** and **33**). It should also be noted that the hydrogen was transported using a zero-emission FC truck.

However, since applicable standards for non-automotive use of 70 MPa resin high-pressure hydrogen tanks have yet to be introduced, there are many issues still to be resolved before these tanks can be utilized for hydrogen transportation. The government is studying various measures to safely expand hydrogen usage. Toyota intends to adapt in accordance with these national studies and work to build partnerships and carry out FOTs to help realize even wider utilization of hydrogen.

Fig. 32 Hydrogen Curdle Containing Resin High-Pressure Hydrogen Tanks

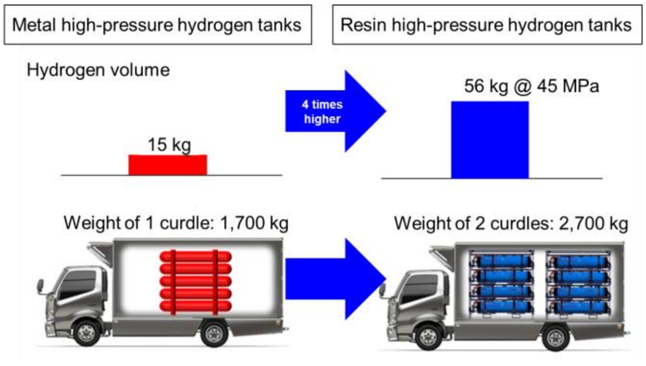

Fig. 33 Comparison of Hydrogen Curdle Transportation

4. Initiatives to Create New Value (FCreation)

4.1 Objectives of FCreation

FCreation is the name of a project aiming to create new value through FCEVs. Its targets were to provide useful services by delivering new hydrogen-related value through FCEVs in partnership with users, and to deliver high-quality and reasonably priced systems with development lead times competitive with systems' integrators around the world. The vehicles manufactured through the FCreation project have several similarities.

All the vehicles were manufactured by converting existing internal combustion engine (ICE) models into FCEVs by adding components such as an FC stack, high-pressure hydrogen tanks, hybrid battery, motors, and the like (**Fig. 34**). All components were carried over from the Mirai passenger FCEV and Sora FC bus. However, if the base model was already electrified, the applicable components were retained.

Fig. 34 Vehicle Manufacturing by Conversion

In addition to zero emissions and low noise, the new value of these vehicles derives from the particular characteristics of FCEVs, namely a high-capacity power supply system and the space available in the vehicle. For these reasons, commercial vehicles with spacious interiors, such as vans, microbuses, and heavy-duty buses were used as the base models. Furthermore, to help create real, tangible value, professional assistance was obtained for the conversion work. For example, if the vehicle is for medical use, assistance was obtained from hospitals. For disaster relief vehicles, assistance was offered by the relevant sections of local authorities.

Large numbers of users inside and outside Toyota have been given the opportunity to experience these vehicles. The aim of such initiatives is to familiarize people with hydrogen and FCEVs, and to obtain feedback for further development. The following sections describe some specific examples of these vehicles.

4.2 Mobile office and food truck using commercial vans

4.2.1 Purpose of manufacturing mobile FC office

Innovative practices have been introduced in recent years to create more efficient ways of working. From this perspective, being able to use dead time, such as queuing, commuting, or waiting, would be productive. For example, participation in online meetings in train stations or trains, or while waiting at the airport has become a common practice. It is also quite usual to work inside vehicles, which shows the growing need for mobile offices. However, conventional vehicles are difficult to use as mobile offices for a whole range of reasons. In addition to establishing the necessary working environment such as a table to place a PC or tablet and stable communications, issues related to the emissions generated when the vehicle is parked for an extended period, noise inside and outside the vehicle, vibration, and the like must also be addressed.

Therefore, it was decided to manufacture a mobile office using an FCEV to take advantage of its electricity power capabilities, low noise, and zero emissions.

4.2.2 Concept of mobile FC office

Fig. 35 shows the exterior and interior of the developed mobile FC office (called the "FCV Intelligent Office"). The concept was to utilize the ample power supply capabilities of an FCEV to enable online meetings, material preparation, breaks, and the like while on the move during working hours. In the event of a natural disaster, this vehicle can also be used as a mobile disaster relief HQ. The maximum capacity of the vehicle is five people, two in the first row, one in the second, and two in the third. A partition is set between the first and second rows, and the rear two rows are arranged into an office space with facing seats. The interior is equipped with tables, power outlets, monitors, cameras, phone chargers, air purifiers, and a high-performance Wi-Fi router that is less likely to be affected by vehicle movement, even in a tunnel.

Fig. 35 Mobile FCV Intelligent Office

4.2.3 Manufacture of mobile FC office

Considering the installation space required for FC components, a conventional Granace was selected as the base model. To minimize the scale of the conversion, the banjo differential and other components of the base model were retained. The FC stack and hydrogen tanks from the Mirai were carried over. The FC stack was installed in the engine compartment and two hydrogen tanks were mounted under the floor. The hybrid battery was placed in the center console between the driver and passenger seats. The motor was inserted into the empty transmission space and connected to the propeller shaft (**Fig. 36**). In addition, a new interface ECU was added between the ECUs of the base model and the FC system. The hydrogen storage capacity of the vehicle is approximately 5.2 kg, which enables a cruising range of around 400 km (Toyota measurement). On the move, the five outlets in the vehicle can use up to 3 kW. While the vehicle is stopped, the power supply system can be used to deliver up to 9 kW. This power generation capacity is enough to realize the vehicle concept described above.

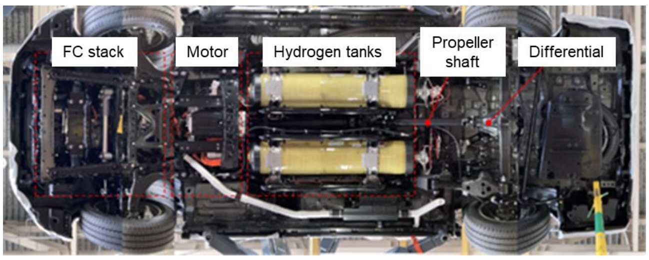

Fig. 36 Underfloor Image of the Mobile FC Office

4.2.4 Example of mobile FC office in use

Fig. 37 shows the mobile FC office being used in a car racing paddock for discussions among team members, online meetings, as well as for meetings with visiting customers. At the same time, the vehicle also supplied power for the lights, monitors, air conditioning, and other facilities in the tent used as the drivers' waiting room. Usually, a racing paddock is full of noise from mobile generators. The quiet mobile FC office enabled easy communication and demonstrated its practicality under real usage conditions.

Fig. 37 Mobile FC Office in Use at Race Circuit

4.2.5 FC food truck concept and vehicle conversion

Another example of a van conversion is the FCV Express Diner food truck (**Fig. 38**). The concept for this vehicle was to provide hot and delicious meals, such as freshly cooked rice, soup, and microwavable frozen ready meals, to a large number of people. Unlike conventional food trucks, the FCV Express Diner has access to electrical power equivalent to that in a stationary restaurant. This includes up to 9 kW via the power supply system as well as power for a single-phase 200 V IH cooker.

The Hiace for the Australian market, which is one size larger than the Granace, was selected as the base model. As with the mobile FC office, the FC stack and hydrogen tanks from the Mirai were carried over.

Fig. 38 FCV Express Diner Food Truck

4.2.6 Examples of FC food truck in use

The image on the left in **Fig. 39** shows someone cooking at a racing circuit. It has also been used as an outdoor restaurant at a food camp and as a food truck at summer festivals and other outdoor events. It can also supply power to other nearby food trucks as required (right image in **Fig. 39**).

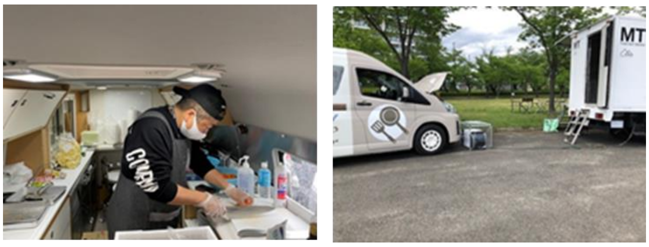

Fig. 39 Food Truck in Use (Left) and Supplying Power (Right)

4.2.7 Other applications of commercial FC vans

Commercial FC vans have been adopted for other purposes in addition to the mobile FC office and FC food truck. **Fig. 40** shows a mobile shop. This vehicle was converted from the same Australian Hiace as the FC food truck and was evaluated by Toyota. Some regions in the towns of Futaba and Namie in Fukushima Prefecture need assistance in providing shopping facilities for residents, particularly in zones designated for reconstruction and recovery after the 2011 Tohoku earthquake and tsunami. This converted Hiace has been used as a mobile shop in these regions since June 2022. Equipped with refrigerators and freezers powered by the FC, this vehicle can stock up to around 500 different items. The vehicle can continue using the power it generates while parked even after the shop closes. This means that items requiring refrigeration or freezing can be left in the vehicle after returning to the mother shop. Toyota intends to continue studying the use of commercial FC vans for other applications.

Fig. 40 Mobile FC Shop in Use

4.3 Microbus-based mobile clinic and shuttlebus

4.3.1 Purpose of manufacturing mobile FC clinic

Toyota is also converting the Coaster microbus, which is one size larger than a van, for use as an FCEV. **Fig. 41** shows the Doctor Car NEO, a mobile FC clinic, which is part of a joint trial project with the Japanese Red Cross Kumamoto Hospital.(8) This vehicle uses its power supply capability to provide local medical services, thereby expanding the scope of services available in local regions. In the event of a natural disaster, this mobile clinic can also be used to serve affected areas and to supply electricity.

Fig. 41 Doctor Car Neo Mobile FC Clinic

4.3.2 Concept and realization of mobile FC clinic

The aim of this project is to provide high-level mobile medical services using the power generated by the vehicle. This project is also a case study to confirm whether the lower noise and vibration of an FCEV can reduce stress in both medical staff and patients.

This mobile clinic uses the FC system installed in the Mirai as a high-power and high-capacity power supply system (output: 9 kW, power: 90 kWh). The interior is equipped with a ventilation system consisting of air conditioning and a high-efficiency particulate air filter (HEPA) to enhance protection against infection.

4.3.3 Manufacture of mobile FC clinic

In the mobile FC clinic, the FC stack is positioned at the front and three hydrogen tanks are installed under the floor. The vehicle has a hydrogen storage volume of approximately 7 kg and a cruising range of approximately 210 km (Toyota measurement).

4.3.4 Manufacture of FC microbus-based shuttlebus

In addition to the mobile FC clinic, Toyota also manufactures a shuttlebus called the “FCV Executive Lounge,” taking advantage of the low noise and ride comfort offered by FCEVs. Each seat is equipped with a power outlet and USB port and the interior also features a large screen. The FCV Executive Lounge is being used as a shuttlebus within Toyota, and is frequently utilized to take customers to and from Toyota’s Head Office in Toyota city and the train station. It has been well-received in this role (**Fig. 42**).

Fig. 42 The FCV Executive Lounge Shuttlebus

4.3.5 Further FC microbus applications

The FC microbus is also being used as a bus inside Toyota's facilities as part of its measures to promote carbon neutrality (**Fig. 43**). As well as simply transporting people, this microbus can also supply clean power while stopped. By installing removable seats or seats that can be turned to face each other, the microbus can also be used for meetings.

Fig. 43 Internal FC Bus: Rear Seats Turned in Facing Position

4.4 Moving e

4.4.1 Aims and concept

Recent natural disasters such as typhoons and torrential rainstorms have damaged power grids, cutting off electricity supplies to homes and evacuation centers. Honda R&D Co., Ltd. and Toyota have combined technologies to create a mobile power generation and supply system called "Moving e" that consists of an FC bus, portable external power output devices, and portable batteries. The FC bus is equipped with high-capacity hydrogen tanks and functions as the power source for the portable external power output devices and batteries. These then supply power to electric devices in a bucket-relay style system (**Fig. 44**).

