TOYOTA
Technical Review

Special Feature

Toyota's Role in a Circular Economy

Technical Articles of the New Model
LAND CRUISER 250

January 2025 Vol.70 No.1

Preface

The special feature of this issue of the *Toyota Technical Review* (Volume 70-1) is Toyota's role in a circular economy.

The last three editions from Vol. 68 to Vol. 69-2 have discussed the details of Toyota's initiatives for achieving carbon neutrality with the objective of making sure no one is left behind. Toyota is also pursuing a wide range of options following its multi-pathway approach to building cars. This issue of the *Toyota Technical Review* introduces several of the company's initiatives to realize these objectives.

Creating a recycling-based circular economy is equally important as achieving carbon neutrality. In addition to expanding existing initiatives to reduce, reuse, and recycle resources (known as the "3Rs"), this means making sure that raw materials and products provide value for as long as possible, and ensuring that waste is minimized in design. This approach must be implemented in parallel with efforts to achieve carbon neutrality, while also establishing new recycling-oriented economic systems.

Therefore, over the next two issues, the *Toyota Technical Review* will present an overall image of Toyota's initiatives for a circular economy alongside various measures that will play a key role in their success. As an introduction, this issue presents an outline of what a circular economy means and describes the following three initiatives.

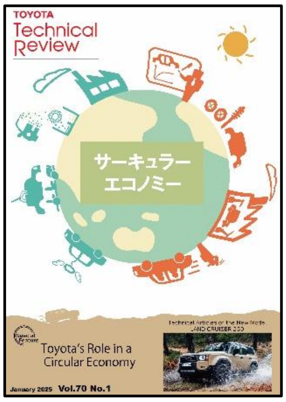
- Measures adopted at the design phase to make used vehicles easier to dismantle.
- The recycling of materials (aluminum, magnets, and plastics).
- The proper disposal and cyclical use of automotive batteries.

Complementing the special feature articles, this edition also features a deep dive into the latest model in the Land Cruiser lineup, the new 250 series. We hope that you will enjoy reading all of these wide-ranging articles.

Achieving carbon neutrality and building a circular economy will depend on the pooled knowledge and strength of every stakeholder in today's society. Through the *Toyota Technical Review*, we plan to continue showcasing Toyota's initiatives to our readers. We look forward to hearing your comments and advice as we move toward achieving a mobility society for an ever-better future.

Head of Planning, *Toyota Technical Review*

Cover design



The illustration in the center of the cover symbolizes Toyota's role in a circular economy. In sequence from the top right, it shows the sequence of processes from planning and design to part manufacturing, vehicle manufacturing, and use in orange, followed by the processes of scrapping, dismantling, crushing, sorting, and material manufacturing in green. This represents the circulation-based concept of arterial and venous processes in the vehicle life cycle. When this cover design was created, one of the main priorities was to adopt a simple and pop-art style that would pique the interest of as many people as possible. As a member of the Toyota family, this was an excellent opportunity for me to learn about the company's initiatives for a circular economy, and another chance to consider how I can make a contribution through my work.

Kohei Toyoda, MS Design Div., Mid-size Vehicle Company

Contents

Initiatives for the Circular Economy

Takayuki Nagai[*1]

Abstract

The transition from a linear economy built on the premise of mass production, mass consumption, and mass disposal to a circular economy based on the recycling of resources and products has started to take place on a global scale. Although Toyota has been continuously engaged in efforts related to vehicle recycling for many years, it has responded to this transition by commencing further initiatives aimed at extending the useful life of vehicles and parts, realizing more efficient use, and eliminating waste. The special feature of this edition of the *Toyota Technical Review* outlines Toyota's current initiatives for the circular economy, and discusses potential future developments.

Keywords: *circular economy, resource recycling, recycling, design for easier dismantling*

1. Introduction

The global population currently stands at 8 billion people and it has been reported that this number of people consumes 1.75 times more natural resources than the Earth's ecological system is capable of regenerating.(1) The transition from a traditional linear economy built on the premise of mass production, mass consumption, and mass disposal to a circular economy based on the recycling of resources and products has started to take place on a global scale. Toyota has been continuously engaged in efforts related to vehicle recycling for many years and has responded to this transition by starting a range of further initiatives. At the same time, government policies around the world are becoming increasingly proactive. For example, in around 2020, Europe started working on a resource recycling vision and more stringent end-of-life vehicle (ELV) regulations. Japan has introduced measures to reduce resource consumption and address the issue of the final disposal location, known conventionally as the reduce, reuse, and recycle (3R) approach. Building on this approach and to help realize a circular economy, the Japanese Ministry of Economy, Trade and Industry (METI) formulated the Growth-Oriented, Resource-Autonomous Circular Economy Strategy in 2023. Circular Partners, a partnership between industry, government, and academia, was established based on this strategy. As of March 2024, participation in this partnership had grown to 398 members. Circular Partners has begun studies toward creating a target vision for Japan's circular economy and the measures required to achieve this vision, a sign of the growing attention being given to this issue on a national level. This edition of the *Toyota Technical Review* presents an overview of the circular economy as it applies to vehicles as well as the issues faced by the automotive industry. It also elaborates on the following four initiatives: vehicle circularity, design for easier vehicle dismantling, material circularity, and vehicle battery circularity.

*1 CE Promoting Dept., Advanced R&D and Engineering Company

2. Current Situation

2.1 The circular economy

The concept of the circular economy can be illustrated in various ways. One way is the "butterfly diagram" created by the Ellen MacArthur Foundation that expresses the idea of breaking away from a linear economy founded on mass production, mass consumption, and mass disposal.(2) **Fig. 1** shows an annotated version of this diagram. The right side of the figure shows the technical cycle, which illustrates the circulation of finite resources. In sequence from the inner aspects of the overall cycle, this involves maintenance and sharing followed by reuse, remanufacturing, and recycling to create a more preferable cycle of energy use. Then, the left side shows the biological cycle, which illustrates the circulation of renewable resources. The individual aspects of the biological cycle are longer than the aspects of the technical cycle.

Next, it is important to consider the relationship between a circular economy and carbon neutrality. The objective of carbon neutrality is to reduce CO_2 based on the context of alleviating climate change. Consequently, the main methods of achieving carbon neutrality are activities to reduce CO_2 derived from fossil fuels, energy-saving, and the like. In contrast, the objective of the circular economy is to prevent the generation of waste and enable the long-term continued use of resources. The use of recycled materials may be regarded as an essential initiative for achieving both the circular economy and carbon neutrality from the perspectives of converting waste that would normally be incinerated into resources and reducing the CO_2 generated during the incineration process (**Fig. 2**).

Based on the approaches outlined above, Toyota is working to promote the realization of a circular economy under the following concepts: minimizing the extraction of efficiently using the Earth's natural resources, enabling the profitable long-term use of valuable resources, and regenerating these resources to a valuable state after use.

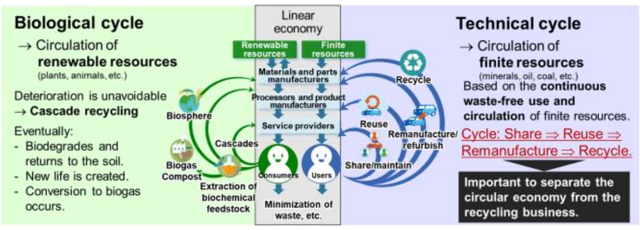


Fig. 1 Butterfly Diagram

Source: created based on materials provided by the Ellen MacArthur Foundation(2)

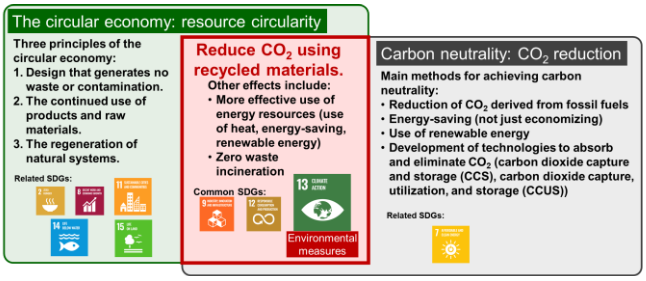


Fig. 2 Relationship between the Circular Economy and Carbon Neutrality

2.2 Regulatory trends

2.2.1 European trends: European ELV regulations(3)

In July 2023, the European Commission (EC) released a proposal for revised regulations covering ELVs. **Figs. 3** and **4** describe the contents of this proposal. From the standpoint of materials, it specifies recycled material usage rate targets for plastics (the rate of recycled plastic in the total weight of plastic used in the vehicle) in new vehicles from 2031, requiring that recycled plastic (specifically post-consumer recycled (PCR) plastic) should make up 25% of the total amount of plastic used in the vehicle. In addition, the proposal also states that 25% of this 25% PCR content (i.e., 6.25% of the total amount) should be recycled materials derived from ELVs. The proposed revised regulations also cover materials not mentioned in previous rules. In addition to obligating disclosure of the usage rates of recycled steel, aluminum, magnets, magnesium, and other materials, the regulations also state the intention to discuss setting usage targets for recycled materials in the same way as plastic. In addition to materials, the proposal also indicates the direction for regulations related to design and information disclosure. It describes targets for achieving design considering the ease of dismantling of nineteen parts, including electric vehicle (EV) batteries, traction motors, catalysts, and bumpers, targets for the removal of nineteen parts before crushing by venous industries, as well as targets for prohibiting the shipment of ELVs outside the region. Taken together, the objective of the regulations is to promote the recycling of resources within Europe. This approach requires serious initiatives from all aspects of the industry, both arterial and venous. Although this regulation is likely to be enacted in 2025 at the earliest and includes preparation and study times before its enforcement, rapid measures will be necessary since it will lead to massive changes in existing vehicle structures, as well as in the flow of goods and information.

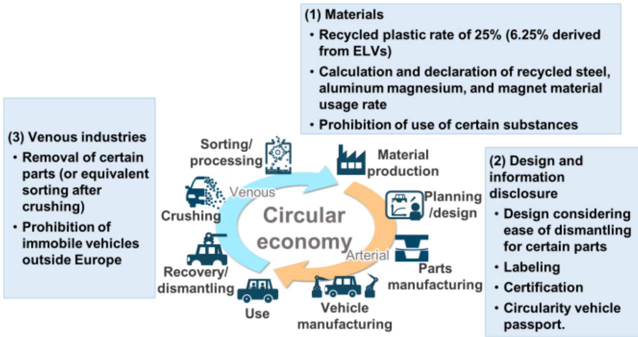


Fig. 3 Outline of the Proposed European ELV Regulation

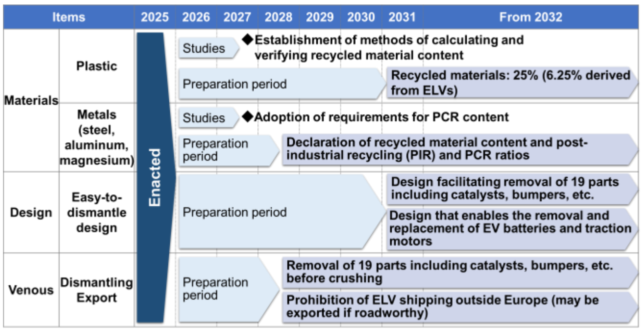


Fig. 4 Schedule for Adoption of Proposed European ELV Regulation

2.2.2 The European Battery Regulation

The European Battery Regulation includes specific requirements to provide basic battery-related information and ELV data, in addition to recycled material usage rate targets for lithium (Li), cobalt (Co), nickel (Ni), and lead (Pb). This regulation also contains provisions that must be satisfied by existing and new model vehicles. Another aspect of this regulation is the requirement to create a system for information disclosure (the so-called "battery passport"). Information to be disclosed includes data on battery material composition, recycled material usage amounts, due diligence, and battery performance. Companies must comply with this regulation before being permitted to sell electrified vehicles in the European market.

2.2.3 Obligations for target setting and disclosure

Another recent trend is the growth in investment that considers environmental, social, and governance-related (ESG) responsibilities. Under the Corporate Sustainability Reporting Directive (CSRD) enacted in November 2022, companies are obliged to disclose their ESG initiatives. The circular economy is included from primarily an environmental perspective. Companies inside Europe (including Toyota Motor Europe (TME)) are required to start disclosing this information in 2026. Subsequently, the directive will be expanded to cover companies outside Europe that do business in the region. As a result, Toyota will also be required to disclose on a global basis for fiscal years 2028 and 2029. At this timing, Toyota must disclose information on its targets, progress, and details of its initiatives toward achieving a circular economy.

2.3 Trends of the automotive industry

Automakers have set targets for the overall usage rates of recycled materials or plastics (**Table 1**). These figures might change if biomaterials or renewable plastics are included. The Toyota Environmental Challenge 2050 encompasses the Challenge of Establishing a Recycling-Based Society and Systems as one of the company's initiatives. Activities for this challenge started in 2015.[(2)] Additionally, in its Sustainability Data Book in October 2023, Toyota declared a target of at least 30% for the use of recycled steel, aluminum, plastic, rubber, and other materials (**Table 2**). Other companies are demonstrating concept vehicles to help achieve a circular economy, alongside various proposals indicating the future direction of initiatives at these companies.

Table 1 National and Regional Trends and Recycled Material Targets Set by Automakers

	Government targets	OEM targets

Europe and the U.S.	**European ELV regulations (to be enacted from 2025 at the earliest)**
	• Recycled (PCR) plastic rate: 25%, of which 25% derived from ELVs: to be enforced 72 months after enactment of the regulations.
	• Provisions extend gradually to metals.
	  • Steel: targets to be determined 23 months after enactment of regulation.
	  • Other metals: targets to be determined 35 months after enactment of the regulations.
	• Provisions gradually extend to obligation to disclose recycled material rates, and to satisfy design, manufacturing, recovery, and dismantling requirements.
	U.S. Environmental Protection Agency: 2021 National Recycling Strategy
	• Improve market for recycled products, increase number of products, and reduce contamination.
		Renault: Launched "The Future is NEUTRAL" strategy to increase amount of recycled plastic by 50% compared to 2013 (2025).
		BMW: 100% renewable concept car (i Vision Circular). Plans to increase recycled material usage rate from current 30% to 50% (2030).
		Mercedes: Plans to make all models 85% recyclable. Plans to reduce use of virgin materials in EVs by 30% (2030).
		Volvo: Started Circular Loop Project. Plans to make 25% of plastic parts from recycled materials (2025).
		GM: Plans to use 50% sustainable materials in its new cars (in 10 years).
		Ford: Plans to make 20% of plastic parts from recycled materials.

Japan	**METI: Circular Economy Vision 2020 ➡ Growth-Oriented, Resource-Autonomous Circular Economy Strategy (2023)** 1. Prepare competitive environment (regulations and rules) 2. Circular economy toolkit (support via government policies) 3. Circular economy partnership (collaboration between industry, government, and academia)	**Nissan:** Planned to reduce new material usage in each model to 70% (2022). **Honda:** Plans to adopt 100% sustainable materials (2050). **Subaru:** Plans to increase the use of recycled plastic in its new models to 25% or more (2030). **Toyota:** Plans to triple usage of recycled plastic (2030). Plans to use at least 30% recycled materials (2030).
China	**Currently studying extended producer responsibility (EPR) system for automotive products (announcement planned in 2025)**	**11 Chinese automakers including FAW, SAIC, Dongfeng, and Geely are participating in demonstration tests with 62 ELV recycling companies, remanufacturers, and resource recycling companies.**

Table 2 Status of Horizontal Vehicle Recycling

Materials		Recycling rate in vehicles (horizontal recycling rate)	Examples of parts
Steel	Sheet steels	Low	
	Special steel	Medium	Gears, shafts, etc.
	Castings	Low	
Aluminum	Sheets	Low	
	Extrusions	Low	
	Castings (components)	High	Engine blocks, etc.
	Castings (body)	Low	
	Forgings	Low	
Plastic, rubber		Very low	

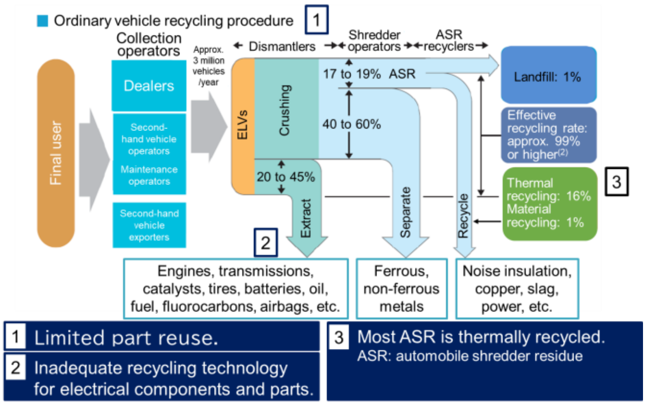


Fig. 5 Recycling Procedure for Ordinary Vehicles

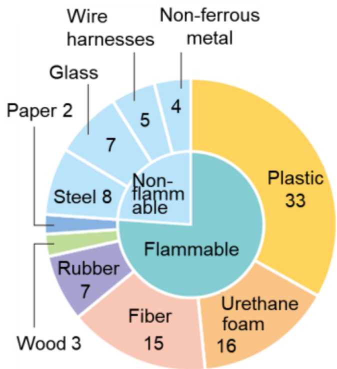


Fig. 6 Material Composition of ASR (Weight %)

2.4 Issues of vehicle recycling from the perspectives of a circular economy

In Japan, the proper disposal and recycling of vehicles is carried out based on the Act on Recycling of End-of-Life Automobiles, which mainly focuses on airbags, fluorocarbons, and automobile shredder residue (ASR). Parts and materials are already being recycled through dismantlers and crushing operators, and the effective recycling rate is reported to be 99% or higher (**Fig. 5**). ASR accounts for between 17 and 19% of the weight of an ELV. Since flammable materials such as plastic and rubber account for approximately three-quarters of the composition of ASR (**Fig. 6**), most ASR is currently thermally recycled. The current issues of vehicle recycling from the perspective of the circular economy may be summarized as follows.

(1) Limited part recovery and reuse
Dismantlers are primarily concerned with removing engine parts and the like. Although these parts return to the market for reuse, the number is limited. Although some items are recycled as materials, this mainly applies to precious metals such as platinum found in catalysts and copper found in wire harnesses. In contrast, the only plastic parts that are recycled are economically viable components such as bumpers.

(2) Inadequate recycling technology for parts related to electrification
The use of battery, motors, and other components is increasing in line with vehicle electrification. However, the reuse of these components as parts is limited due to the unavailability of material recycling technologies.

(3) Thermal recycling of most ASR
Fig. 6 shows the material composition of ASR. Currently ASR is used as feedstock for solid refuse-derived paper and plastics densified fuel (RPF). Consequently, it will be important to expand the recovery of plastic and rubber from ASR and to establish material recycling technologies.

2.5 Toyota's initiatives

2.5.1 Past initiatives

With the objective of promoting measures for vehicle and resource recycling, Toyota founded Toyota Metal Co., Ltd. in 1970 as a joint venture with Toyota Tsusho Corporation to carry out proper disposal and recover resources. Toyota Metal Co., Ltd. carries out crushing and resource recovery from ASR (**Fig. 3**).

Challenge 5 of the Toyota Environmental Challenge 2050 was released in 2015 as the Challenge of Establishing a Recycling-Based Society and Systems. Through this challenge, Toyota is promoting two main initiatives, the Toyota Global 100 Dismantlers Project and the Toyota Global Car-to-Car Recycle Project. Under the former project, Toyota is setting up recognized vehicle dismantlers to promote a system for proper vehicle disposal by safely recovering and processing a wide range of resources from ELVs without harming the environment. Under the latter project, recycling technologies and systems developed in Japan are being rolled out on a global basis to enable the reuse of resources from ELVs in vehicle manufacturing. In addition, under challenge 2, the Life Cycle Zero CO_2 Emissions Challenge, various initiatives for resource recycling have been started. At the same time, Toyota is also working to expand the use of low-CO_2 materials from the development and design phases, and in designs that facilitate dismantling.

2.5.2 Overall image of the circular economy

From January 2022, Toyota started the Circular Economy Promotion Project. In October 2023, the CE Promoting Dept. took responsibility for this project. **Fig. 7** illustrates the overall nature of a circular economy. The main pillars of this project are initiatives to extend the useful life of products, realize more efficient use of products, and eliminate waste. The concepts between these three pillars can be explained in more details as follows. Extending the useful life of a product refers to changing design structures to make full use of target components, as well as performing diagnostics and repairs based on the identified vehicle condition. More efficient use of products refers to ideas such as subscription services such as KINTO, leasing, or the like. Eliminating waste refers to making thorough use of ELVs at the part and material levels. Under this vision, Toyota is specifically promoting the adoption of certain vehicle structures, the construction of recycling systems, the maximization of material recycling, and the building of a foundation to support a circular economy.

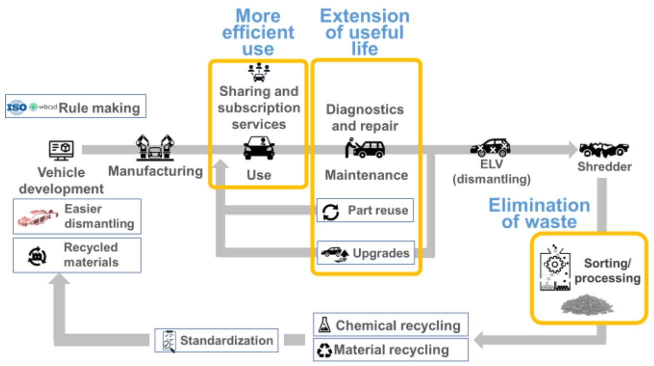


Fig. 7 Overall Nature of Circular Economy

2.5.3 Enhancing vehicle circularity

Toyota has always aimed to achieve vehicles with an environmentally friendly and easy-to-dismantle design. In the future, this approach must be further enhanced from the perspective of recovering parts and materials as resources. Bumpers can be used as an example to describe the current situation of plastic material recovery. Although bumpers are often mainly manufactured from polypropylene, fastening clips are made from different materials (such as polyacetal) and seals are also used on the reverse side. These materials have to be removed by the dismantler, which reduces economic viability if the process is too time consuming. Consequently, for example, it will be important to adopt uniform material types and implement other measures in the design phase.

In addition, to further extend the useful life of vehicles and parts, measures will also be required from the original perspective of identifying the status of individual vehicles and parts based on use histories and facilitating measures in accordance with this status.

In the future, the European ELV regulations will also require the industry to design nineteen parts considering the ease of dismantling. The details of these regulations and Toyota's initiatives are described in the article "**Initiatives for Making Vehicles and Parts Easier to Dismantle**" (starting on page 11 of this edition of the *Toyota Technical Review*). However, one particular urgent task will be to review the conventional designs for parts that must be recovered, such as 10 cm^2 or larger electronic circuit boards.

2.5.4 Maximizing material recycling

Fig. 8 shows the material composition of a vehicle by weight. Steel, aluminum, and plastic account for roughly three-quarters of the total vehicle weight. Consequently, these materials will play an extremely role in initiatives for recycling materials from one vehicle to another. **Table 2** shows the current status of horizontal vehicle recycling and underlines the limited scope of vehicle-to-vehicle recycling. First, steel is recycled and reused for some gears and shafts, mainly in the form of cast iron. However, there are limited examples of recycled materials being applied to steel sheets. Similarly, aluminum can be recycled into engine block castings. However, recycled materials are rarely used in sheets or extrusions. The recycling rates of plastic and rubber are extremely low. For these reasons, the rates of material recycling in vehicles are not high. There is still much room for improvement to maximize the use of recycled materials in vehicles, even before considering materials other than the main types described above. This is an issue that must be addressed from the perspective of circularity.

As described above, Toyota is aiming to achieve a recycled material rate in its vehicles sold in Japan and Europe of 30% or more by 2030. This target was disclosed in the Sustainability Data Book released in October 2023. This target usage rate of 30% or more for recycled materials is weight-based with the total material weight as the denominator. To achieve this target, it will be necessary to recover and sort all types of materials from ELVs and step up the development of a wide range of recycled materials.

Steel is already recycled for use in castings. The next step is its adoption in electric arc furnace steel sheets. Different from blast furnace sheet steels, the term "electric arc furnace steel sheets" refers to steel sheets that have been recycled by electrically dissolving commercially available steel scrap, principally using coke to melt and reduce iron ore feedstock. Currently high-strength electric arc furnace steel sheets are not available, and it will be important to continue development in collaboration with steel manufacturers.

Similar to steel, aluminum is also recycled for use in castings. However, one issue is the application of recycled materials into wrought products such as sheets and extrusions. One development project in Toyota enabled leftover process material from heat exchangers to be used as recycled aluminum for body parts. This material began to be used in hood inners from 2020. Toyota plans to continue promoting recycling from ELVs in the future. The details of Toyota's initiatives for metal recycling are described in the article "**Initiatives for Material Recycling**"(starting on page 22 of this edition of the *Toyota Technical Review*).

Virtually no plastics are used as recycled materials. Although Toyota recovers bumpers replaced in repair work at its dealers to reuse as a resource, the available applications are limited. The details of Toyota's initiatives for plastic recycling are also described in the article "**Initiatives for Material Recycling**."

With respect to other materials, a growing number of batteries, motors, and other parts are being used as vehicle electrification gains pace. The establishment of recycling technologies for these parts is also an important issue. The details of Toyota's initiatives for magnets are described in the article "**Initiatives for Material Recycling**," and those for batteries in the article "**Initiatives for Battery Recycling**" (starting on page 29 of this edition of the *Toyota Technical Review*).

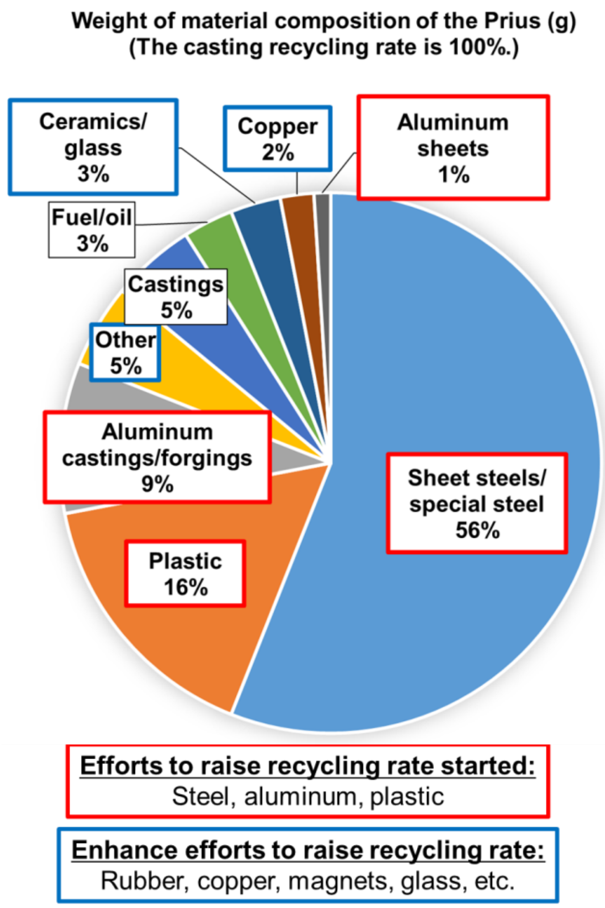


Fig. 8 Material Composition of Vehicles (Weight %)

2.5.5 Building a foundation

Individual companies can only have a limited impact on achieving a circular economy. Forming partnerships with arterial and venous industries, industries outside the automotive field, as well as between industry, government, and academia is a vital part of this process. In Japan, METI and the Ministry of the Environment have initiated various projects. In addition, the Japan Automobile Manufacturers Association (JAMA) has established a Global Recycling Subcommittee under the Recycled Waste Committee to enhance its measures.

1) Measures for international standardization

(1) International Organization for Standardization (ISO)

ISO Technical Committee 323 (ISO/TC 323) was established in 2018 to take charge of standardization efforts for the circular economy. Starting in 2019, this TC has held annual general meetings and proceeded with standardization work. TC 323 consists of five working groups (WGs) and one joint working group (JWG) that act as discussion forums. These are WG 1: overall terminology, WG 2: business models, WG 3: measuring and assessing circularity, WG 4: sharing of practical case studies, WG 5: standardization of information data sheets, and JWG 14 (TC 207/SC 5-TC 323): recovery, reuse, and resource recovery of secondary materials. As the head country of WG 2, Japan is leading studies into practical approaches toward organizing the transition of business models and value networks from a linear to a circular style. Japan is also contributing case study proposals to WG 4. WGs 1, 2, and 3 respectively issued ISOs 59004, 59010, and 59020 in May 2024. WG 5 is the forum for discussions about items with the potential to facilitate social implementation and the creation of regulations, such as digital product passports. As a participant in the Japanese committee of TC 323, Toyota is focusing on contributing to standardization.

(2) WBCSD

The World Business Council for Sustainable Development (WBCSD) is a forum for discussing initiatives to accelerate the transition to a sustainable world in partnership with more than 200 companies. The CEOs of these companies are part of the governing structure. One of the most famous outcomes of the WBCSD is the Greenhouse Gas (GHG) Protocol. For circularity, the WBCSD published the Circular Transition Indicators (CTI) in 2020, which it updates every year. To accelerate the transition to a circular economy, the WBCSD started drafting the Global Circularity Protocol

(GCP) in 2024 to help set global circularity standards. This GCP will be issued in November 2025 and is likely to have a major impact on international standardization efforts. Currently, four workstreams (WS) have been established to facilitate the formulation of the GCP and act as forums for discussion. These are WS 1: impact analysis for the transition to a circular economy, WS 2: corporate performance and accountability, WS 3: necessary policy framework, and WS 4: science-based targets. Toyota is a technical working group member involved in formulating the GCP and actively participates in discussions.

2) Industry partnerships

(1) JAMA

In 2024, JAMA newly established the Global Recycling Subcommittee under the auspices of the Recycled Waste Committee (**Fig. 9**). This subcommittee is implementing the following three initiatives.

(i) Actions for European regulations: Public relations activities in partnership with the European Automobile Manufacturers Association (ACEA), as well as identifying regulatory trends in Europe and collating the inputs of JAMA members.

(ii) Actions for rules and standardization: Common industry-wide actions based on the information obtained in (i). Under this initiative, it is also planned to promote the definition of common industry-based numerical requirements for recycled materials and to address the issue of plastics. The intention is to enhance the availability of recycled materials in the market.

(iii) Actions for emerging markets: Identification of ELV regulatory trends in emerging markets and actions for identified trends. For example, India and other countries are currently discussing ELV regulations. Under this initiative, these trends are discussed and actions formulated.