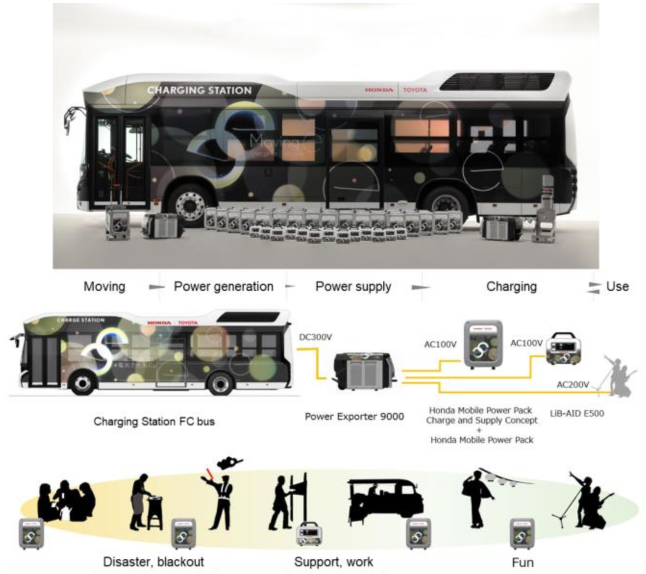

Fig. 44 Moving e

The hydrogen storage capacity of Toyota's Charging Station FC bus was increased to enable a longer power supply capability. More specifically, the Charging Station FC bus is based on the previous version of Toyota's FC bus. It is equipped with almost twice as many high-pressure hydrogen tanks to substantially increase its hydrogen storage capacity. Assuming a one-way journey of 100 km or a two-way journey of 200 km, it has enough hydrogen to supply electricity to a fifty-person evacuation center for three days. This bus features two power supply outlets compared to one on the base model, and can supply up to 9 kW through two circuits (**Fig. 45**).

Fig. 45 Charging Station FC Bus

In the event of a blackout caused by a natural disaster, the bus provides power to Honda Power Exporter 9000 external power supply devices. These units are used to charge high-capacity Honda Mobile Power Pack or LiB-AID E500 units, which can then be used to power electric devices. The use of mobile batteries means that power sources can be carried into individual living spaces in the evacuation center or into individual vehicles.

4.4.2 Example FOTs of Moving e under non-emergency and emergency conditions

Moving e is a mobile power generation and electricity supply system. It can be used to provide electricity to support regions affected by natural disasters, or to provide electricity at outdoor events and the like. A system with this kind of dual function is often described as a “phase-free” system. FOTs involving the Moving e system assuming use under non-emergency and emergency conditions are described below.

The first example is of an FOT that examined the response to a natural disaster. A simulated natural disaster evacuation center was constructed using cardboard to create partitioned living spaces in a gymnasium in Kyoto during the middle of winter. Participants in the FOT spent a whole night and day in this evacuation center to measure the power consumption of electric devices (**Fig. 46**). The results of this test confirmed that the Moving e system could supply enough electricity to power a 50-person evacuation center for three days, even after driving 200 km. The power consumption assumed the cooking of three meals per day, 12 hours of lighting, and round-the-clock use of electric blankets in the individual living spaces. The power required for heating is also likely to fluctuate depending on the season.

Fig. 46 FOT Assuming Emergency Use

The following examples demonstrate the application of the Moving e system under non-emergency conditions. Since outdoor events may be held in areas without a local power supply, the Moving e system was used to supply power under similar conditions. **Fig. 47** shows an example of the Moving e system being used at an event in Iwaki, Fukushima Prefecture, to supply electricity to ten outdoor stalls and a small stage. Assuming that each stall uses one Honda Mobile Power Pack Charge & Supply Concept charger/discharger, it was confirmed that the system could supply electricity to a maximum of 18 stalls at the same time.

Fig. 47 Example of Use under Non-Emergency Conditions

As another example, **Fig. 48** shows the Moving e system being used to supply electricity to devices in the COVID-19 testing area at the entrance to a concert. The testing area on the right of **Fig. 48** (the white tents) was supplied with electricity from the Moving e system and other FCEVs to power the equipment such as lights, heaters, and ventilation systems.

Fig. 48 Example of Electricity Supply at Concert Venue

These FOTs demonstrated the usability of the Moving e system as a mobile power generation and electricity supply system under non-emergency conditions, as well as for evacuation centers in an emergency.

Although the ability of this system to provide aid after a natural disaster is extremely important, these situations do not occur particularly frequently. Therefore, its usability under non-emergency circumstances as a phase-free system is important from a cost effectiveness perspective.

5. Conclusion

The research and development activities described in this article are the result of extensive cooperation between Toyota, customers who chose to purchase and drive the Mirai, partner companies, suppliers, hydrogen infrastructure companies, the relevant government ministries, and local authorities. The authors would like to express their gratitude to everyone involved.

Toyota is looking to deepen its contribution to society and the wider adoption of hydrogen energy by continuing its efforts to enhance and expand the use of hydrogen in a wide range of applications, while working closely with everyone engaged in the fields of production, transportation, and storage.

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Abnormal Combustion Control Technology for Hydrogen Engines

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Abstract

The use of hydrogen produced from renewable energy is regarded as a promising way of helping to achieve a carbon neutral society. In the transportation sector, studies are being carried out into hydrogen engines as well as fuel cell electric vehicles (FCEVs). Hydrogen is easier to ignite than gasoline and is therefore more susceptible to abnormal combustion. This article analyzes the particular abnormal combustion mechanism of hydrogen engines and examines technologies capable of controlling this phenomenon.

Keywords: *carbon neutrality, hydrogen engine, abnormal combustion, pre-ignition, backfire, ignition, spark plug*

1. Background

The use of hydrogen produced from renewable energy is regarded as a promising way of helping to achieve a carbon neutral society. For this reason, various initiatives are under way to promote the use of hydrogen energy.(1) In the transportation sector, compressed hydrogen is the focus of attention due to its high energy density and potential to realize long driving ranges. The utilization of hydrogen has progressed since the launch of the world's first mass-produced fuel cell electric vehicle (FCEV) in 2014. More recently, research has been conducted into hydrogen engines for heavy-duty commercial vehicles, particularly in Europe. To help accelerate these initiatives toward carbon neutrality, Toyota has been promoting partnerships, research, and development related to making, transporting, and using carbon-neutral fuels such as hydrogen by entering a car equipped with a hydrogen engine in the Super Taikyu race series in Japan.

One issue of hydrogen engines is abnormal combustion. Hydrogen induces abnormal combustion more easily than gasoline and is more challenging to use under high-load driving conditions. This article analyzes the particular abnormal combustion mechanism of hydrogen and examines technologies for mitigating this phenomenon.

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2. Characteristics of Hydrogen Combustion

As shown in **Table 1**, the minimum ignition energy of hydrogen is one-tenth that of gasoline, which makes it easier to ignite. The laminar burning velocity of hydrogen is also extremely high (at least five times faster than gasoline). Consequently, hydrogen is capable of achieving stable ignition and combustion even under lean fuel conditions. The resulting reduction in combustion temperature has the potential to increase thermal efficiency.

Table 1 Comparison of Fuel Characteristics(2)(3)

		Hydrogen	Methane	Gasoline
Molecular weight	g/mol	2	16	70 to 90
Density	kg/m^3	0.084	0.651	740
Diffusion coefficient	m^2/s	6.66 × 10^{-5}	2.14 × 10^{-5}	0.5×10^{-5}
Thermal conductivity	W/m･K	0.168	0.030	-
Flammable range	Vol%	4 to 75	5 to 15	2 to 10
Minimum ignition energy	mJ	0.02	0.28	0.25
Laminar burning velocity	m/s	2.65	0.4	0.4 to 0.5

In addition, as shown in **Fig. 1**, compared with isooctane (one of the typical components of gasoline), hydrogen has a longer ignition delay time in high-pressure fields, which makes hydrogen less likely to induce self-ignition (knocking) during the combustion period. However, the trade-off effect of these useful characteristics is a shorter ignition delay time in low-pressure and high-temperature fields, which means that hydrogen induces abnormal combustion more easily under these conditions. As shown in **Fig. 2**, spark ignition is used in both hydrogen and gasoline engines to control the start of combustion. Pre-ignition is a type of abnormal combustion in which ignition occurs before the ignition timing. When pre-ignition occurs, the maximum in-cylinder pressure becomes excessively high and may exceed the design tolerances of the engine. Therefore, abnormal combustion must be suppressed to ensure engine durability.

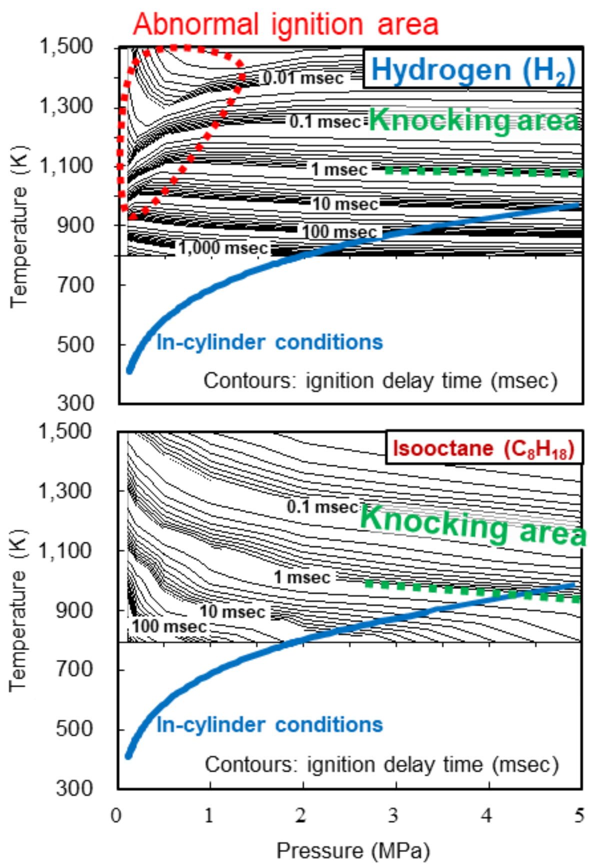

Fig. 1 Ignition Delay Map of Hydrogen and Isooctane (RON: 100)

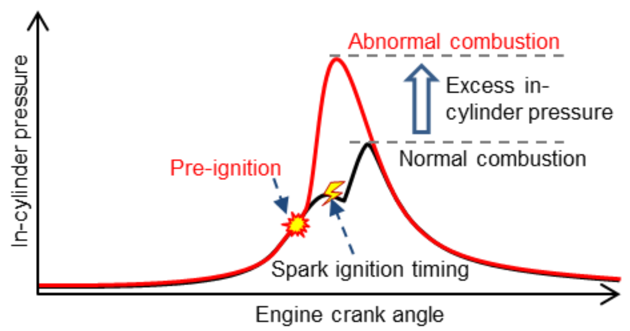

Fig. 2 Comparison of Normal and Abnormal Combustion (Pre-Ignition)

3. Pre-Ignition in Hydrogen Engines

Pre-ignition in hydrogen engines can be broadly categorized into three types in accordance with the ignition phenomenon that occurs: (1) self-ignition in the intake stroke (backfire), (2) runaway type pre-ignition, and (3) sporadic type pre-ignition. The factors causing each pre-ignition phenomenon were analyzed and countermeasures were studied.

3.1 Self-ignition in intake stroke (backfire)

Backfire mainly occurs in engines that intake a mix of air and hydrogen into the cylinder. As shown in **Fig. 3**, when the air-fuel mixture self-ignites during the intake stroke, the mixture completes combustion before compression. Since combustion does not occur at the normal ignition timing after piston compression, the nominal power of the engine is not generated. In addition, since the intake valve is open during the intake stroke, the combustion gas flows back into the intake port at high speed due to the rapidity of combustion, accompanied by explosive noises. Consequently, the intake port and intake manifold may be exposed to unexpectedly high combustion gas temperatures and pressures.

The ignition source of this backfire phenomenon is thought to be high-temperature residual gas in the cylinder. This is because the occurrence of backfire is known to be sensitive to the amount and temperature of the burned gas left in the cylinder by the previous stroke, and because no sensitivity to the cylinder wall or spark plug temperature has been identified.

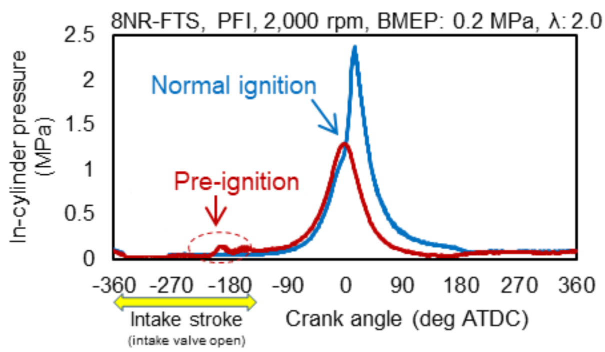

Fig. 3 Example of Self-Ignition in Intake Stroke

One factor why hydrogen induces backfire more easily is thought to be its particularly short ignition delay at low pressures around atmospheric pressure, as illustrated in **Fig. 4**.