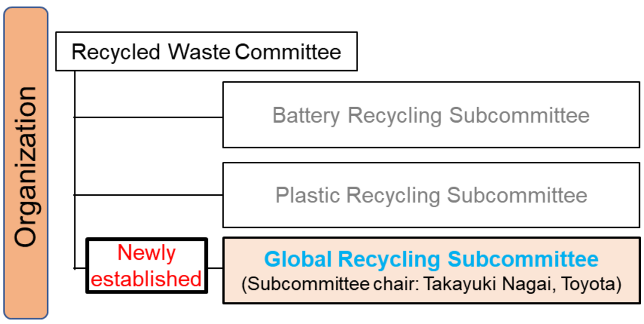


Fig. 9 Configuration of JAMA Recycled Waste Committee

(2) Domestic projects in Japan

The Japanese Cabinet Office is in charge of the cross-ministerial Strategic Innovation Promotion Program (SIP). In fiscal year 2023, this program entered its third phase focusing on the construction of circular economy systems.[4] The mission of this phase is to enable Japan to be the first country in the world to build a circular economy for upgradable plastics. The final target is to improve the dynamic characteristics of recycled plastics by 100% (reaching the equivalent of virgin materials), and to incorporate these plastics in household electronics and vehicles. From fiscal year 2024, the project was awarded an additional budget related to the utilization of plastics derived from other industries in vehicles. Toyota is an advisor to this project and intends to work closely with part manufacturers to actively engage with members of industry, government, and academia.

3. Conclusion

Europe has recently accelerated efforts to strengthen regulations and standardization in line with the concept of a circular economy. Japan has traditionally acted as a global leader by promoting the 3R approach. From the perspectives of the spirit and implementation of the 3Rs, the recent initiatives in Europe may be seen as an extension of Japan's approach. The concept of coexisting with nature is embedded in Japan, and its approach to waste (the so-called "*mottainai* spirit") has the potential to make a positive contribution to the global environment. Toyota's initiatives are guided by the concepts of minimizing the extraction of and efficiently using the Earth's natural resources, enabling the profitable long-term use of valuable resources, and regenerating these resources to a valuable state after use. Following these concepts, Toyota is aiming to further enhance its technologies for the sake of the next generations over the whole supply chain and help realize a sustainable society.

References

(1) P. Lacey, Long, Spindler. *The Circular Economy Handbook*. Nikkei Business Publications, Inc. Tokyo.

(2) *The Butterfly Diagram*. Ellen MacArthur Foundation. https://www.ellenmacarthurfoundation.org/circular-economy-diagram

(3) *Circular Economy: Improving Design and End-of-Life Management of Cars for More Resource-Efficient Automotive Sector*. Press Release of the European Commission. https://ec.europa.eu/commission/presscorner/detail/en/IP_23_3819

(4) SIP homepage of the Japanese Cabinet Office (in Japanese). https://www8.cao.go.jp/cstp/gaiyo/sip/index.html

Initiatives for Making Vehicles and Parts Easier to Dismantle

Daichi Kunishi[*1]
Reiji Iwaihara[*2]
Hiroyuki Ishikawa[*2]
Ryohei Tsuruta[*3]
Masaya Takeda[*1]
Tetsuro Fukuhara[*1]
Tsutomu Hamabe[*1]
Takayuki Nagai[*2]

Abstract

Toyota has developed its design processes to facilitate the long-term use and recyclability of its vehicles. This article discusses the design-related initiatives that Toyota has implemented to make parts easier to remove from vehicles being repaired and end-of-life vehicles (ELVs), as well its design efforts for making ELVs easier to dismantle. These initiatives for making vehicles and parts easier to dismantle help to reduce the work hours required to repair, disassemble, or dismantle a vehicle, while also facilitating the long-term use of products, the reuse and refurbishment of parts, as well as material recycling.

Keywords: *ELV regulations, easier dismantling, DSM, circular economy, vehicle development, vehicle design, production management*

1. Introduction

Toyota has evolved its design processes to facilitate vehicle recyclability. To this end, it is pursuing a range of design-related initiatives to make parts easier to remove from both vehicles under repair and end-of-life vehicles (ELVs), as well as to make ELVs easier to dismantle. Section 2 describes some of the specific measures taken by Toyota over the years, before moving onto a discussion of the future direction of these measures. Section 3 outlines a method that uses the design structure matrix (DSM) as an engineering study tool to enable designs that make vehicles and parts easier to dismantle. Section 4 then presents a case study of how this method was adopted in the design of an easy-to-dismantle door module.

2. Importance of Making Vehicles and Parts Easier to Dismantle

2.1 Past initiatives

To recycle resources from ELVs, Toyota visited and surveyed a wide range of dismantling business operators (described by Toyota as “dismantlers”). This activity started with the Raum, which was launched in 2003. To ensure safety and minimize the time required for dismantling, Toyota’s new models now actively adopt easy-to-dismantle structures.

To improve the dismantling process, special markings were added to components that were particular targets of dismantling (**Fig. 1**). On heavy parts, these markings indicate the center of gravity of the part (**Fig. 2**). The aim of these markings is to improve both the efficiency and safety of dismantling. Specific examples are described below.

Fig. 1 Marking to Improve Dismantling Process

Fig. 2 Marking Indicating the Center of Gravity

(1) Indication of hoisting points of large parts
Markings indicating the center of gravity and hoist positions of parts enable the balanced transportation of heavy components, such as batteries for battery electric vehicles (BEVs) and fuel cell stacks (**Figs. 3** and **4**).

*1 Advanced Product Development Div., Advanced R&D and Engineering Company
*2 CE Promoting Dept., Advanced R&D and Engineering Company
*3 Toyota Central R&D Labs., Inc.

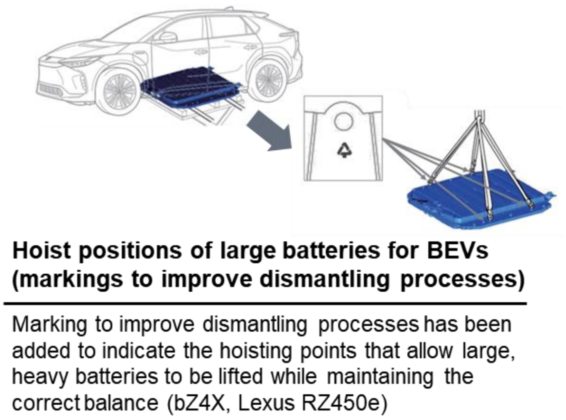


Fig. 3 Markings on the Large Battery of the bZ4X and Lexus RZ450e

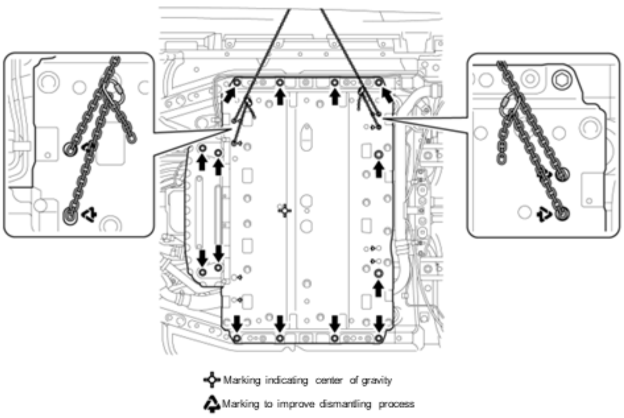


Fig. 4 Markings to Improve Dismantling Process and Indicate the Center of Gravity on the Fuel Cell Stack of the Mirai

(2) Indication of position for pulling off door trim
This marking to improve the dismantling process of the door trim is prominently located to identify the position at which the trim can be pulled off with 30% less force than previous models (**Fig. 5**).

Fig. 5 Marking to Improve Dismantling Process of Door Trim

(3) Indication of instrument panel dismantling positions
V-shaped grooves indicate parts on the instrument panel that can be removed easily just by pulling (**Fig. 6**).

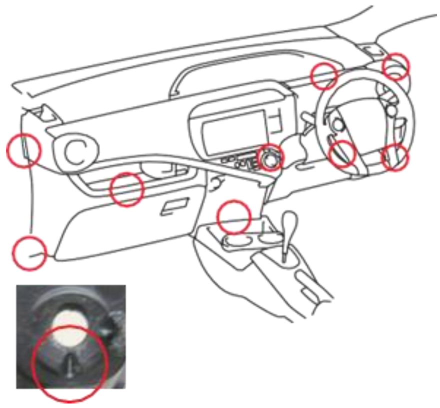


Fig. 6 Grooves to Make Instrument Panel Easier to Dismantle

(4) Wire harness pull-tab grounding terminal structure
A structure resembling the ring tab of an aluminum can was adopted to enable grounding parts to be separated and dismantled simply by pulling (**Fig. 7**).

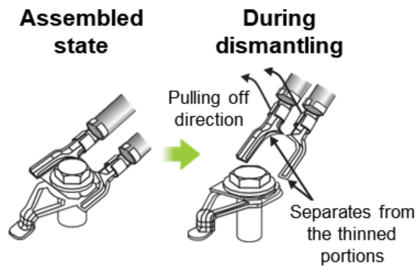


Fig. 7 Wire Harness Ring Tab Grounding Terminal Structure

(5) Use of tape to raise visibility of wire harnesses
A visible yellow-green tape is wound around locations close to where wire harnesses can be pulled out most efficiently (**Fig. 8**).

Fig. 8 Tape to Raise Visibility for Wire Harness Dismantling

(6) Innovative wire harness layout
As far as possible, the wire harness layout is designed to enable wire harnesses to be pulled out without making contact with other parts (**Fig. 9**).

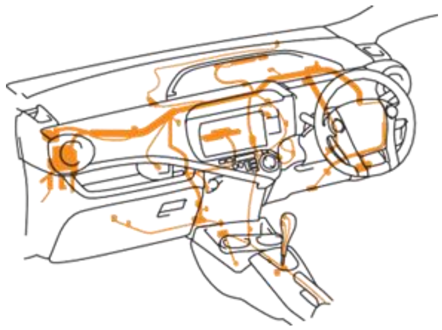


Fig. 9 Innovative Wire Harness Layout

2.2 Changes in external environment and current initiatives

2.2.1 Requirements for easy-to-dismantle design according to proposed European ELV regulations

In Europe, awareness and measures addressing environmental issues are advancing rapidly. In this context, European ELV regulations are likely to be enacted in 2025. Although currently just a proposal, these regulations will require automakers to ensure that the nineteen automotive parts listed below can be removed before the vehicle is crushed (by 2029) and to introduce easy-to-dismantle design measures (by 2031). Consequently, the adoption of easy-to-dismantle structures is becoming increasingly important to achieve these objectives (**Fig. 10**).

(1) Electric vehicle batteries
(2) E-drive motors, including their casings and any associated control units, wiring, and other parts, components and materials
(3) Auxiliary batteries (SLI batteries)
(4) Engines
(5) Catalytic converters
(6) Gear boxes
(7) Windshields, and rear and side windows made of glass
(8) Wheels
(9) Tires
(10) Dashboards
(11) Accessible parts of the infotainment system, including sound, navigation, and multimedia controllers, including displays with a surface area greater than 100 cm^2
(12) Headlights, including their actuators
(13) Wire harnesses
(14) Bumpers
(15) Fluid containers
(16) Heat exchangers
(17) Any other mono-material metal components heavier than 10 kg
(18) Any other mono-material plastic components heavier than 10 kg
(19) Electrical and electronic components
 (a) Inverters of electric vehicles
 (b) Printed circuit boards with a surface area larger than 10 cm^2
 (c) Photovoltaic panels with a surface area larger than 0.2 m^2
 (d) Control modules and valve boxes for automatic transmissions

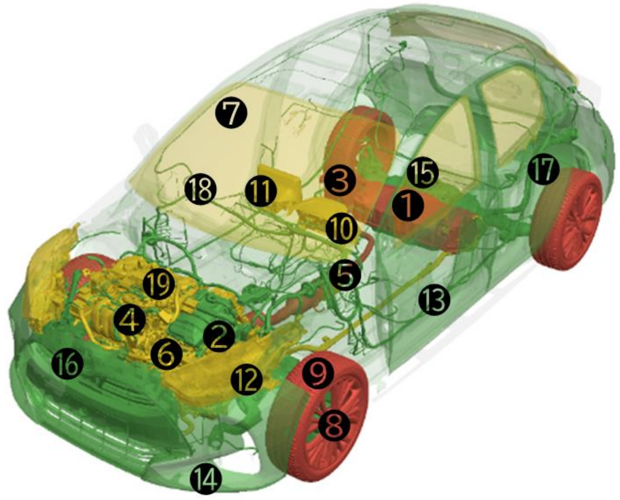


Fig. 10 Parts to Be Reused or Recycled under European ELV Regulations

2.2.2 Second-hand parts market

Currently, in second-hand markets, there is some demand for parts removed from ELVs. This includes engines, alternators, and air conditioning compressors to be used as service parts when a part needs to be replaced. Bumpers, side mirrors, and headlamps are other parts that need to be replaced after an accident. The free flow of parts removed from ELVs is an important aspect of measures to ensure the economic viability of the dismantling industry.

In addition, when the nineteen parts described in Section 2.2.1 are removed, the surrounding parts also have to be removed. As a result, it may be possible to find a market for other second-hand parts that are in demand but had not been previously removed.

2.2.3 Toyota's current initiatives

Toyota worked with its suppliers to dismantle and disassemble parts, identify which components and structures are difficult to remove or take apart, and understand the issues involved (**Fig. 11**). Surveys were also conducted for items (19) (b) printed circuit boards and (c) photovoltaic panels described in Section 2.2.1.

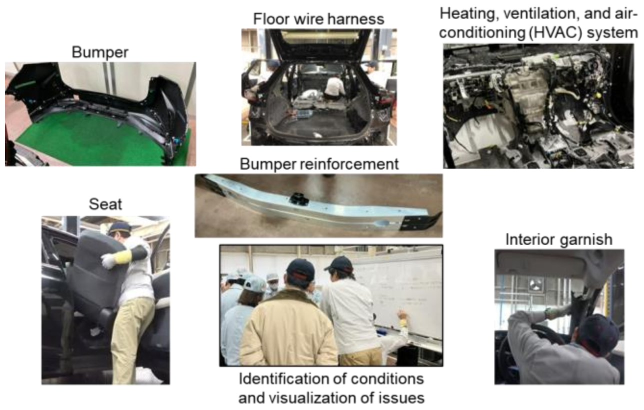


Fig. 11 Identification of Conditions and Issues Surrounding Current Vehicle Structures

2.3 Future direction

Responding to rising social trends toward achieving a circular economy, the automotive industry must take actions to comply with the proposed European ELV regulations. In addition to the conventional focus on easy-to-assemble design, future designs will need to take into consideration maintenance, repair, reuse, rebuilding, and recycling.

In response, Toyota has adopted the DSM digital tool as a means of visualizing information related to dismantling work (processes), as well as the physical exertion of part removal and part value (cost/benefit). With this information, Toyota can quantitatively evaluate the cost/benefit relationship of each process and examine how to utilize these results in design. By reversing the process flow, this tool can also be used for assembly evaluations.

3. Outline of DSM and Progress of Research

The DSM tool is based on a matrix that shows the dependency relationship between elements. It is a method for resolving issues by analyzing the relationships and interactions between multiple objects. As a network modeling tool that expresses the elements in a system and the interactions between these elements, the merit of DSM is its ability to express these interactions in a more compact, legible, and intuitive form than graph-based methods. DSM was devised by Professor Donald V. Steward in the 1970s(1) and the first paper about DSM was published in 1981.(2) Subsequently, in 2012, Steven D. Eppinger and Tyson R. Browning of the Massachusetts Institute of Technology published a systematic summary about DSM methods and applications,(3) expanding is applicability to product research and development.