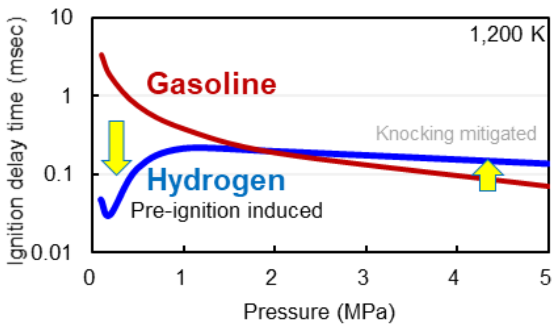

Fig. 4 Comparison of Pressure Sensitivity of Ignition Delay Time of Hydrogen and Gasoline

One effective countermeasure against backfire is to ensure that the temperature of the residual gas in the cylinder is sufficiently reduced. This can be realized by, for example, lean combustion, which increases the amount of air in the mixture, or by adding exhaust gas recirculation (EGR) into the combustion process. However, one concern about using combustion with a leaner air mixture is the fact that hydrogen is easier to ignite in the temperature range between 700 and 750°C (**Fig. 5**). This unique property has the effect of actually increasing the potential for backfire.

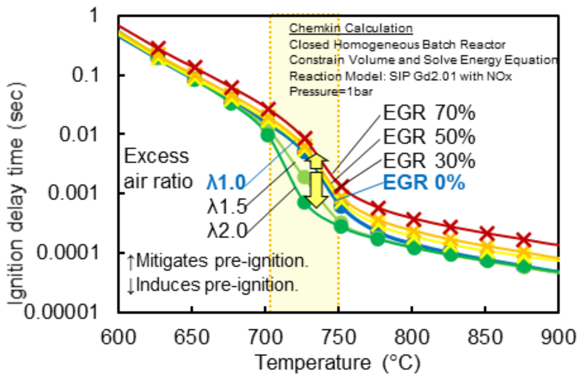

Fig. 5 Effects on Hydrogen Ignition Delay of Using Air or EGR to Form Lean Mixture

Another feasible countermeasure is to use direct injection technology, which adds the fuel after the residual gas and air have mixed thoroughly, to reduce the temperature, rather than pre-mixing the fuel with the air (**Fig. 6**). This is an extremely effective means of preventing backfire and enabling engine operation up to high load regions. However, even when direct injection technology is used, pre-ignition may still occur if the hydrogen fuel jet comes into contact with high-temperature objects or localized areas of high-temperature gas. Therefore, countermeasures to eliminate and separate the hydrogen jet from ignition sources are necessary.

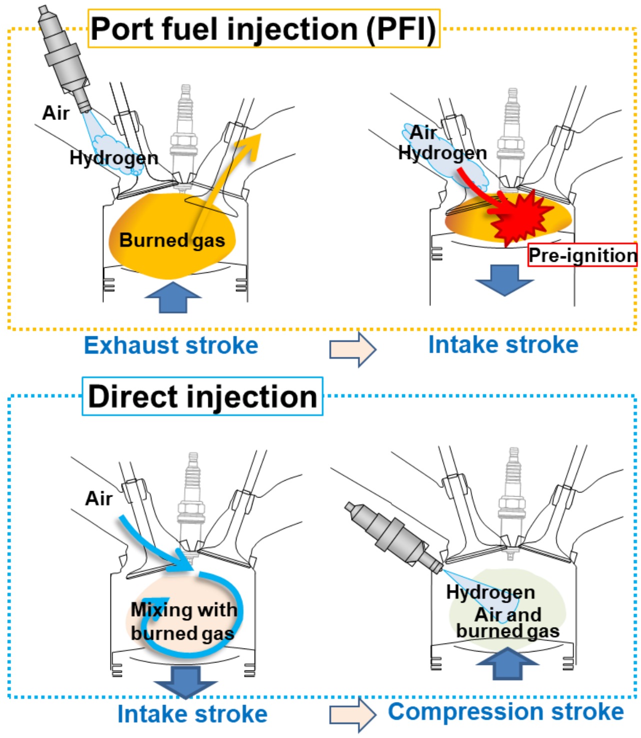

Fig. 6 Comparison of Port Fuel Injection and Direct Injection

3.2 Runaway type pre-ignition

In the same way as gasoline combustion, runaway type pre-ignition can also occur with hydrogen. As shown in **Fig. 7**, if this type of pre-ignition occurs, the ignition timing becomes earlier from cycle-to-cycle, resulting in a continuous state of excess in-cylinder pressure.

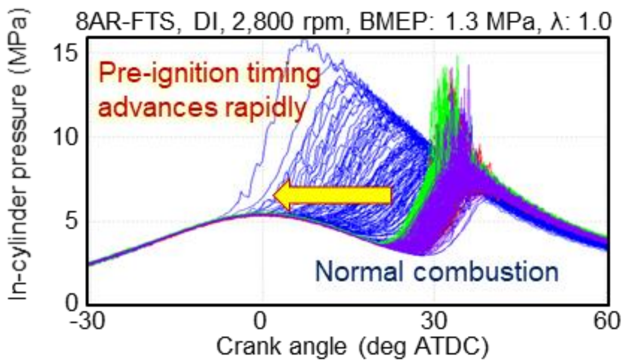

Fig. 7 Example of Runaway Type Pre-Ignition

The appearance of runaway type pre-ignition was observed by visualizing inside a cylinder. **Fig. 8** shows that surface ignition occurred at the high-temperature portion of the spark plug, which is the same ignition source as in a gasoline engine.

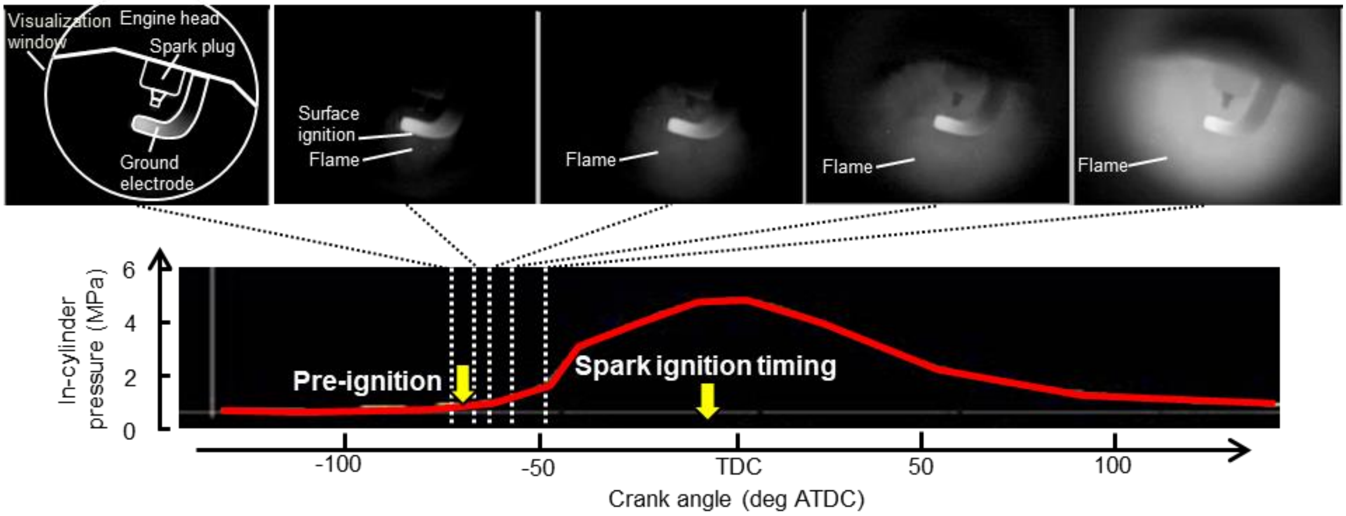

Fig. 8 Visualization and Measurement of Runaway Type Pre-Ignition

Next, the surface temperature of the spark plug that acted as the hydrogen ignition source was measured. **Fig. 9** shows a comparison with the results for a gasoline engine. The surface ignition temperature of hydrogen is approximately 200°C lower than that of gasoline. This is probably due to the higher thermal conductivity of hydrogen (**Table 1**), which is more likely to increase the temperature of the air-fuel mixture. The ground and center electrodes of a spark plug are often the highest temperature portions in an engine cylinder. Therefore, as a countermeasure, a spark plug with a higher heat range was developed to lower the temperature of the ground and center electrodes by about 200°C. Generally, in a gasoline engine, soot deposits on the surface of the spark plug must be burned off to prevent ignition issues. Therefore, there is a limit to how far the spark plug temperature can be reduced. However, since soot deposits are not generated in a hydrogen engine, there is no need to factor in this restriction. As a countermeasure against runaway type pre-ignition, it is important to improve the cooling performance of spark plugs and other high-temperature parts so that the surface ignition temperature is not reached.

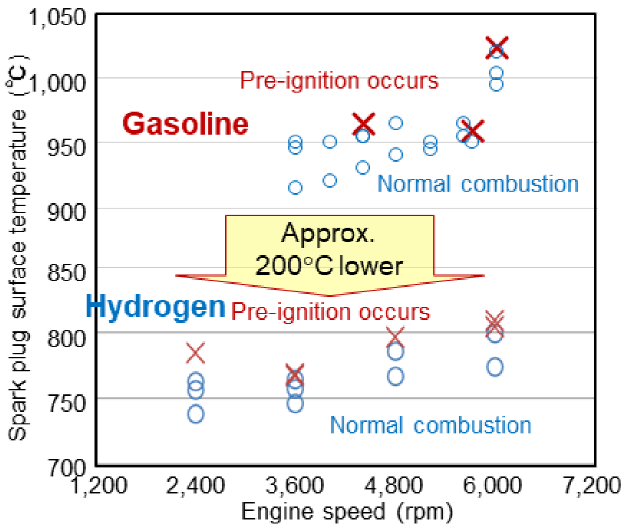

Fig. 9 Temperature of Runaway Type Pre-Ignition

3.3 Sporadic type pre-ignition

Sporadic type pre-ignition frequently occurs when the engine is operated under high loads. **Fig. 10** shows an example in which this type of pre-ignition occurs twice over 1,000 cycles. Unlike runaway type pre-ignition, sporadic type pre-ignition does not occur continuously. Therefore, it is thought that the ignition source changes for each cycle. In addition, since it mainly occurs when the piston is close to top dead center, it is probably caused by gas temperature rise due to compression.

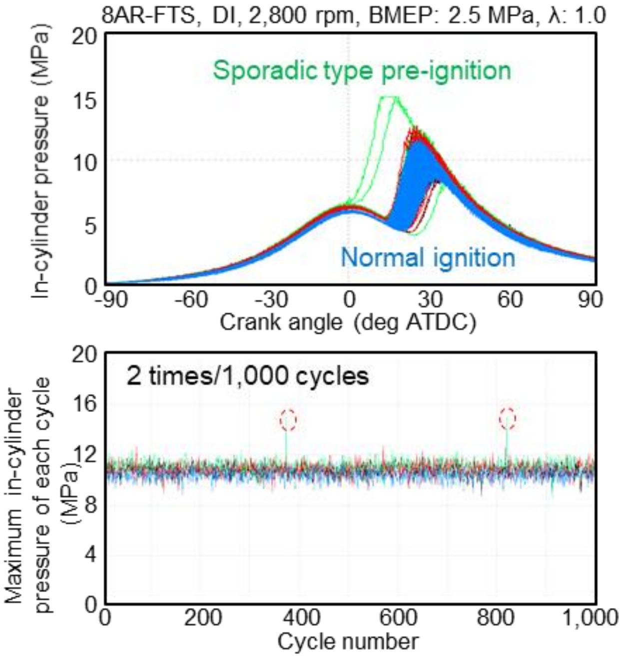

Fig. 10 Example of Sporadic Type Pre-Ignition

Based on these assumptions, the location of cycle-to-cycle changes in the presence of high-temperature gas in the cylinder was investigated by simulations. As shown in **Fig. 11A**, the gas flow velocity becomes slower and stagnates in the gap (pocket) between the spark plug insulator and screw. This result suggests that the temperature of the gas in this pocket increases in cycles when high-temperature residual gas is not adequately purged from the pocket. In addition, as shown in **Fig. 11B**, purging becomes more difficult when the volume of this pocket is large, and the temperature is more likely to rise. From these results, it was hypothesized that residual gas in the spark plug pocket acts as the ignition source when the temperature of this gas increases in cycles with inadequate purging.