Within the Toyota group, Shuichi Sato et al. of Toyota Central R&D Labs., Inc. proposed an analytical method for production preparation processes using DSM(4) capable of shortening the forging die design process by 40% by expressing the physical causal relationships between design elements in a matrix. Then, in 2017, Yasuo Asaga and Hidekazu Nishigaki adopted DSM as a modularization method, demonstrating its ability to create layout structures for new products with novel part structures. The method also was able to visualize the optimum part and module configurations for these structures by using the dynamic characteristics of the structure to divide it into separate modules.(5)(6) Using this modularization know-how, Ryohei Tsuruta, Shiki Iwase et al. proposed the use of DSM in evaluations of easy dismantling processes by blending the connections between processes and structures.(7) Using the dismantling of a coffee maker as a case study, this research utilized “-1” flags to identify violations of dismantling sequence constraints in a matrix. Design change locations that act as bottlenecks can then be presented to design engineers in an easy-to-understand form. The next section describes a case study in which this method was further developed and applied to help create an easy-to-dismantle design for a vehicle front door.

4. Matrix-Based Design Method for Circular Economy

4.1 Method

The easy-to-dismantle design method described in this section combines a hybrid DSM,(7) which consists of the product architecture DSM for expressing part connection information and the process architecture DSM proposed by Tsuruta et al. based on the DSM described by Eppinger et al.,(8) alongside the disassembly evaluation strategy described by Kayla Feldmann.(9) This multi-faceted method was applied to an automotive assembly. Sections 4.1.4 and 4.1.5 provide a systematic summary of matrix sorting and sequence constraint condition notation rules to demonstrate the effectiveness of this highly transparent, intuitive, and easy-to-understand DSM-based method.

4.1.1 Configuration of front door

A vehicle front door was selected as the target module to describe an easy-to-dismantle design for circularity. **Fig. 12** shows the configuration of this module. Although an actual door contains more than fifty component parts, the figure shows a simplified thirteen-part version for a clearer explanation of the hybrid DSM method. Generally, a door consists of part groups that use the main materials adopted across the entire vehicle, including metal parts such as the regulator and frame, plastic parts such as door trim, glass parts such as side windows, electronic parts such as speakers and sensors, and wire harness that include bundles of copper wires. **Fig. 13** depicts the connection information of these thirteen parts in a simple diagram. The arrows in this simple diagram show the connections between each part and the color of the arrows show the strength of these connections (i.e., how difficult the parts are to dismantle). Although a simple diagram is a good way of spatially recognizing the correlations between the parts, it is not suitable for quantitatively determining the ease of dismantlability. This can be accomplished by adopting the hybrid DSM technique.

4.1.2 Configuration of hybrid DSM

First, the target part groups for dismantling or recovery are listed from the top row in the sequence that the parts are dismantled. The columns are aligned from the left in the same sequence. Next, the inside of this square matrix is divided into three sections: a triangle at the bottom left, a diagonal, and a triangle at the top right. **Fig. 14** shows a multi-informational matrix (hybrid DSM) assigned with different information. The diagonal term is assigned the recovery value of each part as the benefit function. For the cost function, the cells in the triangles at the bottom left and top right are assigned the time required for dismantling as connection information between the parts, and then the dismantling and recovery sequence constraint conditions are entered into the cells. Since the part value of the diagonal term changes depending on whether the recovered part is reused or recycled, values corresponding to pre-assumptions about how the part will be used are entered. Then, because the dismantling time differs depending on the difficulty of the dismantling process, the figure shows parts that are easier to dismantle in green, and parts that are most difficult to dismantle in yellow. In addition, the sequence constraints are as follows. To dismantle a part with a certain column number, parts with an intersecting row number containing a negative value inside a purple cell must be removed first. Therefore, before dismantling the fifth part in **Fig. 14** (i.e., the part represented by the fifth column), parts 1 to 3 (i.e., the parts in the 1st to 3rd rows) must be removed. If a purple cell containing a negative value (showing that a sequence constraint exists) is in the bottom left triangle of the graph, this means that the dismantling sequence constraints have been violated. In other words, the part corresponding to the column number cannot be dismantled and the dismantling work will stop at the part in the corresponding column. The negative value notation that expresses the sequence constraints is explained in Section 4.1.5.

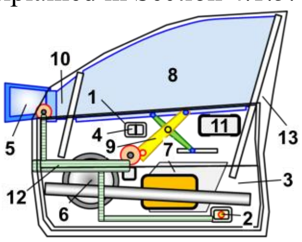


Fig. 12 Door Configuration Diagram

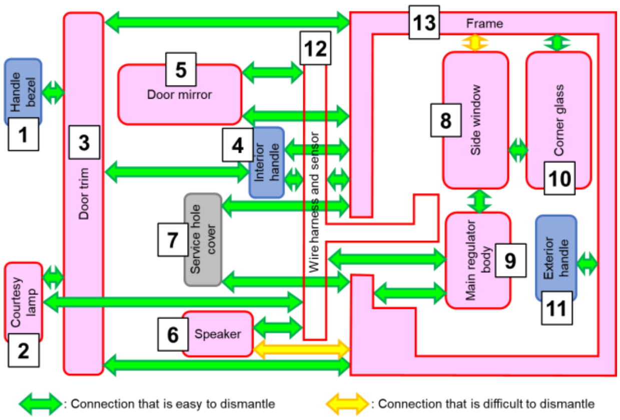


Fig. 13 Information of Parts Connections

		1	2	3	4	5	6	7	8	9	10	11	12	13
Handle bezel	1			-1	-2	-2	-2	-2	-3	-3	-4	-3	-3	-5
Courtesy lamp	2			-1	-2	-2	-2	-2	-3	-3	-4	-3	-3	-5
Door trim	3				-1	-1	-1	-1	-2	-2	-3	-2	-2	-4
Interior handle	4													-1
Door mirror	5													-1
Speaker	6													-1
Service hole cover	7								-1	-1	-2	-1	-1	-3
Side window	8										-1			-2
Main regulator body	9													-1
Quarter glass	10													-1
Exterior handle	11													-1
Wire harness and sensor	12													-1
Frame	13													

Dismantling sequence

Fig. 14 Multi-Informational Matrix (Hybrid DSM)

4.1.3 Evaluation of ease of dismantling and cost/benefit break-even point

The cost/benefit graph is formulated as follows.

- Cost: the time required to dismantle the target part (i) is the sum of the vertically listed dismantling times assigned in the bottom-left triangle. It can be expressed by the following equation.

$$\sum_{k=i+1}^{end} M_{ki} \quad (1)$$

- Benefit: the recovery value of the target part (i) is the diagonal term Mii.

The graph for evaluating the ease of dismantling shown in **Fig. 15** can be plotted by obtaining the sum of each column starting from the left. Steeper gradients in this graph indicate that a high-value part can be recovered efficiently and in a short period of time. In contrast, lower gradients express less efficient recovery. Furthermore, if the dismantling time shown on the horizontal axis is converted to the same kind of value (i.e., a financial value) as used on the vertical axis using an hour rate or the like, the viable recovery scope for a dismantler can be approximately calculated in terms of time and the dismantling processes by adding a break-even line.

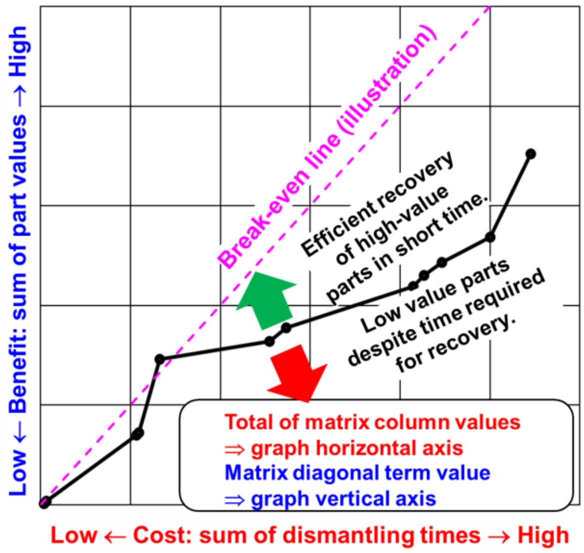


Fig. 15　Graph for Evaluating Ease of Dismantling

4.1.4　Sorting rules

This section explains how the sorting operations of a matrix for raising dismantling efficiency can be implemented by changing the dismantling sequence. Under the rules, the matrix can be sorted in a range as far as cells that have been assigned a negative value (indicating a sequence constraint) remain in the top-right triangle. In other words, the rules are based on the permitted amount of movement of the cells. **Fig. 16** shows the rules controlling the advancement of parts in the dismantling sequence. If K represents a part that the dismantler would like to recover quickly, the permitted amount of movement is the smaller of value Fc and Fr, that is, the amount of movement that reaches the diagonal term the earliest. As shown in the middle diagram of **Fig. 16**, $F_c = k - r_i$ (i represents an arbitrary part number). Since F_r is always smaller than k, the permitted amount of movement is determined by F_c. If multiple r_i are lined up vertically, the permitted amount of movement is determined by the F_c of the largest constraint condition cell closest to K. In summary, as shown by the bottom diagram of **Fig. 16**, when considering the advancement of parts in the sequence, it is acceptable to simply focus on the constraint condition cells closest to K in the upward direction. The constraint condition cells to the right of K are too far from the diagonal to allow the advancement of K and do not have to be considered. Similarly, **Fig. 17** shows the rules controlling the relegation of parts in the dismantling sequence. Parts that do not have to be recovered quickly can be relegated in the sequence. Here, it is acceptable to simply focus on the constraint condition cells closest to K on the right, and the constraint condition cells arranged in the upward direction do not have to be considered.

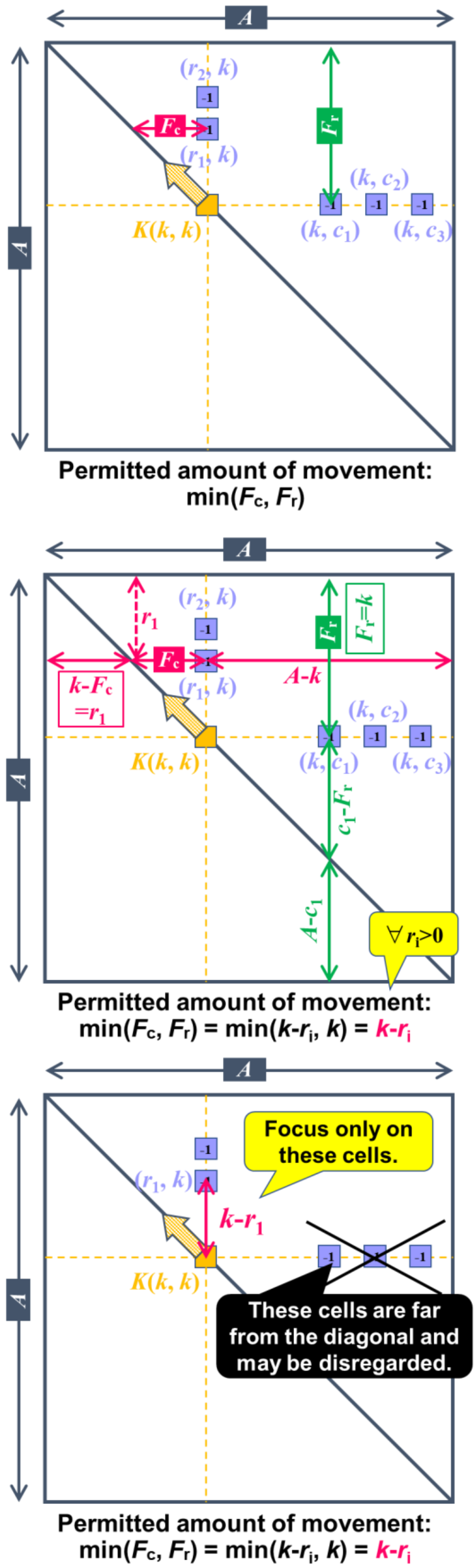


Fig. 16　Sorting for Advancement of Parts in Sequence

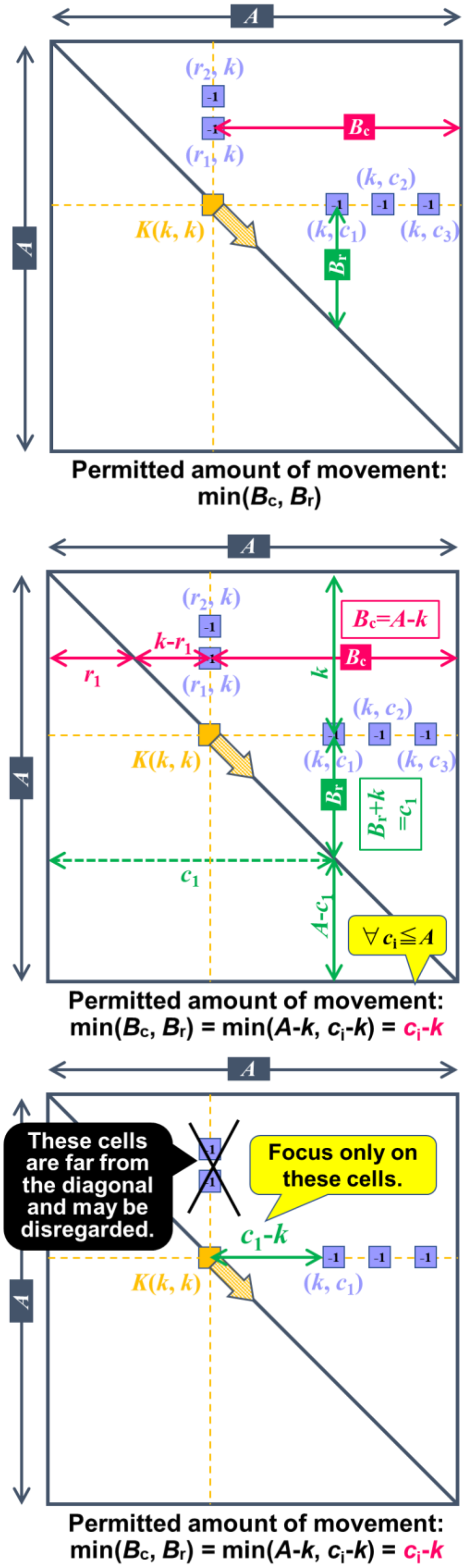


Fig. 17 Sorting for Relegation of Parts in Sequence

4.1.5 Notation for sequence constraint conditions

Fig. 18 shows how the negative values assigned to sequence constraints based on the relationship between parts change. The notation for these constraints can be described as follows. For example, if part K is connected directly to target parts c1, c2, and c3, or is in a directly covering position, meaning that part K must be removed first, then parts c1, c2, c3, and K are assigned a negative value of -1 in the top-right triangle as an intersecting sequence constraint. In addition, if part K is also subject to a sequence constraint pertaining to parts r1 and r2, then parts c1, c2, and c3 will have an indirect sequence constraint pertaining to parts r1 and r2. Therefore, the negative values in the top-right triangle that show the intersecting sequence constraints for parts c1, c2, and c3 and parts r1 and r2 are reduced by 1 to -2. Although not shown in the figure, if parts r1 and r2 are subject to further sequence constraints from other parts and the indirect sequence constraint relationships overlap, then the negative values in the top-right triangle that show the intersecting sequence constraints for parts c1, c2, and c3 and the applicable parts will change sequentially to -3, -4, -5, and beyond. In this way, the indirect sequence constraints can be expressed in the DSM to identify relationships between parts that are not visible simply by looking at the parts. In addition, it is possible to remove lower-order sequence constraints as a knock-on effect by eliminating the topmost sequence constraint (see below for a specific case study). It should be noted that, as described in Section 4.1.4, when sorting the dismantling sequence, it is acceptable only to focus on the constraint condition cells closest to the target part to be sorted. Indirect sequence constraints that are further away have no impact on the sorting process.

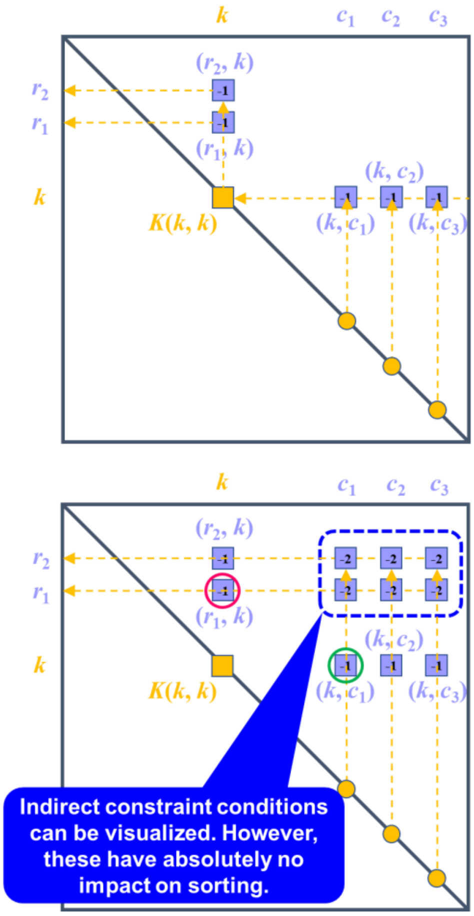


Fig. 18 Direct and Indirect Sequence Constraints

4.2 Case study of easy-to-dismantle door module design

4.2.1 Part recovery for the circular economy

Fig. 19 shows a specific DSM-based case study for the dismantling of door parts. First, **Fig. 19 (a)** shows a matrix sorted in the sequence that the 41 door parts are dismantled manually. The purpose of this design study is to enable the rapid recovery of highly versatile parts for reuse or recycling (i.e., motors, speakers, and sensors) and parts with a high copper content (i.e., wire harness). The corresponding parts are shaded in pink. This dismantling sequence cannot be regarded as efficient since it requires time to recover the target parts individually.

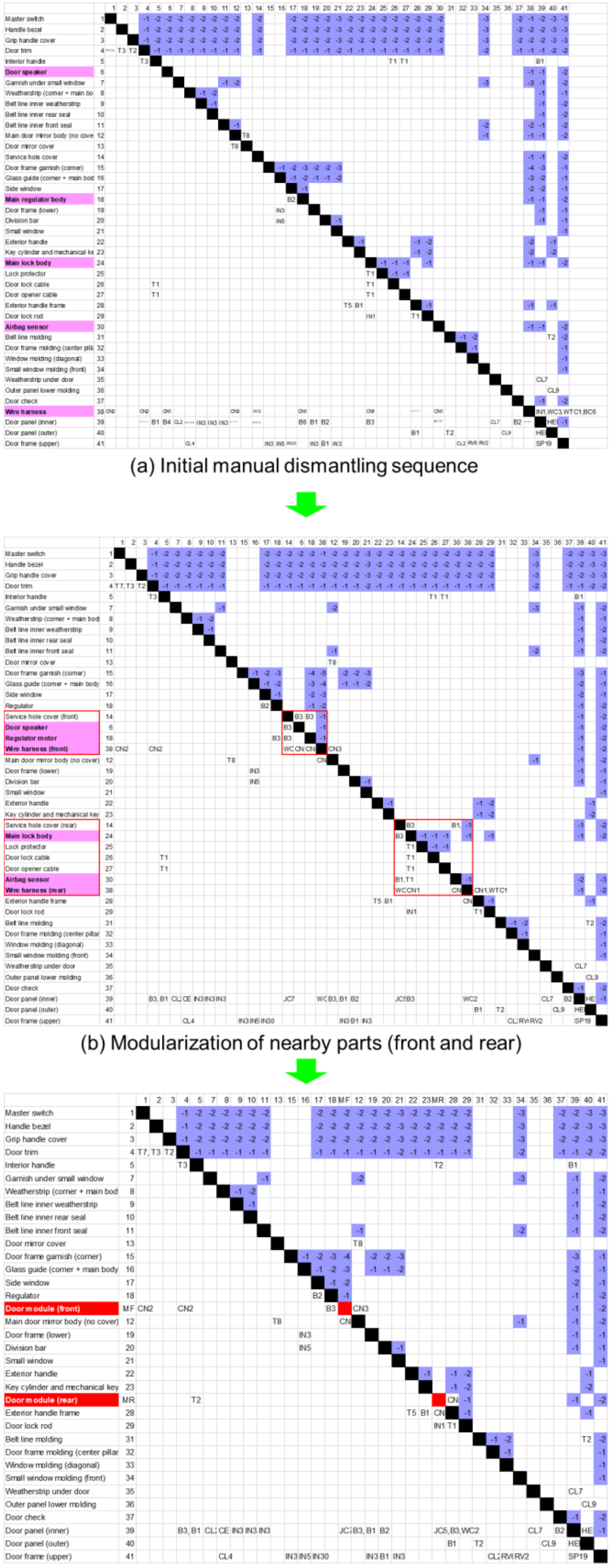
4.2.2 Raising dismantling efficiency through modular design

Therefore, modular design involving the grouping of nearby parts was studied as shown in **Fig. 19 (b)**. First, the regulator assembly was divided into the main regulator body and regulator motor, and the regulator motor and speaker were integrated with the front service hole cover and wire harness to form a front module. Additionally, the airbag sensor and door lock were integrated with the rear service hole cover and wire harness to form a rear module. Furthermore, **Fig. 19 (c)** shows a simplified DSM that consolidates the module components that previously accounted for multiple rows and columns into two single rows and columns.

Next, the red cells were sorted in accordance with the rules described in Section 4.1.4 to move the module parts to be recovered rapidly for reuse or recycling up in the dismantling sequence. Since there are no purple cells denoting sequence constraints immediately above the red cells of the rear module until the fourth row, the rear module was advanced to fifth in the dismantling sequence shown in **Fig. 20 (a)**. In contrast, since the front module was relegated from sixteenth to seventeenth in the sequence and there are purple cells denoting sequence constraints immediately above the red cells of the front module, this module cannot be advanced in the sequence. However, by focusing on the part groups to be recovered before the front module, the matrix shows that some parts can be relegated in the sequence as far as the point to which purple cells that denoting sequence constraints are present on the right. As shown in **Fig. 20 (b)**, the front module can be advanced relatively to tenth in the dismantling sequence by relegating part groups that were to be removed before the front module. It should be noted that if a cell denoting a sequence constraint is present close to the right of a relegated part group, the applicable parts subject to these constraints can be relegated in the sequence together.

4.2.3 Further increases in efficiency by changing the configuration

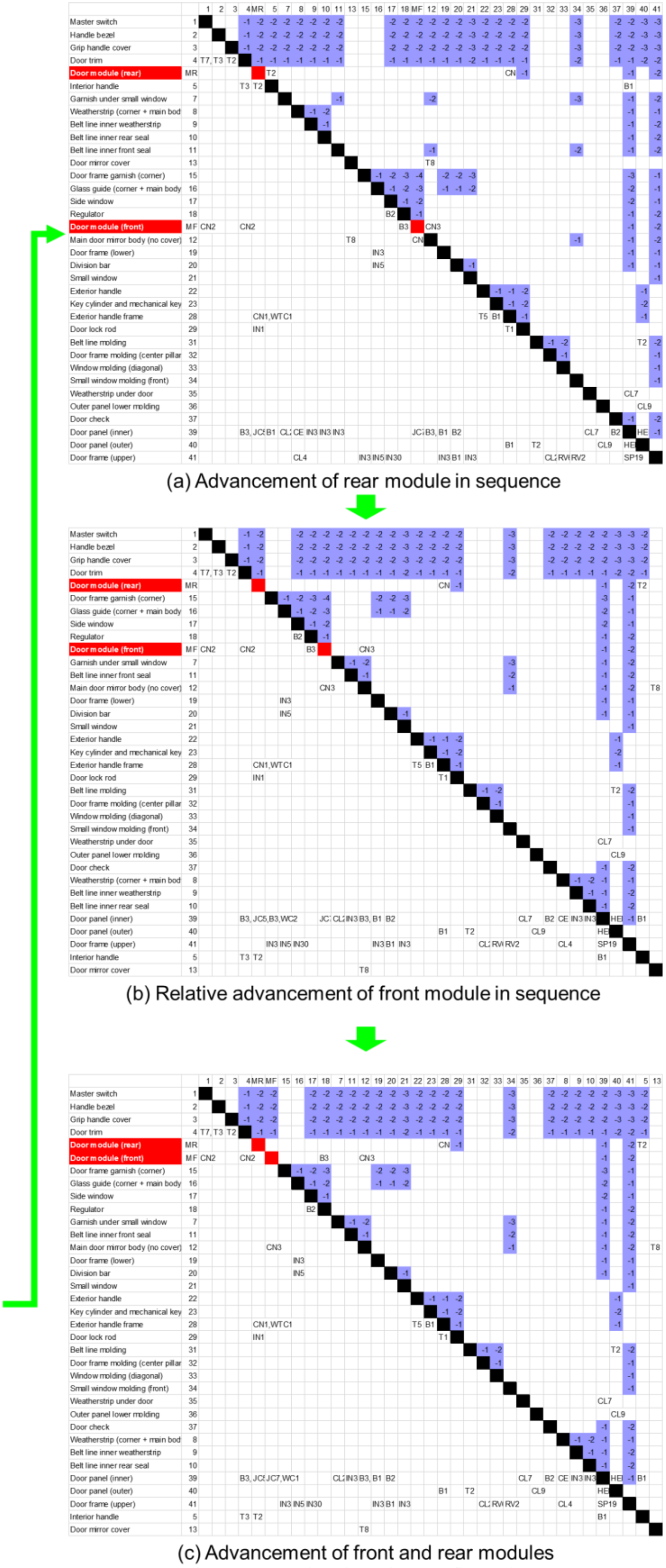
After the front module was raised in the dismantling sequence as illustrated in **Fig. 20 (b)**, the matrix shows the main regulator body and a related series of indirect sequence constraints immediately above the front module. Assuming that the configuration can be changed to eliminate the sequence constraints of the main regulator body and front module (specifically the regulator motor), it may be possible to delete the four sequence constraint cells, including the indirect constraints, as shown in **Fig. 20 (c)**. The ability to eliminate lower-order sequence constraints as a knock-on effect is a merit of these indirect constraint conditions. Therefore, by following this procedure, it was possible to identify a highly efficient and easy-to-dismantle design capable of rapidly recovering target modules for reuse or recycling in six steps.



(a) Initial manual dismantling sequence

(b) Modularization of nearby parts (front and rear)

(c) Simplified matrix using modules



(a) Advancement of rear module in sequence

(b) Relative advancement of front module in sequence

(c) Advancement of front and rear modules in sequence by changing configuration

Fig. 19 (Left) Matrices Expressing Modularization and Simplification
Fig. 20 (Right) Matrices Sorted for Highly Efficient and Easy Dismantling

4.3 Observations and summary

Fig. 21 shows the transition achieved by matrix sorting to ease a dismantling evaluation as illustrated in **Figs. 19** and **20**. Unlike **Fig. 15**, the vertical axis shows the profit after subtracting the costs of the physical exertion and time involved in part recovery instead of the benefit in terms of the value of the recovered parts. In other words, the vertical axis of **Fig. 21** shows the calculation result of subtracting the horizontal axis of **Fig. 15** from the vertical axis of that figure. Since the vertical axis now incorporates the cost element shown on the horizontal axis, profit has increased by changing from the **Fig. 19 (b)** matrix to the **Fig. 19 (c)** matrix by grouping and removing the same parts in a shorter time. The graph in **Fig. 21** ends at the point where the two front and rear modules can be recovered. In this example of an easy-to-dismantle door module, the graph confirms that advancing the recovery sequence of the modules results in increased profit even if the number of secondary parts recovered decreases. Therefore, when considering a business model for easy-to-dismantle parts, it is important to incorporate costs such as physical exertion and time involved in recovery instead of just focusing on the value of the recovered parts.

Section 4.2.3 explained how the matrix-based design method described in Section 4.2.2 can be used for configuration changes by the adoption of modular design. However, changes in recovery value may be an idea that could be integrated into practical part design. As mentioned in Section 4.1.2, the value of a recovered part changes depending on whether it is reused or recycled. When evaluating the ease of dismantling all door parts instead of stopping at the two front and rear modules in this case study, it will be necessary to input values assuming the post-recovery application of the parts to all the diagonal terms and creating graphs that show the totals for all columns in the DSM from the left.

In the easy-to-dismantle door module case study described in this article, sorting was carried out manually within the range that obeyed the sequence constraints in accordance with the rules in Section 4.1.4. The sorting described in this article focused on achieving the rapid recovery of the two modules. Due to the low number of parts involved, manual sorting was adopted to enable clearer understanding of the characteristics of this method. If the number of target parts to be recovered is higher, improvements such as the automatic sorting program devised by Tsuruta et al.[7] and the application of sorting rules to combinatorial optimization problems as constraint conditions may be effective. In addition, although the DSM described in this article was created in the dismantling sequence, reversing the sequence may well enable its application to studies of part assembly and other processes.

Ultimately, through the DSM-based dismantling sequence, modular design, and configuration change study described in this article, it is possible to imagine a door design that can be dismantled highly efficiently from the perspective of a dismantling business. This article also systematically summarized the DSM sorting rules and dismantling sequence constraint condition notation.

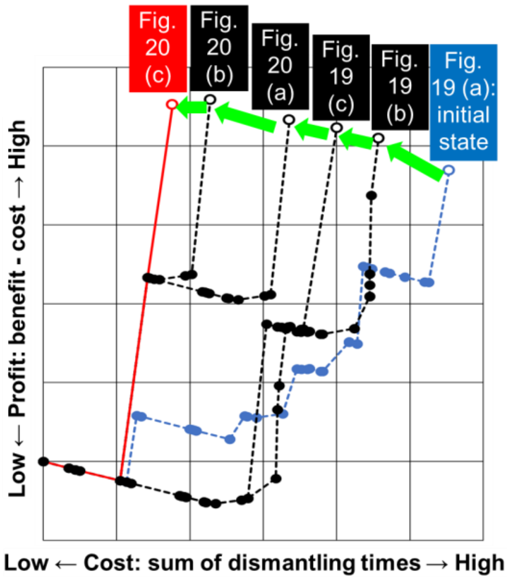


Fig. 21 Transition of Dismantling Efficiency

5. Conclusion

This article described Toyota's initiatives for making vehicles and parts easier to dismantle as a method for promoting resource recycling from vehicles, as well as the future direction of these initiatives. It then presented a case study using DSM as a specific method for carrying out design studies. Although this case study adopted part price as the value of the parts on the diagonal term, weight or size may be adopted from the perspective of a distribution business, or even CO_2 emissions as an index for carbon neutrality. The construction of more robust circular business models will be indispensable to help achieve a circular society. Toyota intends to continue promoting initiatives toward that objective using DSM and a wide range of other methods.