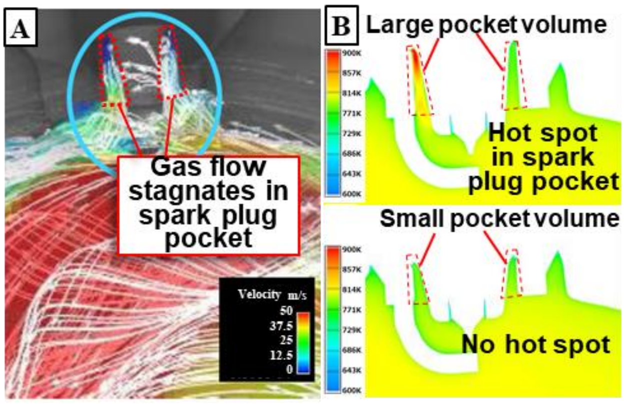

Fig. 11 Stagnation and Temperature Rise in Spark Plug Pocket

To verify this hypothesis, the spark plugs with the specifications shown in **Table 2** were prepared, and the effects on the spark plug temperature and spark plug pocket volume were studied. **Fig. 12** shows the results. As shown in the figure, the sporadic type pre-ignition frequency differed depending on the spark plug specifications, confirming the sensitivity of pre-ignition to the specifications of the spark plug.

Table 2 Spark Plug Specifications

Number	(1)	(2)	(3)	(4)	(5)
Electrode shape	Race shape 1			Creeping surface	Race shape 2
Spark plug heat range	Base	+1			
Spark plug pocket volume (mm^3)	Base	-15	-17	-111	+49

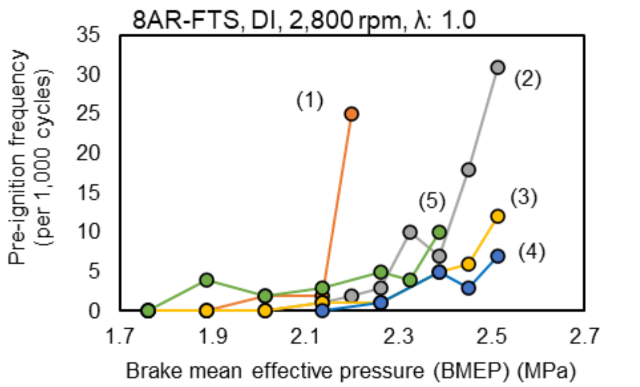

Fig. 12 Sporadic Type Pre-Ignition Frequency

The relationship between the spark plug pocket volume and the minimum torque at which sporadic type pre-ignition occurs was analyzed. **Fig. 13** shows that the pre-ignition torque decreases as the volume increases. This result suggests that minimizing the spark plug pocket volume to facilitate purging of high-temperature gas from the pocket would be an effective countermeasure. For the same reason, it is also important to minimize the volume of concave portions inside the cylinder other than at the spark plug as well. In addition, since high-temperature residual gas in the pocket is derived from exhaust gas remaining inside the cylinder from the previous stroke, this is also an effective countermeasure for lowering the temperature and volume of residual gas.

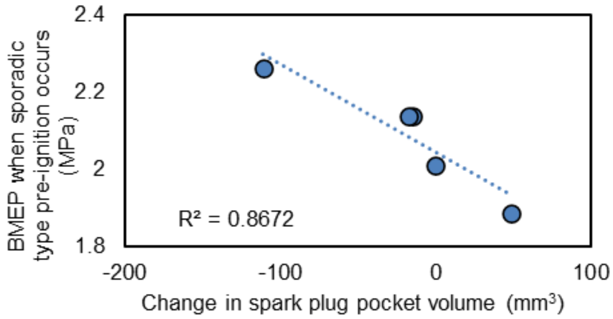

Fig. 13 Effect of Spark Plug Pocket Volume on BMEP when Sporadic Type Pre-Ignition Occurs

4. Conclusions

This research analyzed and studied countermeasures for abnormal combustion phenomena in hydrogen engines. The following knowledge was identified.

(1) Self-ignition during the intake stroke (backfire) is assumed to be caused by heating of the air-fuel mixture by high-temperature burned gas in the cylinder when the air/hydrogen mixture intake occurs. This phenomenon can be addressed by lowering the residual gas temperature or by directly injecting hydrogen into the cylinder after mixing the residual gas with air to adequately reduce its temperature.

(2) Similarly to a gasoline engine, runaway type pre-ignition is caused by surface ignition on high-temperature in-cylinder parts. However, it was found that the self-ignition temperature of hydrogen is approximately 200°C lower than that of gasoline. As a countermeasure, it is important to improve the cooling performance of spark plugs and other high-temperature parts so that the surface ignition temperature is not reached.

(3) Sporadic type pre-ignition involves self-ignition caused by heating of the air-fuel mixture by inadequately purged or cooled high-temperature burned gas remaining in the spark plug pocket or other concave portions from the previous cycle. This phenomenon can be addressed by lowering the temperature or quantity of the residual gas, or by reducing the volume of concave portions in the cylinder, such as the spark plug pocket.

A hydrogen engine developed using these conclusions to mitigate abnormal combustion successfully completed its first race at the Fuji Super TEC 24 Hours race in the 2021 Super Taikyu Race Series. Toyota intends to continue improving this technology and contribute to the achievement of carbon neutrality through the development of high-power, highly efficient hydrogen engines.

Acknowledgments

The results of this research were achieved thanks to the cooperation of Tomoki Fujino, Atsushi Iwami, Yuya Abe, and Ippei Funato at Denso Corporation. The authors would like to express their sincere gratitude to everyone involved.

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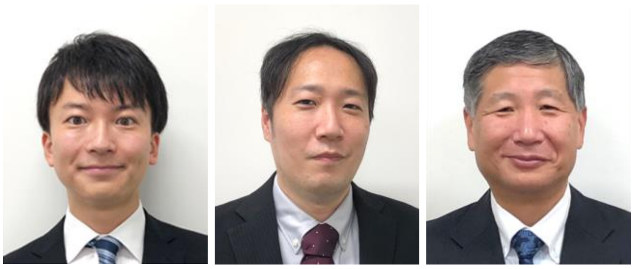

K. Kaneko D. Takahashi K. Nakata

The Spread of Electrified Vehicles as a Power Source

Shinsuke Sugano*1
Shigeki Kinomura*2

Abstract

Toyota has worked to popularize electrified vehicles based on the principle that these vehicles can only contribute to society when used by a large number of people. The capability of electrified vehicles to supply power after a natural disaster when lifelines have stopped functioning has also been recognized and is acting as a driver for popularization. For example, Toyota offered support to affected regions after a massive power outage occurred in Chiba Prefecture in 2019. The many lessons learned through this experience created the opportunity for continuous improvements (*kaizen*) and prompted wider adoption of electrified vehicles as external power supplies. Power supply technologies are also entering wider use as part of next-generation power systems, such as local power generation systems for local consumption coordinated with renewable energy sources to help achieve carbon neutrality.

Keywords: *carbon neutrality, Chiba Prefecture massive power outage, electricity supply system, V2L/V2H/V2G, AC electricity supply system, DC electricity supply system, renewable energy*

1 Introduction

Another merit of electrified vehicles has been attracting attention in addition to the Japanese government's declaration of intent to attain carbon neutrality in 2050 and the rapid advance of vehicle electrification, namely the role of these vehicles as energy reserves if lifelines stop functioning.

The effectiveness of electrified vehicles to carry out this role was recognized after the Great East Japan Earthquake in 2011. Since then, more than twenty Toyota models have been equipped with an electricity supply system, starting with the Prius and followed by subsequent hybrid (HEVs) and plug-in electric vehicles (PHEVs).

Although electricity is often the first lifeline to be restored after a natural disaster, the massive power outage that affected Chiba Prefecture after a typhoon in 2019 continued for an extended period of time. Toyota responded to this situation by dispatching electrified vehicles to the affected area to provide relief. Learning from this experience, Toyota is continuing to promote initiatives related to electricity supply systems.

One of the lessons learned from Chiba is that equipping mass production vehicles like the Prius and Aqua with electricity supply systems as standard is one way to encourage the rapid popularization of vehicles that can provide a useful service in the event of a natural disaster.

2 Relief Efforts during the Massive Power Outage in Chiba Prefecture

2.1 Outline of the massive power outage

Typhoon number 15 of the 2019 Pacific typhoon season (Typhoon Faxai) struck the Kanto region on September 9, 2019, recording wind speeds of 57.5 m in Chiba City and causing massive damage throughout the prefecture. The typhoon toppled electricity pylons and uprooted trees that severed power lines, causing power outages that took much longer than expected to restore (**Fig. 1**).

Fig. 1 Severed Power Lines Caused by Uprooted Trees

*1 TCZ, Toyota Compact Car Company
*2 Electricity Converter Development Div., Powertrain Unit Business Field, Powertrain Company

2.2 Toyota's relief efforts

After receiving a request from the Ministry of Economy, Trade and Industry and Tokyo Electric Power Company (TEPCO), Toyota, Nissan, Honda, and Mitsubishi contributed electrified vehicles to the relief efforts. Toyota dispatched 75 vehicles including HEVs, PHEVs, and fuel cell electric vehicles (FCEVs), and provided assistance to 199 people over 12 days from September 16 to 27.

The authors participated in relief efforts in Sanmu City, Chiba Prefecture by receiving requests from people affected by the power outages and dispatching electrified vehicles to provide assistance (**Figs. 2**, **3**, and **4**).

Fig. 2 Electrified Vehicle Dispatched to Home Affected by Power Outage

Fig. 3 Five Hair Dryers in Use Powered by Fuel Cell Bus

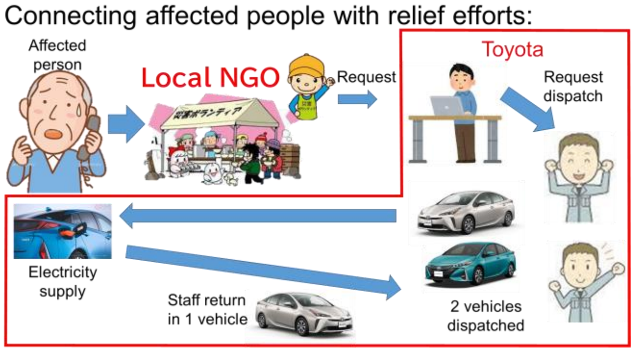

Fig. 4 Connecting Affected People with Relief Efforts

2.3 Lessons learned from the massive power outage

The following four issues were identified after carrying out these electricity supply relief efforts.

(1) Even when electrified vehicles are available, relief efforts stall if contact cannot be made with affected people.
(2) Electrified vehicles close to affected areas (such as test drive cars at dealers and the like) were not used effectively.
(3) Low awareness of electricity supply systems hampers more effective use.
(4) When the accessory outlets inside HEVs are used to supply electricity, the power cord has to pass through an open window. Water intrusion in the rain and vehicle security were raised as concerns.

2.4 Improvements carried out based on these lessons

For issues (1) and (2) above, Toyota City, Toyota dealers, and Toyota Motor Corporation teamed up to develop a matching app capable of connecting with people affected by a natural disaster, and are currently conducting a field operational test (FOT) (**Fig. 5**).

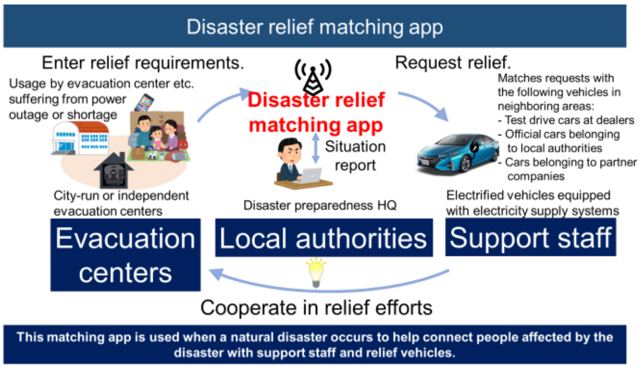

Fig. 5 Matching App for People Affected by Natural Disaster

As a measure to help raise awareness of electricity supply systems to address issue (3), a Japanese language web page called *Toyota no Kyuden* (Toyota's Electricity Supply Systems) was set up (**Fig. 6**).

Fig. 6 *Toyota no Kyuden* Page on Toyota's Website

As measures to address rainwater intrusion and security (issue (4)), an electricity supply system attachment that can be inserted into the window glass was developed (**Fig. 7**) and adopted on the new Aqua and Prius as standard equipment. Power cords can pass through this electricity supply system attachment without rainwater entering the vehicle.

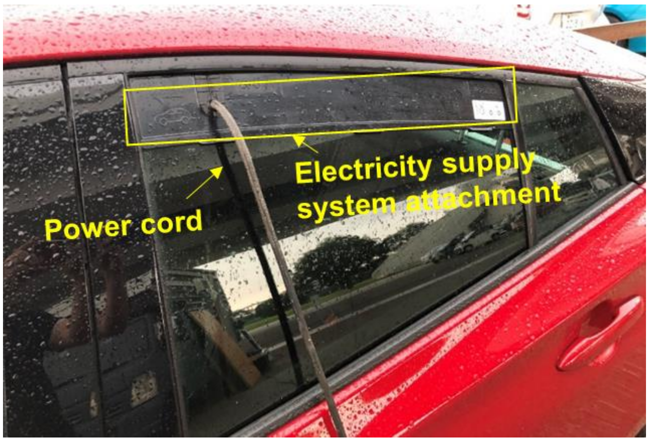

Fig. 7 Electricity Supply System Attachment

2.5 Spread of electricity supply systems

To encourage the rapid popularization of vehicles that can perform a robust role in the event of a natural disaster, the mass-production Prius (from July 2020) and Aqua (from July 2021) were equipped with an electricity supply system as standard equipment in Japan. The massive power outage in Chiba Prefecture also apparently served as the impetus for Toyota Housing Corporation to accelerate development of *Kuruma de Kyuden* (Electricity Supply by Car), a reasonably priced V2H electricity supply system targeting the popular market (**Fig. 8**).

The next section discusses the popularization of V2L, V2H, and V2G systems.

Fig. 8 *Kuruma de Kyuden* (Toyota Housing Corporation)

3 Use of Electrified Vehicles as Power Source

3.1 Types of electricity supply system

This section describes the different types of electricity supply systems using electrified vehicles.

Depending on the destination of the electricity supplied by the vehicle, these systems can be categorized as vehicle-to-load (V2L) systems that supply electricity directly to electrical equipment, vehicle-to-home (V2H) systems that supply electricity to homes, and vehicle-to-grid (V2G) systems that supply electricity directly to the power grid. Of these, V2H systems can be further categorized into V2H systems for power outages that function as a backup electricity supply when the power grid is offline during a blackout, and V2H systems for energy management that are connected to the power grid and function by charging and discharging electricity from the vehicle. A connection to the power grid refers to an electrical connection to a grid managed by power companies (**Fig. 9**). The equipment that realizes this connection must have a power source of equivalent quality to the power grid, and is required to comply with the regulations, standards, and certifications demanded by each region and power company.

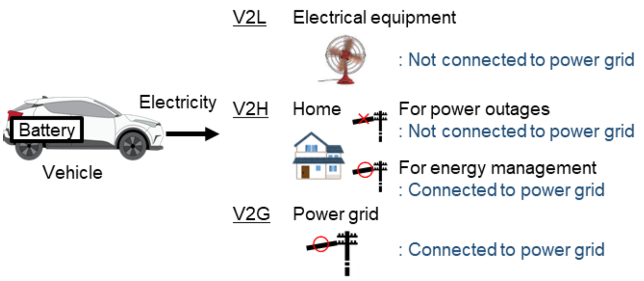

Fig. 9 Types of System Depending on Destination of Electricity Supply

In addition, electricity supply systems are also defined as alternating current (AC) or direct current (DC) systems in accordance with the method that the electricity is supplied from the vehicle.

AC electricity supply systems use a bidirectional onboard charger (OnBC) or the like to convert DC from the battery to AC and supply this AC electricity via V2X equipment connected to the vehicle outlet or charging inlet. In an AC electricity supply system, the vehicle can be regarded as a generator and AC output from the vehicle can be used as-is to power electrical equipment.

In contrast, DC electricity supply systems supply DC electricity via the charging inlet. Subsequently, a bidirectional offboard charger (OffBC) or the like provided for use with the V2X equipment connected to the charging inlet converts this DC to AC for supply to the equipment. In a DC electricity supply system, the vehicle can be regarded as a stationary battery and the V2X equipment as a power conditioner. In the same way as an actual power conditioner, the V2X equipment can be connected to the power grid as necessary (**Fig. 10**).

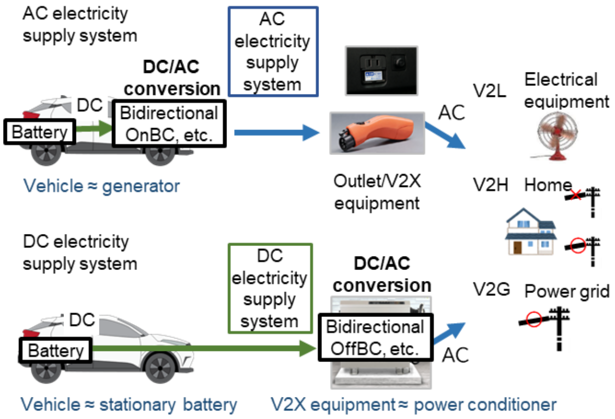

Fig. 10　Types of System Depending on Method of Electricity Supply

3.2 Comparison by type of electricity supply system

Table 1 compares the functions of AC and DC electricity supply systems based on the destination of electricity supply.

Although V2L and V2H (for power outages) systems that do not require a connection to the power grid need a bidirectional OnBC or the like, AC is the most suitable method of electricity supply since this allows the overall system to be delivered at low cost.

In contrast, although V2H (for energy management) and V2G systems that require a connection to the power grid do not need any additional onboard parts, the V2X equipment must comply with the regulations, standards, and certifications demanded by each region and power company. DC, which can satisfy this requirement is the most suitable method of electricity supply in this case.

Table 1　Comparison by Type of Electricity Supply System

Destination of electricity supply	Item	AC electricity supply system	DC electricity supply system
V2L V2H (for power outages) Not connected to power grid	Vehicle	△ Bidirectional OnBC required.	○ Additional parts not required.
	V2X equipment	○ DC/AC conversion not required.	△ DC/AC conversion required.
	Overall system	○ Bidirectional OnBC is lower cost than DC electricity supply system.	△ High cost since DC/AC conversion required for V2X equipment.
V2H (for energy management) V2G Connected to power grid	Vehicle	△ Connection to power grid required (must be compliant with regulations, standards, and certifications. Vehicle cost increases even without V2H/G use).	○ Additional parts not required (can be accomplished by software).
	V2X equipment	○ DC/AC conversion not required.	△ DC/AC conversion required.
	Overall system	△ Vehicle connection to power grid required.	○ Connection to power grid by V2X equipment is possible.

4 Spread of Electricity Supply Systems Using Electrified Vehicles

Recently, a number of field operation tests (FOTs) have been conducted into the construction of virtual power plants (VPPs) that control demand from homes and enterprises in line with electricity generated using renewable energy, and consolidate the various energy resources of homes demanding power as a single power plant (**Fig. 11**). The project shown in this figure involves energy management to control demand from electrified vehicles, heat pump water heaters, storage batteries, and the like of homes and enterprises in line with electricity generated from renewable energy sources such as wind, solar, and biomass, which fluctuates depending on the weather and other conditions. This project aims to verify the feasibility of the local generation of renewable energy for local consumption as a CO_2-free source of energy.

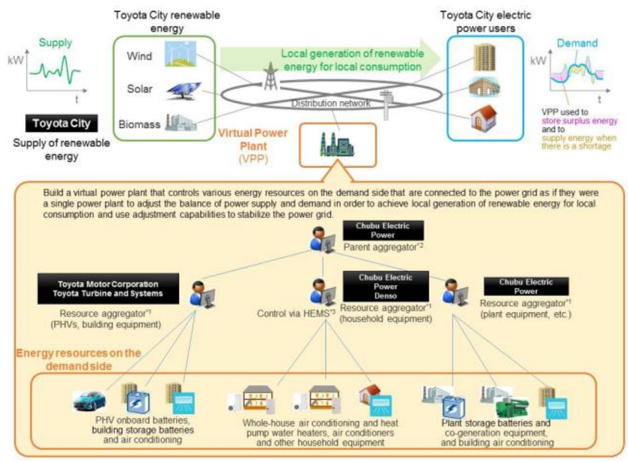

Fig. 11　Structure of VPP FOT Involving Toyota City, Chubu Electric Power, Denso Corporation, Toyota Turbine and Systems, and Toyota Motor Corporation

To examine potential applications of VPPs, FOTs of V2G systems using electrified vehicles are also being conducted. Electrified vehicles are required to function as a distributed power source via a V2G system to stabilize the power grid while adding renewable energy sources such as solar and wind. In the FOT shown in **Fig. 12**, homes demanding power (prosumers[*3]) that possess distributed power sources (an electrified vehicle, solar panels, and storage batteries) and electricity consumers are buying and selling electricity at a fluctuating price in accordance with supply and demand via an electricity trading market. The FOT is verifying the economic efficiency of this system and the effectiveness of bidirectional and autonomous electricity supply systems that enable electricity generated by prosumers to be direct traded with other homes demanding power.[(1)]

[*3] Term derived from the words "consumer" and "producer" to refer to electricity consumers who also possess power generation equipment and produce their own electricity.

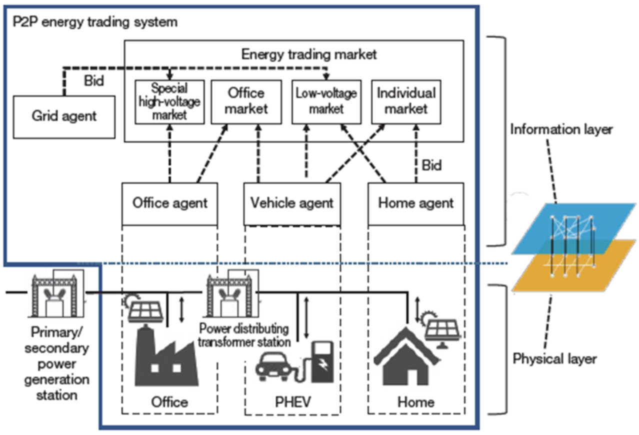

Fig. 12 Structure of Joint FOT of Next-Generation Electricity System Involving the University of Tokyo, TRENDE Inc., and Toyota Motor Corporation

In Japan, standards for DC electricity supply systems using the CHAdeMO system are defined by a document called the "Guidelines of Charge/Discharge System for Electric Vehicle" (issued by the Electric Vehicle Power Supply System Association). Electrified vehicles compatible with V2H and other V2X equipment and capable of DC electricity supply have already been launched onto the market.

In contrast, outside Japan, standards are being formulated for DC electricity supply using the Combined Charging System (CCS), which is growing in popularity mainly in Europe and the U.S., and the GB/T system that is spreading in China. It is likely that electrified vehicles compatible with V2X equipment and capable of DC electricity supply will become more widespread in the future when these standards are issued.

5 Conclusion

In Japan, which frequently suffers from typhoons, earthquakes, and other natural disasters, the role of electrified vehicles in supplying electricity as a backup power source in the event of an emergency is attracting attention. Electricity supply systems have also started to attract attention outside Japan as well as electrified vehicles become more widespread. In the future, electrified vehicles are likely to be seen as potentially useful distributed power sources in V2G systems to help realize carbon neutrality.

Through electricity supply systems, electrified vehicles have the potential to be used as mobile power sources. Toyota intends to continue popularizing electricity supply technologies as part of its mission to mass-produce happiness for people and the planet by spreading the benefits and peace of mind of unrestricted and location-free mobile electricity supply systems for both every-day and emergency use.

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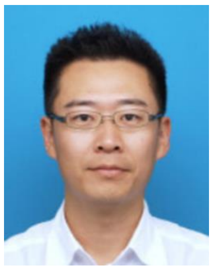

S. Sugano S. Kinomura

2021 Energy Conservation Grand Prize (Minister Prize of Economic, Trade and Industry)

Energy-Saving Activities Based on New Perspectives through Collaboration in Manufacturing, Production Engineering, and Utility (Infrastructure) Sectors

Shinichiro Tamura[*1] Fumio Tamura[*2] Kenichi Ikeya[*1]

1. Background and History of Energy-Saving Activities at Toyota

1.1 Toyota Environmental Challenge 2050

Due to the global financial crisis of 2007 to 2008, cooperative energy-saving activities involving the utility sector and manufacturing divisions became an absolute necessity. Energy-saving efforts across the whole company then gained further momentum with the announcement of the Toyota Environmental Challenge 2050 in 2015. These activities are currently ongoing with involvement from every part of the company (**Fig. 1**).