Acknowledgments

The development of this easy-to-dismantle design technology to help achieve a circular economy was accomplished thanks to the wide-ranging support and cooperation of every member of the development team, particularly Yasuhiro Yogo, Chie Nagashima, Hidekazu Nishigaki, and Shiki Iwase of Toyota Central R&D Labs., Inc. The authors would like to take this opportunity to express their gratitude to everyone involved.

References

(1) D. Steward. “DSM - Where it’s Been - Where it Needs to Go.” *DSM 2007: Proceedings of the 9th International DSM Conference* (2007).

(2) D. Steward. “The Design Structure System: A Method for Managing the Design of Complex Systems.” *IEEE Transactions on Engineering Management* No. 28 (1981) pp. 71-74.

(3) S. Eppinger, Browning. *Design Structure Matrix Methods and Applications*” MIT Press. Cambridge (2012).

(4) S. Sato, Inamori, Nakano, Suzuki, Miyajima. “Analysis Method for Overseas Production Preparation Process.” *Transactions of the Japan Society of Mechanical Engineers C* Vol. 71 No. 705 (2005) pp. 1734-1741.

(5) H. Nishigaki, Asaga. “Modularization Method Based on Creation of New Layout Structure.” *Transactions of the Japan Society of Mechanical Engineers* Vol. 83 No. 853 (2017).

(6) Y. Asaga, Nishigaki. “Modularization Method Based on New Layout Design in Conceptual Design Stage - Application of Multi-Material Lightweight Structures Utilizing Machine Learning -.” *21st International DSM Conference* (2019).

(7) R. Tsuruta, Iwase, Kuwano, Asaga, Nishigaki. “Easy Disassembly Process Evaluation Methods for Circular Economy.” *Proceedings of the Design & Systems Conference* Vol. 2023.33 (2023) p. 1109.

(8) S. Eppinger, Browning. *Design Structure Matrix Methods and Applications*. MIT Press. Cambridge (2016).

(9) K. Feldmann, Trautner, Meedt. “Innovative Disassembly Strategies Based on Flexible Partial Destructive Tools.” *Annual Reviews in Control* Vol. 23 (1999), pp. 159-164.

Note: Section 4 is based on the following article.

D. Kunishi. “Matrix Based Design Method of the Structure for Circular Economy.” *Proceedings of the JSAE Annual Congress (Spring)* No. 310 (2024).

Initiatives for Material Recycling

Kei Tashiro[*1]
Reona Takagishi[*1]
Mizuki Sakamoto[*1]
Kazuhide Tabata[*1]
Kazuhiro Tanahashi[*1]
Yuichi Furukawa[*2]
Takayuki Nagai[*1]

Abstract

To help realize a circular economy, Toyota is focusing on building a stronger foundation for recycling automotive materials. This article describes Toyota's initiatives for material recycling, focusing on the current situation and issues surrounding aluminum, magnet, and plastic recycling.

Keywords: *material recycling, inner hood, heat treatment, permanent magnet, motor, ASR, sorting technology, chemical recycling*

1. Introduction

Government policies around the world are becoming increasingly proactive in response to growing interest in the transition to a circular economy. One of the typical key performance indicators (KPIs) for determining progress toward a circular economy is the recycled material usage rate, which has even been included in end-of-life vehicle (ELV) regulations in Europe. Following these regulations, car manufacturers have set targets for the use of recycled materials. In October 2023, Toyota announced targets for recycled material usage rates and has stepped up its efforts to use these materials. This article describes Toyota's initiatives for material recycling, focusing on the current situation and issues surrounding the recycling of aluminum, magnets, and plastics.

2. Aluminum Recycling

2.1 Current situation

As described in the article "Initiatives for the Circular Economy" elsewhere in this edition of the *Toyota Technical Review* (Section 2.5.4: Maximizing material recycling), steel, aluminum, and other metals make up the highest proportion of automotive materials in terms of weight. In particular, increasing amounts of aluminum are being used as automakers seek to electrify and reduce the weight of vehicles. For these reasons, since vehicle manufacturing processes will probably use increasing amounts of aluminum in the future, it will be necessary to secure sufficient supplies of recycled aluminum to raise the recycled material usage rate, while also developing enhanced technologies for aluminum use.

Toyota is already engaged in activities to use recycled aluminum, as evidenced by the adoption of aluminum sheets reused from heat exchanger cladding for the inner hood of the Mirai in 2020.

2.2 Issues

One major issue related to expanding the use of recycled aluminum is whether parts manufactured using recycled materials satisfy the requirements for strength and other characteristics, such as corrosion resistance, fatigue strength, and paint film adhesion. In general terms, chemical composition has a major impact on such characteristics. Commercially available post-consumer recycled (PCR) scrap materials tend to incorporate high proportions of impurity elements, which inhibit the use of this type of scrap as recycled material. In addition, even when PCR scrap is utilized, it is necessary to add large quantities of new aluminum to dilute the concentration of impurity elements. If this issue can be addressed and the impurity tolerance increased, then it may be possible to widen the range of usable scrap, which should facilitate material procurement and raise the recycled material usage rate.

2.3 Toyota's initiatives

Several countermeasures can be applied to address the issue of impurity elements described above. When aluminum sheets were adopted for the inner hood, adjustments were made to the material composition in the manufacturing process to minimize material elongation. Innovative design and product machining technologies were also adopted to enable the use of materials containing large amounts of impurities. Other initiatives are also under way to expand impurity tolerances through technical approaches. Additionally, Toyota proposed a method of simplifying heat treatment for high ductility aluminum die casting alloys.(1) This proposed method involves eliminating heat treatment based on the precipitated elements contained in steel within the temperature history during casting, and completing the heat treatment process using the optimum pattern for the casting temperature history only. In this method, the precipitation of clumps of $Al_{15}Si_2(Fe, Mn)_4$

*1 CE Promoting Dept., Advanced R&D and Engineering Company
*2 Raw Material Development Div., Production Engineering Development Center

containing no magnesium (Mg) inclusions in the α-Al is prioritized under specific temperature conditions. By precipitating silicon (Si) first, the precipitation of Mg_2Si is suppressed and the elongation characteristics of the material are secured. This method may be capable of resolving the issue of impure steel with lower elongation, thereby helping to increase steel impurity tolerances. This technology may also help to expand the use of scrap recycled from ELVs sold on the market, and efforts are under way for that purpose.

3. Magnet Recycling

3.1 Current situation

As electrification and digitization progresses, the number of permanent magnets in use is likely to continue increasing. More than 50% of all permanent magnets are for vehicle applications, a proportion that is likely to rise as vehicle electrification advances (**Fig. 1**). Supplies of the rare earth elements (neodymium (Nd), dysprosium (Dy), terbium (Tb), and the like) that form the raw material component of permanent magnets rely on certain countries of origin, including China. As a result, China is capable of supplying magnets at low cost and is expanding its market share, whereas the market share of Japan is decreasing. Although some motors do not use permanent magnets, the energy-saving performance of these motors is worse than those that use permanent magnets. As a result, since used magnets are not currently recycled from the market, these parts are vulnerable to geopolitical risks such as supply chain disruptions and sudden price increases (**Fig. 2**).

In Europe, rare earth elements for magnets fall under the European ELV regulations and the European Critical Raw Materials Act (CRMA). In the near future, suppliers will likely be required to recycle magnets and disclose numerical targets.

Toyota is currently developing measures and technology to (1) recover component parts from the market, (2) extract magnets from component parts, and (3) recycle the recovered magnets. The initiatives and issues related to these objectives are described below.

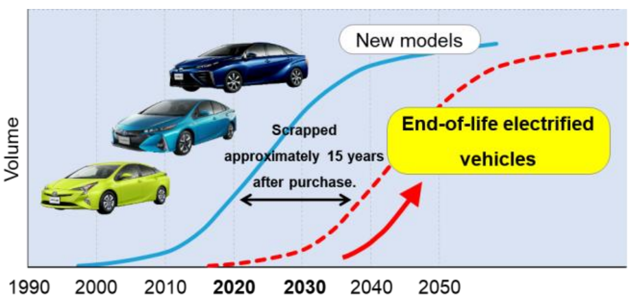


Fig. 1 Vehicle Electrification Trend Forecast

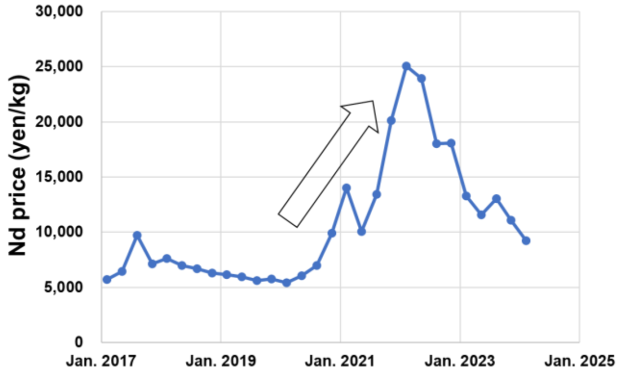


Fig. 2 Market Price of Rare Earth Elements

Source: Created from materials provided by Trading Economics[2]

3.2 Issues and Toyota's initiatives

Toyota's first objective is to recover component parts from the market. Insufficient component part volumes during the transition period toward electrification means that no recycling business chain currently exists (red dotted line in **Fig 1**). However, as more electrified vehicles are scrapped in the future, it will be necessary to promote the development of technology to achieve objective (2) the extraction of magnets from component parts to enable recycling just as the European regulatory system comes into effect.

Toyota is working with Toyota Metal Co., Ltd. on a trial project to recover magnets from in-process scrap, test vehicles, and the like. As an example, **Fig. 3** illustrates the structure of how most magnets are fitted inside a rotor. When extracting magnets from component parts, the key issue is how to remove these rotor magnets. This is because magnets inside electromagnetic steel sheets are sealed and adhered to the sheet steel using thermosetting resin.

Fig. 4 shows an outline of the process used to extract magnets from a rotor. When recovering these magnets, the adhesive strength of the resin is erased by carbonization via heating in a high-temperature bath. However, this causes a reduction in the strength of the magnets. The rotor is then rapidly cooled, causing the layered electromagnetic steel sheets to deform and creating gaps between the layers (increasing stress). Finally, vibration is applied to the bar passing through the rotor to extract the magnets. The recovery rate of this method is virtually 100%. The benefit of this method is that it is compatible with different rotor structures. In contrast, issues include the energy, cost, and time required by the heating process, as well as magnet oxidation and impurity intrusion, leading to extra costs in the recycling process for separation and refining.

Toyota is aiming to continue improving this extraction process to make magnet recovery more efficient (for example, by reducing the number of steps and shortening the time required for the process). Furthermore, over the medium- to long-term, it will also be important to improve structures to make magnet extraction easier.

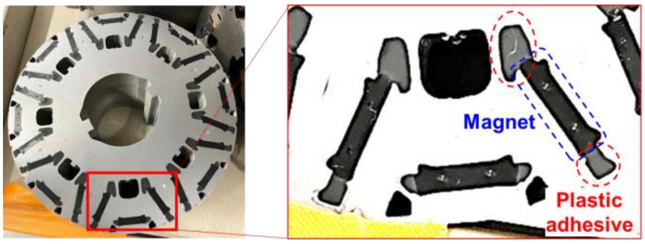


Fig. 3 Main Magnet Fixing Structure

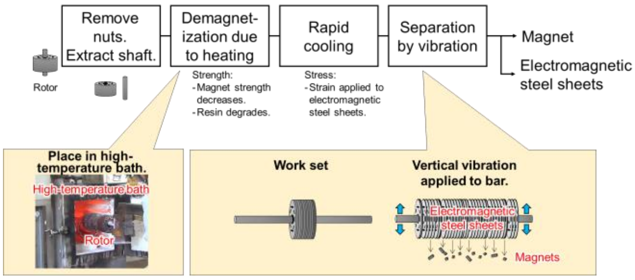


Fig. 4 Outline of Process for Extracting Magnets from Rotors

4. Plastic Recycling

4.1 Current situation of plastic recycling in Japan

In May 2019, the Japanese government released its Resource Circulation Strategy for Plastics to promote the recycling of plastic resources. This was created in response to the incorporation of a strategy for plastic material recycling in the fourth Fundamental Plan for Establishing a Sound Material-Cycle Society as determined by the Cabinet on June 19, 2018. After the publication of an interim report in November of the same year and the acceptance of public comments, the Minister of the Environment released the final strategy via the Central Environmental Council of Japan on March 26, 2019.

One recent major issue related to plastics has been the environmental pollution caused by the discharge of plastic waste into the Pacific Ocean. In addition, the introduction of restrictions on the import of waste plastic by a number of countries has created the concern that it will become impossible to export waste plastic from Japan. For these reasons, the importance of recycling plastic resources inside Japan is growing. One major accomplishment of the fifth session of the United Nations Environment Assembly held in March 2022 was the adoption of a global plastics agreement that aims to resolve the international issue of plastic pollution by 2040. This agreement is likely to come into effect at the end of 2024.

In 2021, the amount of plastic waste discarded inside Japan reached 8.24 million tons. This included 4.19 million tons of general waste and 4.05 million tons of industrial waste. After disposal, 1.77 million tons (21%) were recycled as materials and 290,000 tons (4%) were processed by chemical recycling methods. Most of the recycled material came from the re-use of bottles made from polyethylene terephthalate (PET bottles). Furthermore, 5.1 million tons (63%) were used as fuel for thermal recovery processes, including 2.52 million tons (31%) that were incinerated to generate electricity, 1.95 million tons (24%) that were incinerated to provide feedstock for cement or for conversion into fuel, and 0.5 million tons (6%) that were incinerated to provide heat. Finally, 1.07 million tons of discarded plastic were unused, including 0.63 million tons (9%) that were incinerated and 0.45 million tons (5%) that were placed in landfill sites (**Fig. 5**).

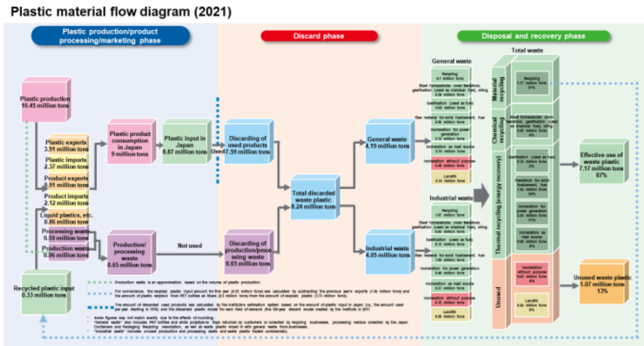


Fig. 5 Plastic Material Flows in Japan
Source: Plastic Waste Management Institute(3)

4.2 Current situation of automotive plastic recycling

Japan's Act on Recycling of End-of-Life Automobiles was used as the foundation for the creation of ELV recycling procedures. ELVs are handed over to dismantlers, who are responsible for recovering fluorocarbon gases as part of measures to help prevent global warming, for deploying and recovering airbags to ensure worker safety, as well as for draining fuel and fluids from radiators and the like. Dismantlers then remove parts that can be sold on the second-hand market and parts that can be used for material recycling (precious metals including copper). Parts that can be used for material recycling are dismantled and recovered manually or using a nibbler tool, before being sold to a second-tier dismantler such as a specialist engine dismantler or wire harness disposal firm. Although this process also includes the dismantling of plastic parts, economic factors such as cost and transportation issues due to the lightweight but bulky nature of plastic parts means that plastic waste is usually handed over to shredding operators (**Fig. 6**). Furthermore, since dismantlers are not informed about which plastic parts need to be dismantled, many parts are simply left unrecovered.

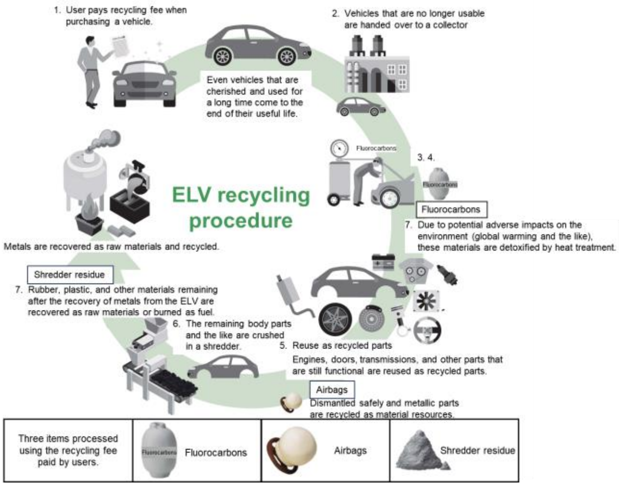


Fig. 6 ELV Recycling Procedure

Source: Japan Automobile Recycling Promotion Center (JARC)[4]

Shredding operators are responsible for shredding crushed vehicle bodies (**Fig. 7**). Using a combination of air, magnetism, specific gravity, and manual sorting, between 40 and 60% of the ferrous and non-ferrous metals in the vehicle are recovered. The recovered ferrous metals are sold to steel manufacturers and non-ferrous metals are sold to manufacturers of non-ferrous metal products. Lightweight automobile shredder residue (ASR) accounts for approximately 17 to 19% of a scrapped vehicle by weight. Since plastic, rubber, fibers, and other flammable materials account for around 70% of ASR (**Fig. 8**), most ASR is thermally recycled (**Fig. 9**). In other words, only a portion of the plastic and rubber parts used on a vehicle can be recovered as parts or materials in the vehicle scrapping process as most of these parts are processed into ASR and are thermally recycled by metal refining or in a melting furnace or fluidized bed incinerator. Some parts may be recycled as materials (such as raw materials for feedstock or pallets). If not, parts are processed by incineration or placed in landfill (**Fig. 9**). Annually, 330,000 tons of plastic waste is collected from vehicles, approximately 4% of the overall total of plastic waste. At the same time, 220,000 tons of ASR is also generated on an annual basis.

Fig. 7 Shredding of Crushed Vehicle Bodies

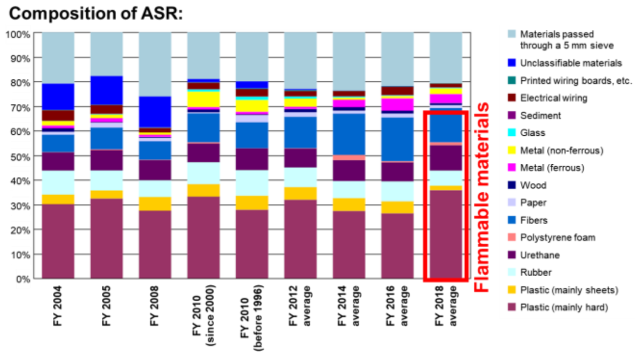


Fig. 8 Composition of ASR

Source: Created based on materials from the Japanese Ministry of the Environment[5]

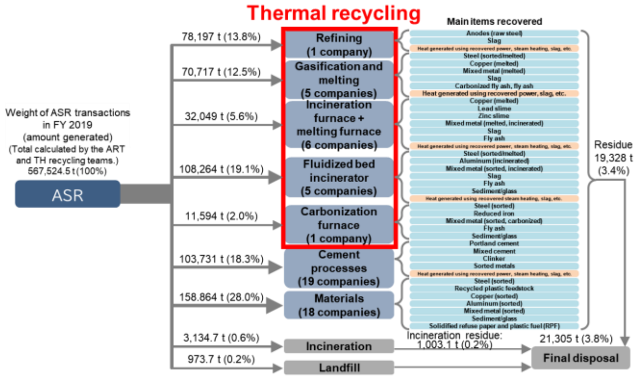


Fig. 9 ASR Material Flow

Source: Created based on materials from the Japanese Ministry of the Environment[5]

4.3 Toyota's initiatives to date

Toyota has been developing ASR recycling technologies in partnership with Toyota Metal Co., Ltd. since 1993 with the aim of facilitating the sorting and recovery of materials from ASR. In August 1998, the Toyota group started recovering resources at mass-production scale (ASR capacity: approximately 2,000 tons/month) through its own recycling plant. To completely reuse all ASR, it must be turned back into raw materials. Since this requires sorting processes that raise the purity of the components, a special sorting technology has been developed for ASR recycling plants to increase the rate of material recycling from ASR.

In an ELV shredding plant, sorting of ASR with a low specific gravity is carried out by a two-step air sorting process (**Fig. 10**) after passing through both a pre- and main shredder. Subsequently, non-ferrous metals such as aluminum, copper, and the like are sorted by magnetic and eddy current processes. ASR recycling plants use a trommel sieve to sort material by size. Then, after glass and other similar materials are recovered, the grain size of the ASR is reduced by crushing and pulverization. Air sorting is then applied to recover materials with a low specific gravity such as urethane foam and fibers. Urethane foam and fibers are turned into molten solids by solidification molding machines (**Fig. 11**). Subsequently, this is mixed with ferrous scrap from vehicle assembly plants, molded, and used as raw fuel in electric arc furnaces. After air sorting, large materials with a high specific gravity are sorted by a combination of float-sink sorting, pulverization, and specific gravity sorting. Materials that float are sorted as plastics and materials that sink are sorted as non-ferrous metals (**Figs. 12** and **13**). This sorting technology helps to realize Japan’s highest recovery rate of between 20 and 25%, enabling the sorting and recovery of polypropylene-rich plastic from ASR (**Fig. 14**).

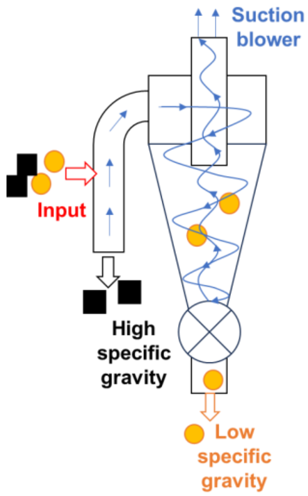


Fig. 10 Air Sorting

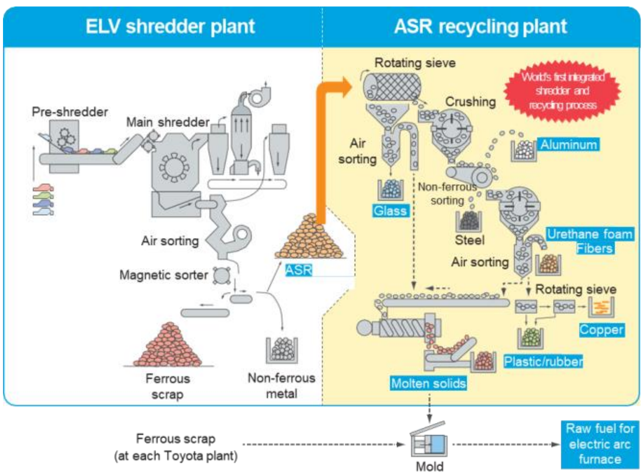


Fig. 11 Shredding and ASR Recycling Process Developed by Toyota Metal Co., Ltd.

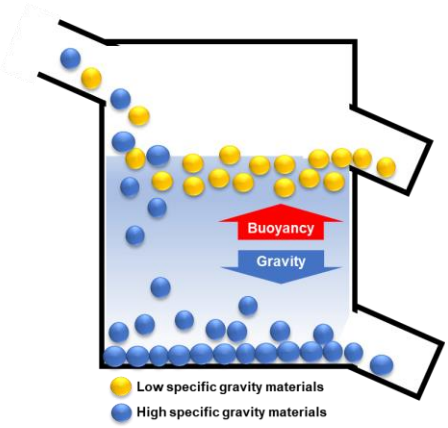


Fig. 12 Float-Sink Sorting

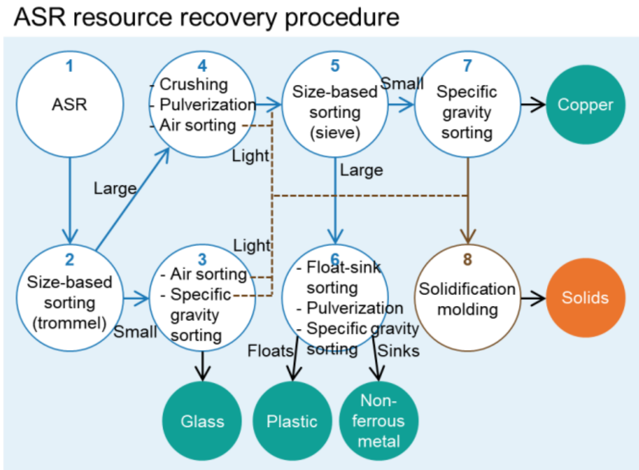


Fig. 13 Resource Recovery Procedure Developed by Toyota Metal Co., Ltd.

Source: Toyota Metal Co., Ltd.(6)

Fig. 14 ASR before and after Sorting

4.4 Issues and future initiatives

4.4.1 Material recycling

As described above, ELVs are processed by dismantlers to recover fluorocarbons, ensure airbag safety, and drain fluids. Parts are then recovered before the ELV is crushed. Subsequently, shredding operators process the crushed vehicle bodies to recover ferrous and non-ferrous metals and then carry out ASR processing. Plastic recycling can follow two patterns, using either before shredder technology (BST), which recovers and recycles parts as materials before shredding, or post shredder technology (PST), which carries out material recycling from ASR after shredding.

(1) BST (material recycling from recovered parts)

Material recycling using plastic parts recovered from ELVs has the merit of creating a comparatively uniform end product. In addition to the bumpers, dismantlers remove plastic parts such as the underbody, instrument panel, door trim, and other parts. However, dismantlers do not currently carry out material recycling. One reason for this is the state of the parts, which are dirty and affixed with other materials such as seals on the reverse side, vibration damping tape, clips, and so on. As a result, material recycling requires a two-step dismantling process, which is not economically viable. To expand recovery from BST, Toyota is studying simple methods for efficiently removing non-target materials. It is also looking into establishing a system to expand material recycling by notifying dismantlers about which plastic parts should be recovered.

The Japan Automobile Manufacturers Association (JAMA) is also studying the introduction of a resource recycling incentive scheme in 2026 to help raise the level of plastic recycling. This scheme will encourage material recycling by incentivizing the removal of materials such as plastics and glass before the dismantling and crushing steps by paying dismantlers and crushing operators an ASR recycling fee that would ordinarily not apply to parts removed in advance.[7] Since the introduction of this scheme is regarded as a promising way of raising the quality and purity of recycled plastic, expanding the use of recycled plastic is currently being prioritized.

(2) PST (material recycling by sorting and recovery from ASR)

Section 4.3 described a sorting and recovery procedure capable of obtaining polypropylene-rich plastic. However, some plastic materials cannot be fully sorted using specific gravity (**Table 1**). The establishment of technology capable of expanding the range of material recycling by sorting and recovering these plastics into more easily recyclable materials is extremely important. As **Table 2** shows, non-specific gravity sorting methods such as optical sorting and electrostatic separation technologies are not fully capable of completely sorting all materials contained in ASR. Optical sorting incorporates a wide range of technologies from near-infrared to laser systems, some of which are still in the research phase. However, all these technologies are affected by common issues. For example, sorting may not be possible due to sample weight or contamination, and the materials that can be sorted of each technology are limited. More specifically, near-infrared sorting is not suitable for identifying black plastics. In addition, electrostatic separation cannot easily sort material types with a similar triboelectric charge. Investigations and studies of new sorting technologies will continue in the future alongside efforts to identify effective combinations of sorting technologies.

(3) Common

One common issue of both BST and PST is the occurrence of volatile components such as odors and volatile organic compounds (VOCs) in interior parts. Efforts are ongoing to establish efficient and effective technology to reduce these volatile components, such as so-called VOC catcher additives. In addition, since most recycled materials are black, it is difficult to colorize paler styling parts. Color sorting can be carried out when recovering feedstock for recycling, but this can be costly. Consequently, technology to either decolorize or colorize parts will be important and studies are currently under way. Before using recycled materials, it is also necessary to consider the impact of foreign matter mixed into the material, which can have negative effects on both physical properties and appearance quality. Measures to address these issues include designing parts considering the potential deterioration in physical properties and the development of both material and manufacturing technology to eliminate foreign matter. Finally, it is also important to establish control methods to comply with regulations related to chemical substances.

Table 1 Specific Gravity of Plastics

	PP	PE	TSOP	ABS	PA	PMMA	PC	PVC (soft)	PA-GF	PET	POM
<1.00	●	●									
1.00 to 1.04			●	●							
1.04 to 1.10			●	●	●						
1.10 to 1.15				(●)	●						
1.15 to 1.20						●	●				
1.20 to 1.35								●	●		
1.35 to 1.40									●	●	
>1.40											●

Table 2 Comparison of Sorting Technologies

	Optical sorting					Electrostatic separation
	Near-infrared	Mid-infrared	Raman	Terahertz wave	Laser-induced breakdown spectroscopy	
Issues	Sorting not possible due to sample weight or contamination. Limited types of sortable materials.					Affected by humidity.
	–	High equipment cost	Long black color recognition times.	Unclear processing capability	High equipment cost	Material types with a similar triboelectric charge cannot be sorted.
Black plastic sorting	×	○	○	○	○	○
Phase	Commercial		Pilot	Research	Research	Commercial

×: Not available
○: Available

4.4.2 Chemical recycling

Chemical recycling can be broadly categorized into a method that converts plastics into intermediate monomer feedstock (called monomerization) and oiling or gasification methods that convert plastics into feedstock used in processes further upstream. Recycling methods that are being considered include microwave heating, processing using subcritical or supercritical water, and processing using solvents (**Table 3**). As described in this table, each of these methods has its merits. However, these methods are essentially suitable for single materials and are difficult to apply to multiple materials. For this reason, it is difficult to adopt these methods with ASR. Although pyrolysis can be used to process mixed plastics, hydrochloric acid will be generated during processing if the plastic contains vinyl chloride. Since this will corrode the equipment, vinyl chloride must be eliminated before processing. Subcritical and supercritical water processes have the merit of short processing times. However, since high-pressure equipment is needed to create subcritical and supercritical water in the first place, equipment costs are high. Investigations and studies of chemical recycling technologies capable of processing ASR in combination with the sorting technologies described above are ongoing.