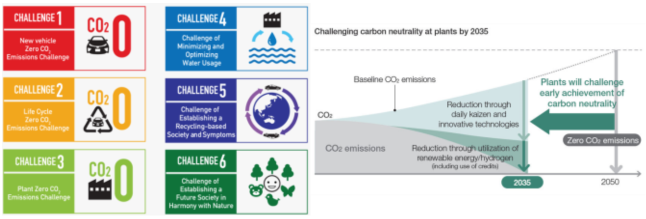

Fig. 1 Toyota Environmental Challenge 2050

1.2 Model line activities taking advantage of the respective the strengths of the three sectors

This article focuses on the painting process, which has the highest energy consumption of all the production processes (**Fig. 2**). **Fig. 3** illustrates the cooperative approach of the activities being carried out by the production engineering, manufacturing, and utility (infrastructure) sectors. These activities are utilizing the strengths of each sector to help broaden perspectives, realize a deeper understanding of specific working fields, and implement the activities as quickly as possible.

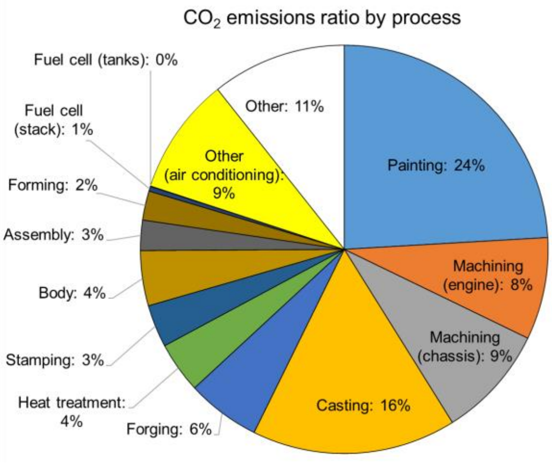

Fig. 2 CO_2 Emissions of each Process

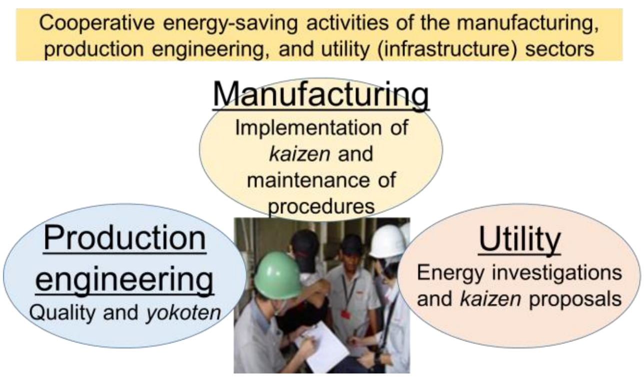

Fig. 3 Cooperative Three-Sector Approach to Energy-Saving Activities

2. Activity Perspectives

2.1 Energy-saving activities with participation by every team member

These activities involved collaboration between the energy usage and supply sides to obtain an overview of the total loss. As shown in **Fig. 4**, various types of loss (such as exhaust gases, heat dissipation, drainage, and the like) occur between energy supply from the boiler to its actual usage as steam.

*1 Plant & Environmental Engineering Div., Production Group
*2 Surface Finishing & Plastic Div., Production Group

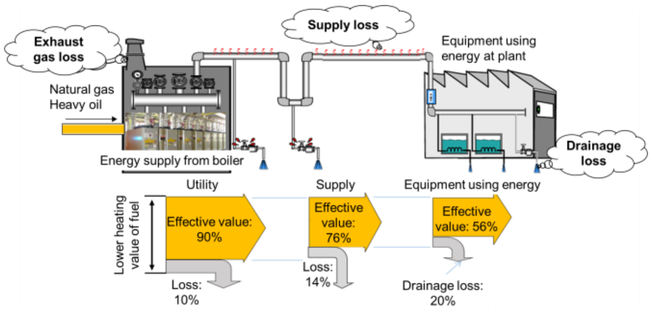

Fig. 4 Visualization of Energy Loss

In addition, to maximize the energy-saving effect and ensure that everyone would be working in the same direction, eliminating the need to supply steam from a centralized heat source was set as the project target. The project also adopted the catchphrase "steam-less" to make the target understandable to everyone.

2.2 Transformation of energy concept from quantity to quality

Conventionally, energy is generated by a large boiler and distributed via a centralized supply system. The various visualized losses (exhaust gases, heat dissipation, and drainage) would be addressed by reducing the *quantity* of losses by, for example, bringing the boiler closer to the equipment, recycling drained elements, and so on. In contrast, these activities focused on the application of heat, factoring in the equipment that uses the energy, the methods of usage, and the equipment requirements to realize a fundamental improvement in energy efficiency. The effectiveness of steam heating can be evaluated in terms of *quality* from the standpoint of the *exergy* of the system, a term that expresses the amount of energy available for use. **Fig. 5** shows a graph that focuses on exergy. Since the graph demonstrates that 76% of steam energy is lost, it was decided to identify an alternative method to steam heating.

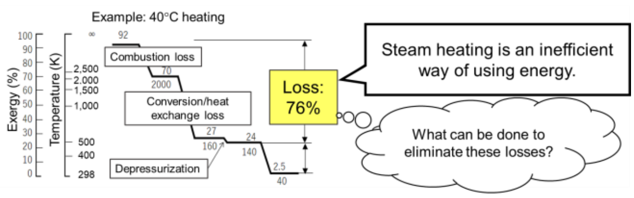

Fig. 5 Visualization of Losses Focusing on Energy *Quality*

2.3 Four perspectives based on process equipment usage

The following four perspectives were adopted in these activities to replace steam heating.

(1) No heating: Eliminate the use of thermal energy entirely.
(2) Recycle renewable energy: Heat recovery from the surroundings using heat pumps.
(3) Utilize waste heat: Raise efficiency using a heat cascade system.
(4) Direct combustion: Raise efficiency by carrying out heating close to the equipment.

3. Activity Examples

3.1 *Kaizen* of oil separator by eliminating heating

This section describes an example of *kaizen* through the application of perspective (1), the elimination of heating. Previously, steam was used to remove oil from the oil separator tank. Focusing on the differences in the specific gravity of oil and the degreased liquid, this activity developed a method that separates the oil by a physical process in a centrifugal separator without heating. This process reduced energy consumption by 99%, while also saving space, realizing stable quality, and reducing waste (**Fig. 6**).

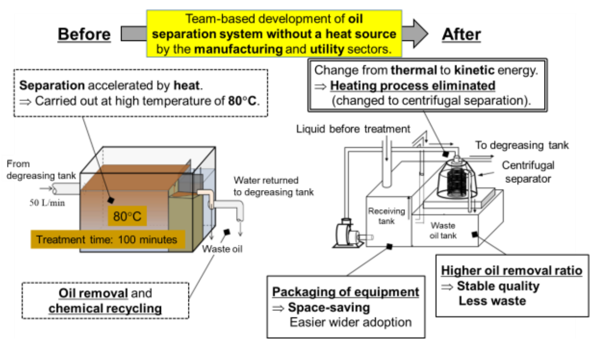

Fig. 6 Example: *Kaizen* of Oil Separator

3.2 Heat management and full heat usage

This section describes an example that adopted perspective (2), the recycling of renewable energy and perspective (3), the utilization of waste heat. Examples of *muda* (waste) in painting pretreatment include the presence of high-temperature waste heat in another process and a requirement to re-heat the vehicle during pretreatment. From the standpoint of overall heat source optimization, it was decided to apply waste heat to the intermediate tank. Instead of steam, this heating process is carried out using a heat pump, which enables thermal recycling and reduces loss (**Fig. 7**).

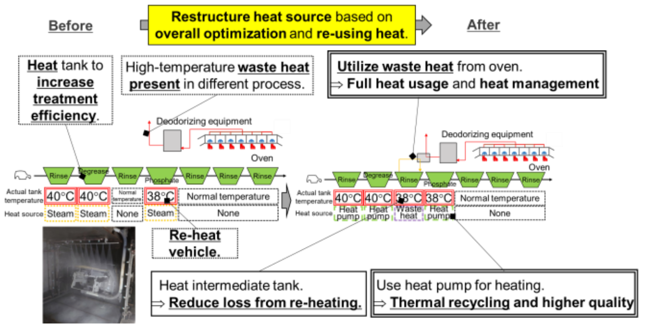

Fig. 7　Heat Management in Painting Pretreatment Process

4. Activity Sustainability and *Yokoten*

4.1 Sustainability through weekly energy report

Fig. 8 shows an example of the weekly energy report, which breaks down energy usage into type. This report shows the results of constant monitoring of abnormal situations during holiday periods as well as detailed abnormalities in energy usage based on a week-to-week comparison. It also allows team members in each working field to clearly identify the effects of small items of *kaizen*. Information like this helps to facilitate thorough working field management and keeps team members onboard with the activities. Additionally, it is used to identify control errors through comparisons with the energy consumption of similar equipment, which also helps to save energy.

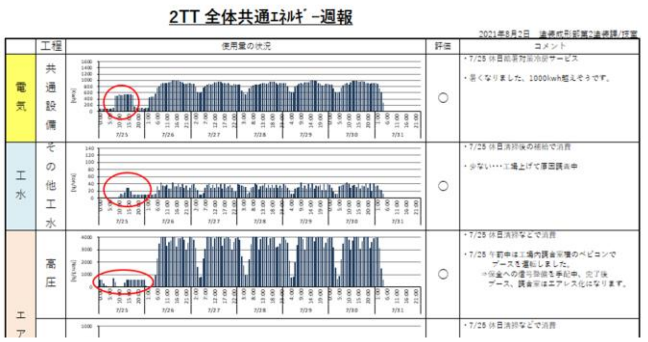

Fig. 8　Weekly Energy Report

4.2 Global and partner company *yokoten*

Fig. 9 shows an engineering key point report that describes one of the examples of *kaizen* outlined in this article. This report is shared both inside and outside Toyota. Matrix-based management of plant-based and *kaizen* information helps to ensure that these activities are fully carried out. **Fig. 10** shows an example of the support provided to apply these activities globally and to partner companies via *genchi-genbutsu* and workshops. These model line activities have also been carried out across the board rather than aimed at specific people, enabling full participation by all team members.

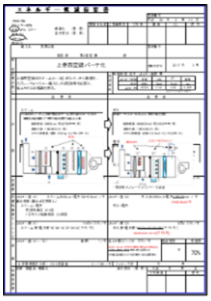

Fig. 9　*Kaizen* Key Point Report

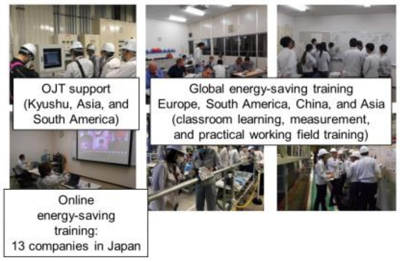

Fig. 10　*Genchi-Genbutsu* Workshop

5. Summary

Activities centered on the cooperative approach to eliminating the use of steam described in this article have reduced Toyota's overall CO_2 emissions by 65,000 tons. In addition, teaching and learning from team members across global Toyota and its partner companies has helped to develop a culture of full participation in energy-saving activities. As the movement toward carbon neutrality gains momentum around the world, Toyota intends to continue its energy-saving activities from a personal first-person perspective, in line with the needs of each working field and society as a whole.

54th Ichimura Prize in Industry for Distinguished Achievement

Virtual Human Body Model

Yuichi Kitagawa[*1] Takao Matsuda[*1] Masami Iwamoto[*2]

1. Introduction

In 2021, the number of traffic collision fatalities in Japan was 2,636 people, the lowest total since record-keeping began.[(1)] However, with the number of collisions and injuries continuing to climb, further efforts are needed to identify the causes of collisions and apply safety countermeasures. Vehicles are designed to absorb collision energy through the partial deformation of the body and to physically restrain the occupants using seatbelts and other devices. Crash tests are carried out at the prototype phase to ensure passive safety performance, and crash test dummies are used in these tests to measure the forces applied to human bodies. Measurement items include acceleration at the location of the brain and the deformation of dummy parts representing bones. However, crash test dummies are constructed robustly for durability and repeatability, and do not recreate actual injuries. Therefore, Toyota and Toyota Central R&D Labs., Inc. jointly developed a virtual human body model called THUMS (**Fig. 1**). THUMS reproduces the structure and vulnerabilities of a human body on a computer, and is capable of simulating the occurrence of injuries. THUMS is used to analyze the factors causing injuries in traffic collisions and plays an important role in the research and development of safety technologies.

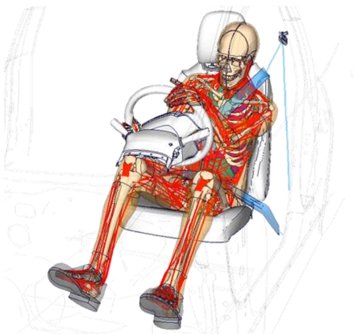

Fig. 1 THUMS Virtual Human Body Model

[*1] Advanced Mobility System Development Div., Advanced R&D and Engineering Company
[*2] Toyota Central R&D Labs., Inc.

2. Details of Technology

2.1 History of development

THUMS Version 1 was released in 2000. This virtual human body model mainly reproduced the bones in the body and was used to predict bone fractures. After a number of incremental advances, Version 4 was released in 2010 with the capability of analyzing injuries to the brain and internal organs. Version 6, which reproduces muscle activity, was released in 2019 (**Fig. 2**). The addition of muscles to the model enables the simulation of posture changes due to, for example, abrupt braking. In addition to a mid-size male model, adult models that simulate the physique of a small female and large male, as well as models that reproduce the physique of children have also been developed.

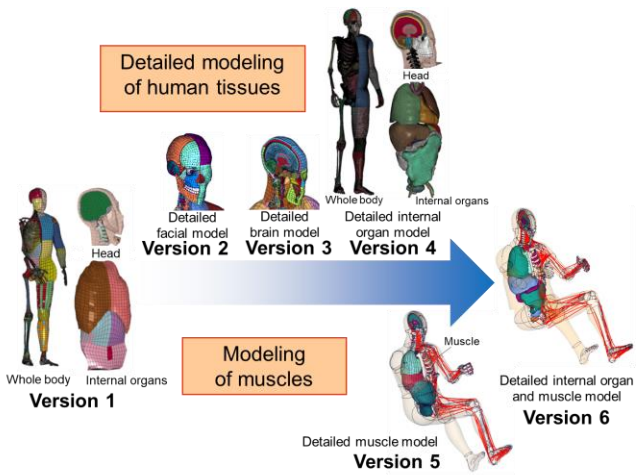

Fig. 2 History of THUMS Development

2.2 Verification of fidelity to human body

THUMS was developed based on computerized tomography (CT) scans of an actual person. The geometry and positional relationships of bones, joints, the brain, internal organs, and other body parts were all faithfully reproduced. To analyze injuries in traffic collisions, it is necessary to realistically reproduce the forces and deformation that occur when a human body contacts a part of the vehicle. The structure, physical properties, injury resistance, and other aspects of each body part from the head to the feet were defined in reference to the literature. In addition, a research paper that investigated the impact tolerance of the human body[2] was also consulted to verify that the mechanical response of THUMS is close to that of a human body (**Fig. 3**).

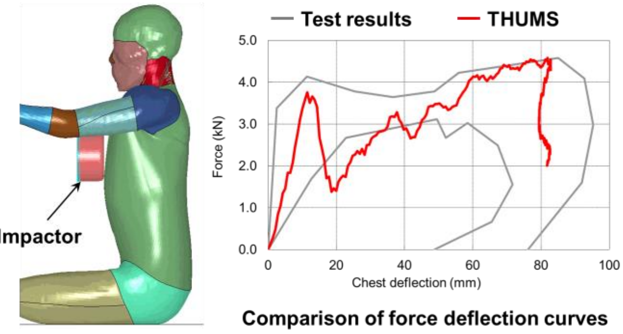

Fig. 3 Example of Verification of Fidelity to Human Body (Chest)

2.3 Examples of utilization of THUMS

Rear-end collisions are the most common type of traffic collisions.[1] Occupants of struck vehicles sometimes experience neck pain commonly referred to as whiplash associated disorders. Although the mechanism of these disorders has not been fully identified, one possible explanation describes how the relative distance between the head and torso generates strain in the neck soft tissue and stimulates the nerves.[3] The WIL Concept Seat was developed utilizing THUMS (**Fig. 4**). In a rear-end collision, this seat functions by sinking the torso into the seat back while the head is firmly supported by the head restraint. This minimizes the relative distance between the head and torso.[4] This technology has been widely adopted in passenger vehicles launched since 2005. According to an insurance company survey, a lower number of whiplash associated disorders occurred in rear-end collisions of Toyota vehicles equipped with the WIL Concept Seat.[5] This is one example in which THUMS-based injury analysis has helped to enhance vehicle safety. THUMS has also been used in research into pedestrian and occupant protection in frontal and lateral collisions. More recently, the introduction of safety assessments using virtual human body models is being discussed.

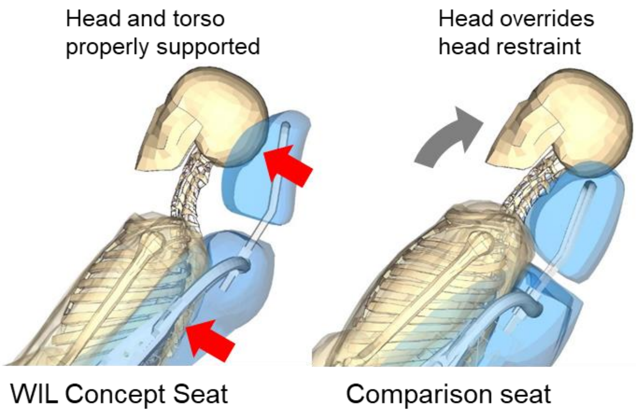

Fig. 4 Example of Application of THUMS to WIL Concept Seat

3. Conclusion

The THUMS virtual human body model has been developed and used to analyze the factors causing injuries in traffic collisions, as well as to facilitate the research and development of safety technologies. In January 2021, the THUMS software was made freely available. Zero traffic collision casualties cannot be achieved by one company and depends on the cooperation of the entire automobile industry, as well as partnerships with governments, other industries, and academia. Toyota hopes that THUMS will be widely used by automotive engineers and researchers to help promote research toward an ever-safer mobility society.

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(3) O. Boström et al. "A New Neck Injury Criterion Candidate-Based on Injury Findings in the Cervical Spinal Ganglia after Experimental Neck Extension Trauma." *International Research Council on Biomechanics of Injury* (IRCOBI) (1996) pp. 123-136.

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Distinctive Merit Award, The 51st Japan Industrial Techniques Grand Prix
The JSAE Technological Development Prize (72nd JSAE Awards)

Toyota/Lexus Teammate Advanced Drive

Tomoya Kawasaki[*1] Masahiro Iwasaki[*1] Masayuki Soga[*2]
Satoru Taniguchi[*3] Osamu Ozaki[*4] Kaiji Itabashi[*4]

1. Introduction

Toyota is working to enhance and widen the adoption of active safety systems toward the ultimate goal of zero casualties and injuries from traffic accidents. Since conventional systems cannot handle all possible types of traffic accident, the scope of these systems must be expanded to help further reduce the number of accidents in the future. Toyota believes that automated driving technology can contribute to accomplishing this objective.

2. System Overview

2.1 System concept

Driving consists of repeated cycles of recognition, judgment, and operation processes. Automated driving technology functions to safely carry out these processes instead of the driver, and may be regarded as an effective means of helping to protect the driver and support safe driving. Toyota's approach to automated driving is defined under the Mobility Teammate Concept. Under this concept, the driver and vehicle share the same purpose and act as partners who understand each other and, at times, watch out for and help one another. This article describes the development of the Toyota and Lexus Teammate Advanced Drive systems. These systems operate on controlled-access expressways under driver supervision, and are capable of supporting overtaking, lane changes, and lane branches toward a destination, as well as hands-free lane tracing and headway distance maintenance.

2.2 System configuration

Fig. 1 shows the system configuration. Its main features are as follows.

(1) The use of radar, LiDAR, and cameras to recognize the 360-degree area around the vehicle precisely, reliably, and robustly.
(2) Sophisticated redundancy design capable of fail-safe operation for four seconds after a malfunction or error.
(3) Over-the-air (OTA) software update system.

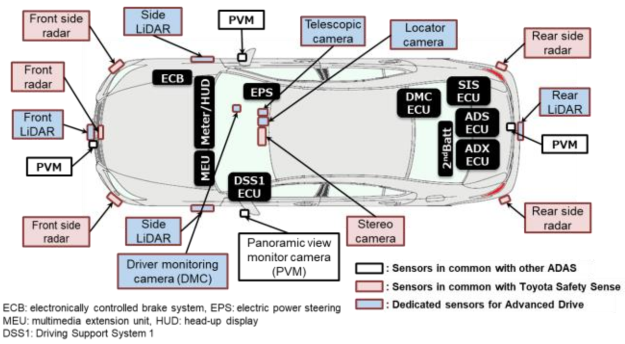

Fig. 1 System Configuration

3. Main Technologies

3.1 Recognition

The Advanced Drive systems combine deep learning technology with conventional rule-based algorithms to recognize objects around the vehicle and lanes on the road. This combination realizes highly reliable and robust recognition performance (**Fig. 2**). Since innovation occurs rapidly in the field of artificial intelligence (AI), OTA software updates are regarded as particularly useful for this technology.

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*4 Woven Core, Inc.

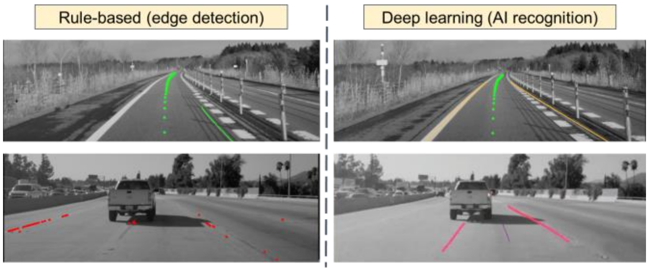

Fig. 2 Examples of AI Image Recognition

3.2 Localization

Localization, which estimates the precise position of the driver's vehicle on a high definition map (HD map), is one of the fundamental technologies of automated driving. The system follows the procedure outlined in **Fig. 3** to realize robust localization even when driving inside tunnels, along urban canyons, and other locations with poor radio wave reception.

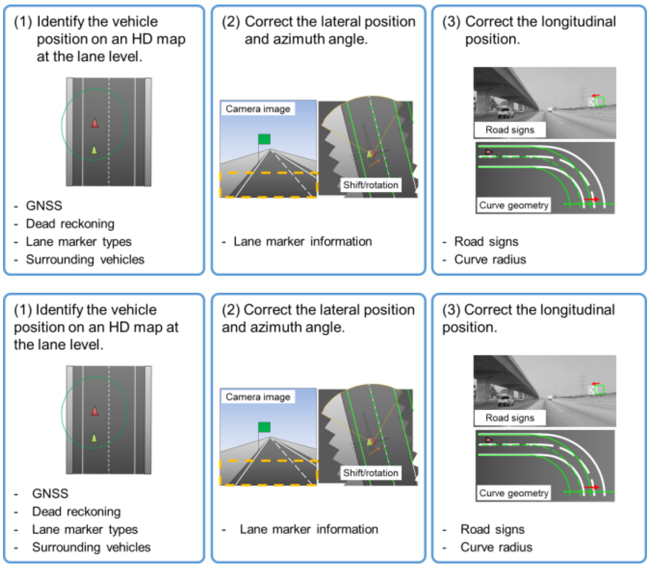

Fig. 3 Localization Function

3.3 Driver management system

For a highly-automated driving support system, it is important to prevent overconfidence or incorrect usage by the driver. Therefore, to ensure that the driver remains engaged in the driving process, a driver management system was developed to ensure intentional driver intervention at key points (**Fig. 4**).

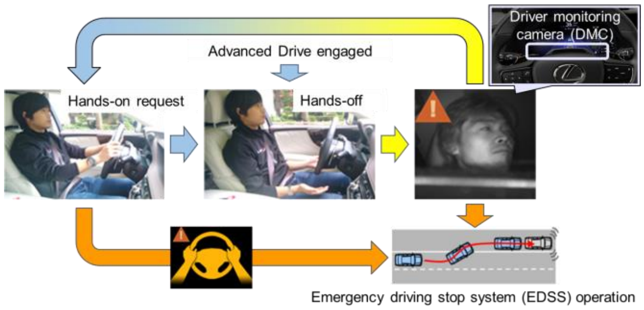

Fig. 4 Driver Management System

3.4 Vehicle dynamics control

To realize confident and natural hands-off driving, the driving operations of skilled drivers were analyzed alongside the resulting vehicle behavior. This enabled smooth dynamic performance by seamlessly connecting the deceleration, turning, and acceleration processes of negotiating a curve (**Fig. 5**).

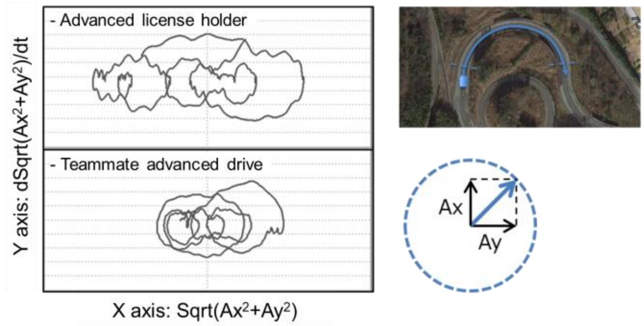

Fig. 5 Example of Dynamic Vehicle Control Analysis

3.5 OTA data uploading and downloading

Using OTA, a function was developed that collects valuable real-world data on how the driver is using the vehicle, near-miss incidents, and the like. The latest performance updates and new features can also be delivered to the user as quickly as possible via OTA (**Fig. 6**). A total of five software updates had already been delivered between the launch of the system in April 2021 and the end of August 2022.

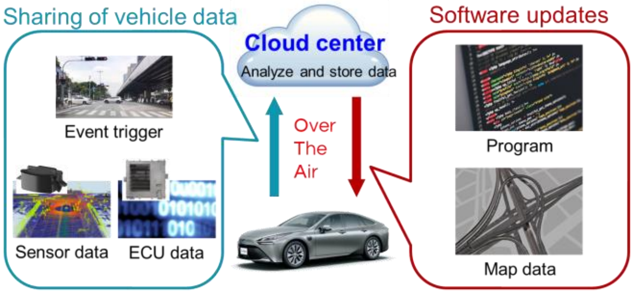

Fig. 6　OTA Data Uploading and Downloading

4. Conclusion

The Toyota and Lexus Teammate Advanced Drive systems were developed and subsequently commercialized in Japan and the U.S. to help achieve Toyota's ultimate goal of realizing a society in which everyone can travel safely, smoothly, and freely. These systems have upgradeable OTA and market data collection capabilities, which should help to accelerate software development and its adoption with new safety applications. Toyota intends to continue development toward the realization of zero casualties and injuries from traffic accidents.

Reference

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List of Externally Published Papers of FY2021

Publication Name	Title	Presenter	Affiliation
Transactions of the Society of Automotive Engineers of Japan, Inc.	Efficient Powertrain System Development by Model Application - Whole Process Framework -	Hideyuki Handa Tsuyoshi Takahashi Takayuki Omachi Munenori Imaeda Shota Nagano	Toyota Motor Corporation (same as above) (same as above) (same as above) (same as above)
Transactions of the Society of Automotive Engineers of Japan, Inc.	Efficient Powertrain System Development by Model Application (Second Report) - A Consistent Process from a System Development to the Calibrations with the Engine Model -	Munenori Imaeda Yoshihiro Nomura Tsuyoshi Takahashi Takayuki Omachi Hirokazu Kurihara Yoichi Tsuda Kosuke Sasaki	Toyota Motor Corporation Toyota Central R&D Labs., Inc. Toyota Motor Corporation (same as above) (same as above) (same as above) (same as above)
Transactions of the Society of Automotive Engineers of Japan, Inc.	Development of Mathod to Measure the State of Fuel Supply During Cold Start and Application of the Data to Modeling of Emission Using Machine Learning	Tomohisa Yamada Hideto Inagaki Yoishiki Takatori Yusuke Hakuta Teruaki Haibara Kazuhiro Umemoto	Toyota Central R&D Labs., Inc. (same as above) (same as above) (same as above) Toyota Motor Corporation (same as above)
Transactions of the Society of Automotive Engineers of Japan, Inc.	Research into integrated vehicle control ordered by six-component force at center of gravity	Etsuo Katsuyama Yoshio Kano Makoto Yamakado Masato Abe	Toyota Motor Corporation Kanagawa Institute of Technology (same as above) (same as above)
Transactions of the Society of Automotive Engineers of Japan, Inc.	Roll Dynamics Control Method for Steering Input Considering Coupling of XY-plane and Roll	Takuma Takeuchi Etsuo Katsuyama	Toyota Motor Corporation (same as above)
Transactions of the Society of Automotive Engineers of Japan, Inc.	Development of Cooling Model of Hybrid Vehicle Transaxle - Experimental Acquisition of Themal Resistance between Motor and Oil -	Takumu Honda Shigeru Kimura Masataka Tanase Takehiko Hirano Takashi Matsumoto	Toyota Motor Corporation (same as above) (same as above) (same as above) (same as above)
Transactions of the Society of Automotive Engineers of Japan, Inc.	Practical Use and High Functionalization of High Heat Resistance Pyrochlore Type CeO_2-ZrO_2 Oxygen Storage Material	Takuya Okuda Akiya Chiba Motoya Abe Masahide Miura Takeshi Nobukawa Akira Morikawa	Cataler Corporation (same as above) (same as above) Toyota Motor Corporation (same as above) Toyota Central R&D Labs., Inc.
Transactions of the Society of Automotive Engineers of Japan, Inc.	Development of Hydrogen Mixing Pipe for New FCV by Using Two-phase Flow Simulation	Hideyuki Arai Shuji Kurita Yushi Suzuki Koro Fujio	Toyota Motor Corporation (same as above) (same as above) (same as above)
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Transactions of the Society of Automotive Engineers of Japan, Inc.	Development of Real-time Measurement Techniques of Hydrocarbons in Vehicle Exhaust Gas by FT-IR and Mass Spectrometric Methods	Kotaro Tanaka Katsuhiro Kushida Yuki Nomura Kenichi Tonokura Toru Uenishi	Ibaraki University (same as above) The University of Tokyo (same as above) Toyota Motor Corporation
Transactions of the Society of Automotive Engineers of Japan, Inc.	Study Reliability Evaluation of C-SMC by Acoustic Emission	Yukihiro Hamada Yuta Ishigami Atsushi Mikuni Shintaro Kitakata	Toyota Motor Corporation (same as above) (same as above) (same as above)
Transactions of the Society of Automotive Engineers of Japan, Inc.	Power Control in Dynamic Wireless Power Transfer for Hybrid Vehicles - Experimental Verification on High-speed Rotary Bench -	Shogo Tsuge Shuntaro Okazaki Toshiya Hashimoto Sakahisa Nagai Toshiyuki Fujita Hiroshi Fujimoto	Toyota Motor Corporation (same as above) (same as above) The University of Tokyo (same as above) (same as above)
Transactions of the Society of Automotive Engineers of Japan, Inc.	Development of High-Pressure Hydrogen Tank for New FCV	Sogo Goto Takashi Inou Masato Ueda Akira Yamashita	Toyota Motor Corporation (same as above) (same as above) (same as above)
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Transactions of the Society of Automotive Engineers of Japan, Inc.	Air Quality Estimation in 2050 - JSAE 2050 Challenge and Air Quality in 2050 -	Tazuko Morikawa Hiroyuki Yamada Kotaro Tanaka Shinichiro Okayama Yoshiaki Shibata Yasumasa Nakata Hiroe Watanabe Toru Kidokoro	Japan Automobile Research Institute Tokyo Denki University Ibaraki University Nissan Motor Co., Ltd. Institute of Integrated Atmospheric Environment. Toyota Motor Corporation Nissan Motor Co., Ltd. Toyota Motor Corporation
Transactions of the Society of Automotive Engineers of Japan, Inc.	Influence of Engine Oil Evaporation Characteristics on Oil Consumption of Internal Combustion Engines.	Takashi Suzuki Takashi Koyama Kazuo Yamamori Yuta Uematsu Satoshi Hirano Noriya Ishizaki Kotaro Wada	Toyota Motor Corporation (same as above) (same as above) (same as above) (same as above) (same as above) ENEOS
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Transactions of the Society of Automotive Engineers of Japan, Inc.	Construction of Autonomous Driving Systems Model Based on the Definition of Operational Design Domain and Proposal of Safety Analysis Approach Based on SOTIF Concept	Fumiaki Kono 1)2) Shinobu Ochiai 1)3) Yoshikazu Sakai 1)4) Yoshiyuki Nagai 1)5) Satoshi Otsuka 1)6) Takeo Hashimoto1)7) Hidekazu Nishimura 8)	1)JASPAR 2)ADVICS CO.,LTD. 3)Honda Motor Co., Ltd. 4)Nissan Motor Co., Ltd. 5)Toyota Motor Corporation 6)Hitachi Astemo, Ltd. 7)Hitachi Industry & Control Solutions, Ltd. 8)Keio University.
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SAE Technical Paper	Development of Coated Gasoline particulate filter design method combining simulation and multi-objective optimization	Yuki Ota Hiroaki Takahasi Ryosuke Maekawa	Toyota Motor Corporation (same as above) (same as above)
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SAE Technical Paper	Teammate Advanced Drive System Using Automated Driving Technology	Tomoya Kawasaki Derek Caveney Masayuki Katoh Daisuke Akaho Yosuke Takashiro Kenji Tomiita	Toyota Motor Corporation Toyota Motor North America Inc. Woven Core Inc. Toyota Motor Corporation (same as above) J-QuAD DYNAMICS Inc.
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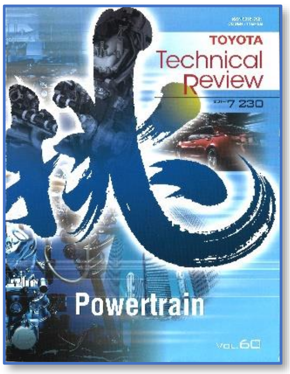

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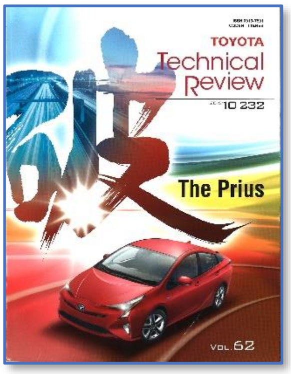

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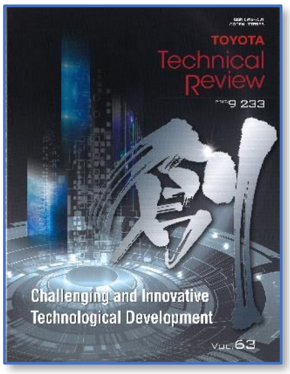

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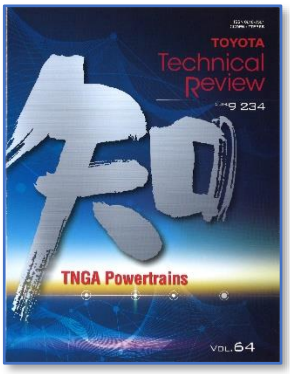

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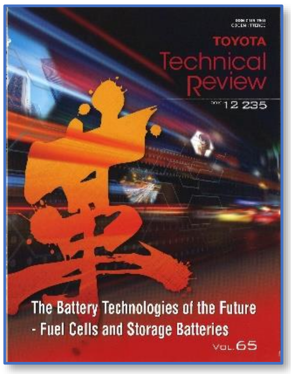

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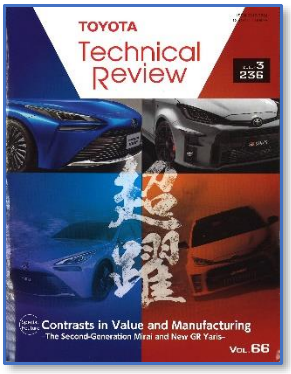

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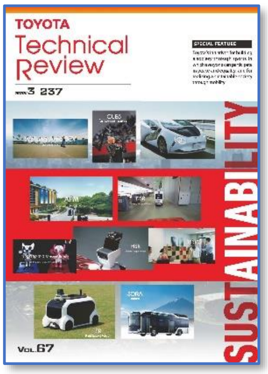

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Planning	Jun Tohyama
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(Publishing Office)	Administration Support Dept.
	Toyota Office
	TOYOTA ENTERPRISE INC.
Published	April 28, 2023