Table 3 Comparison of Chemical Recycling Technologies

	Microwave (monomerization, depolymerization)	Pyrolysis (oiling)	Pyrolysis (gasification)	Subcritical water, supercritical water	Melting, solvent extraction
Example	-Mitsui Chemicals Inc. -Microwave Chemical Co., Ltd.	-BASF -Idemitsu Kosan Co., Ltd.	-Resonac	-Toray Industries Inc. -Mitsubishi Chemical Group Corporation -ENEOS Corporation	-Mitsui Chemicals Inc. -PureCycle Technologies
Outline of technology	Low-temperature pyrolysis (approx. 200°C)	Medium/low-temperature pyrolysis (up to 400°C)	High-temperature pyrolysis (600°C or higher)	Subcritical water, supercritical water decomposition (100 to 374°C, higher than 374°C)	Dissolved in solvent and separated by filtration.
Target materials	-Waste PUF	-Waste plastic -ELV-derived plastic	-Waste plastic	-Waste PA6-GF -Waste plastic	-Waste PP
Phase	-Pilot	-Commercial -Pilot	-Pilot (from 2024)	-Pilot -Pilot (operational from summer 2024)	-Plant under construction (North America)
Merits	Energy-efficient	Mixed plastics can also be processed	Mixed plastics can also be processed	Short processing times, material may include halogens	Low energy
Issues	Single-material only	Polyvinyl chloride must be removed	High energy consumption	High equipment cost (because high-pressure equipment required)	Only single-material solvent reuse

5. Conclusion

Material recycling is essential for realizing a circular economy. Although this article focused on initiatives to recycle aluminum, magnets, and plastics, many issues remain to be resolved. Initiatives and technical development must be continued from multiple directions. Toyota remains committed to taking on the challenge of achieving the circular use of the Earth's limited resources through a wide range of activities and technical development to enable the recycling of all types of automotive materials, including steel, copper, glass, and rubber.

References

(1) Y. Furukawa. "Development of High-Performance Materials Using Interfacial Phenomena of Aluminum Alloys at High Temperatures." *Nagoya University Doctorate Thesis* Grant No. 7432. https://irdb.nii.ac.jp/01152/0006301776

(2) Trading Economics website. Neodymium - Futures Contracts - Price (in Japanese). https://jp.tradingeconomics.com/commodity/neodymium

(3) *Basic Knowledge about Plastic Recycling 2023*. Plastic Waste Management Institute pp. 6-7. https://www.pwmi.or.jp/pdf/panf1.pdf

(4) *ELV Recycling Procedure* (in Japanese). Japan Automobile Recycling Promotion Center (JARC). https://www.jarc.or.jp/automobile/mechanism/recycleflow/

(5) *Current Situation of Vehicle Recycling* (in Japanese). Ministry of Economy, Trade and Industry, Ministry of the Environment https://www.meti.go.jp/shingikai/sankoshin/sangyo_gijutsu/haikibutsu_recycle/jidosha_wg/pdf/048_04_00.pdf pp. 16-17 (2020).

(6) Homepage of Toyota Metal Co., Ltd. ASR Resource Recovery Procedure (in Japanese). https://www.toyotametal.com/business/asr-recycle/

(7) *JAMA Initiatives* (in Japanese). Japan Automobile Manufacturers Association. https://www.meti.go.jp/shingikai/sankoshin/sangyo_gijutsu/resource_circulation/jidosha_wg/pdf/058_06_00.pdf

Initiatives for Battery Recycling

Hiroyuki Ishikawa[*1]
Keisuke Isomura[*2]
Hidenori Takahashi[*3]
Takayuki Nagai[*1]

Abstract

Toyota is the largest manufacturer of electrified vehicles in the world. In addition to selling more than 20 million electrified vehicles on a global basis, the company also carries out battery recycling. This article describes an outline of battery regulations in Europe, the initiatives promoted by the automotive industry related to the proper disposal of batteries, and Toyota's initiatives for battery recycling.

Keywords: *repurpose, rebuild, battery regulations, sweep, energy storage system, used battery, recycling*

1. Introduction

Toyota is the largest manufacturer of electrified vehicles in the world and has achieved global sales of more than 20 million units. Electrified vehicles can be broadly categorized into hybrid electric (HEVs), plug-in hybrid (PHEVs), battery electric (BEVs), and fuel cell electric vehicles (FCEVs). Toyota has mainly focused on the production of HEVs, which require a lower battery capacity than BEVs or PHEVs. Toyota is currently working to achieve carbon neutrality and intends to continue expanding its lineup of electrified vehicles in the future. The shift from internal combustion engines to electrified vehicles is helping to alleviate the impact of climate change and is a global movement that is not limited to Toyota. Since the demand for batteries has increased dramatically, it is likely that the number of used batteries will also increase substantially in the future.

Generally, electrified vehicles are powered by either nickel metal hydride (NiMH) or lithium-ion batteries (LiBs). As battery production increases and electrified vehicles require higher-capacity batteries, it will be necessary to promote battery recycling to help realize the proper disposal of used batteries and achieve stable procurement of scarce resources such as nickel (Ni), lithium (Li), and cobalt (Co). At the same time, Europe has enacted battery regulations that require actions for recycled content and the like. After outlining these European battery regulations, this article describes the initiatives promoted by the automotive industry related to the proper disposal of batteries, as well as Toyota's initiatives for battery recycling.

*1 CE Promoting Dept., Advanced R&D and Engineering Company
*2 Environment Affairs and Engineering Management Div., Carbon Neutral Engineering Development Center
*3 Energy Solution Business Div., Business Development Group

2. Outline of the European Battery Regulation

In 2023, the European Union (EU) enacted the European Battery Regulation to replace the existing Battery Directive. As an EU regulation, this is legally binding in all the member countries of the EU. This regulation supersedes any domestic laws already in place in each member country and creates a unified set of rules across the whole of the EU. This contrasts to the previous EU directive, which was intended to form the basis of domestic laws in the member countries. Each country had a certain degree of discretion in how to legislate based on the directive, leading to differences in laws and regulations across the EU. In other words, battery rules have been raised from the level of an EU directive to an EU regulation, underlining the importance of battery regulations in Europe.

The European Battery Regulation applies to all categories of batteries distributed in Europe. For automotive applications, it applies to all batteries, from those used to start the vehicle, turn on lights, or carry out ignition, as well as batteries used to drive the vehicle. In addition to new models, this regulation also contains provisions that must be satisfied by existing vehicles. Although there is no space in this article for a full breakdown of the European Battery Regulation, it contains the following two numerical targets related to vehicles in the context of a circular economy (**Fig. 1**).

1) Recycling efficiency targets
   These targets apply when batteries are recycled. The term "recycling efficiency" refers to the proportion of resources included in a used battery that are recovered in the recycling process. The regulation sets two types of targets: the recycling efficiency of the overall battery and the recycling efficiency of the metallic materials contained in the battery. The recycling efficiency of the overall battery is still under deliberation since it will depend on how the denominator is calculated. However, specific two-phase targets have already been set for LiBs (65% in

2025 and 70% in 2030). Similarly, two-phase targets for 2027 and 2031 have also been set for the recycling efficiency of battery elements such as Co, Ni, Li, copper (Cu), and lead (Pb). In particular, high targets have been set for Li: 50% in 2027 and 80% in 2031.

2) Regulations for recycled content
These regulations apply at the battery design phase. The term "recycled content" refers to the proportion of recycled materials adopted for specific metallic elements in the battery. Manufacturers are obligated to report this information from August 2028 and to disclose the amount of Co, Ni, Li, and Pb present in the battery as well as recovered from waste for each battery model per year and per manufacturing plant. In the same way as the targets for battery recycling efficiency, these are two-phase regulations with different values specified for 2031 and 2036.

The European Battery Regulation applies to all business operators that distribute batteries within the EU. If the regulation is not satisfied, companies might be prevented from selling electrified vehicles in the European market and will be required to take action to remedy the situation.

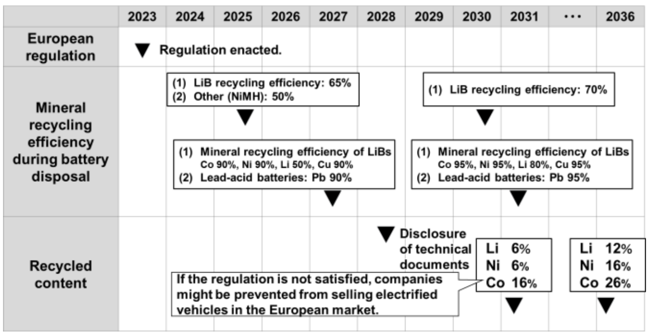


Fig. 1 Outline of European Battery Regulation

3. Initiatives Promoted by Automotive Industry Related to Proper Battery Disposal[1]

This section covers the proper disposal of batteries. Various types of batteries have been adopted in vehicles. Of these types, a financial transaction-based resource recovery business chain has been established for lead acid batteries. In 2015, the government council responsible for Japan's Act on Recycling of End-of-Life Automobiles stated that manufacturers should examine the establishment of systems for stably and sustainably recovering and recycling LiBs used for electrified vehicle traction motors (as described in a September 2015 report describing evaluations and studies into the implementation status of vehicle recycling systems). This statement prompted the automotive industry to start considering recovery and recycling systems for LiBs (**Fig. 2**). Consequently, vehicle dismantlers started building and operating systems for recovery and recycling in 2018. Maintenance operators began operating their own recovery and recycling systems the following year in 2019. Under these systems, dismantling and maintenance operators recover used batteries from end-of-life vehicles (ELVs) and vehicles undergoing maintenance based on the disconnection methods and other information provided by automakers. Then, the dismantling and maintenance operators request the Japan Auto Recycling Partnership (JARP) to collect the recovered batteries. Based on these collection requests, JARP recycles the batteries in partnership with transportation companies and battery recycling facilities. Batteries are currently recovered free-of-charge under these systems.

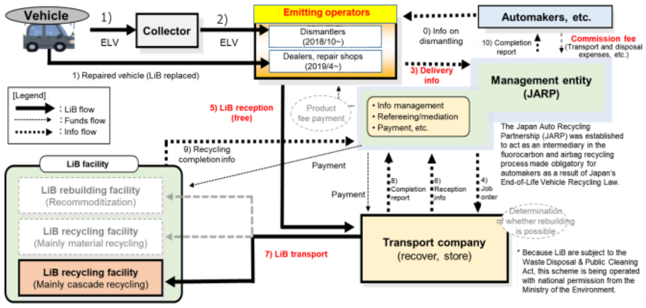


Fig. 2 LiB Recycling System
Source: Japan Automobile Manufacturers Association (JAMA)[1]

In addition, the automotive industry has established a scheme for rebuilding used batteries (**Fig. 3**). Under this scheme, the recovery/recycling system described above is expanded to include items such as a product fee payment system and a process to determine the feasibility of rebuilding. This helps to promote a stable and safe system for reusing and rebuilding batteries in the market.

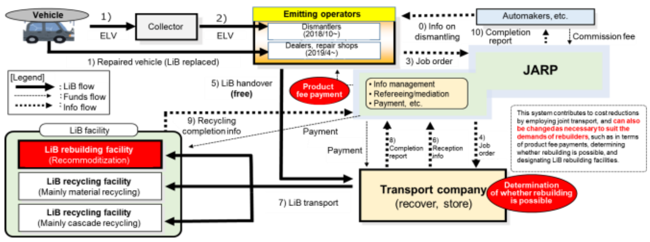


Fig. 3 Approach for Battery Rebuilding
Source: Japan Automobile Manufacturers Association (JAMA)[1]

Since the number of used batteries will increase in step with sales of electrified vehicles, battery recovery and recycling systems will play an even more important role in the future. However, due to the sixteen-year gap between the sale and scrapping of a vehicle (**Fig. 4**), the number of used batteries will remain low until around 2035 before increasing rapidly in 2040 onwards. For this reason, as a first step, it will be necessary to develop technologies for recycling materials from the battery manufacturing process. It will also be important to continue the development of technologies for recycling, reusing, and rebuilding used batteries. The next section describes Toyota's initiatives for enabling the longer use of batteries.

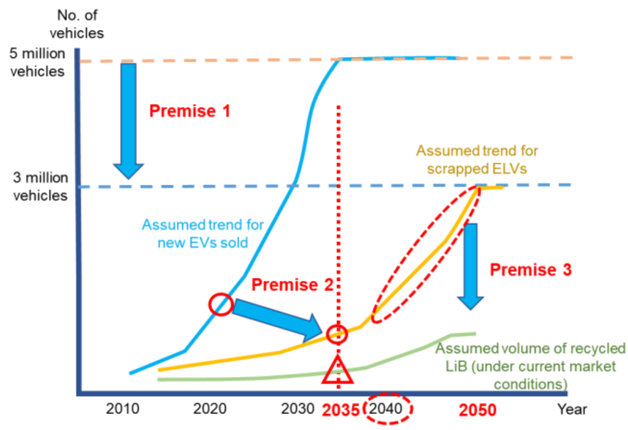


Fig. 4 Forecast for Number of Used LiBs
Source: Japan Automobile Manufacturers Association (JAMA)(1)

4. Toyota's Initiatives Related to the Recycling of Used Batteries

4.1 Battery 3R initiatives

In addition to the mass production of electrified vehicles, Toyota has a long history of initiatives related to the recycling of used batteries. As part of the process for realizing a circular economy, Toyota is promoting the circular use of products and materials through reducing, rebuilding or reusing, and recycling batteries (i.e., the 3Rs) alongside design measures to enable long-term use and minimize waste. The recovery of used batteries is an essential part of the battery 3R initiatives. Two examples are described below.

(1) Disclosure of battery disconnection information
To recover used batteries from electrified vehicles, Toyota has set up a website that describes key points for enabling the safe removal of used vehicle batteries by dismantlers.

(2) Construction of used battery recovery network
Toyota has established a battery recovery network in Japan (**Fig. 5**) that receives collection requests from all over the country. This recovery system uses the return journeys of transportation services of replacement Toyota parts. In 2022, approximately 40,000 HEV batteries were recovered.

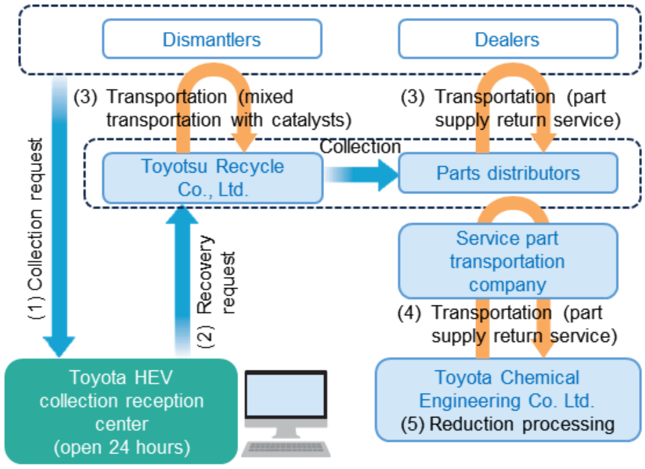


Fig. 5 Used Battery Recovery Network

Used batteries are being repurposed effectively by rebuilding, reusing, and recycling. Since 2014, Toyota has sold used batteries removed from its HEVs (starting with the second-generation Prius before expanding to other models) as service parts (**Fig. 6**). As described in the following sections, Toyota is also working to recover resources from batteries when reuse as a battery is difficult. The purpose of these efforts is to facilitate the profitable long-term use of recovered batteries in non-vehicle applications.

Fig. 6 Rebuilding of NiMH Batteries

4.2 Energy storage system business

The adoption of used batteries recovered from electrified vehicles in non-automotive applications is known as "repurposing." Electrified vehicle batteries must have a high energy density to reduce vehicle weight and improve power consumption efficiency. Although the capacity of used batteries decreases as the battery degrades, some can be rebuilt and reused in other electrified vehicles. However, some are used in applications that do not require a high specific energy density, such as stationary storage batteries. Realizing this fact, Toyota studied the feasibility of technology to repurpose used batteries as stationary storage batteries, resulting in the development of a large-capacity sweep energy storage system (**Fig. 7**). After an operational trial carried out in partnership with JERA Co. Ltd., a 1,260 kWh power grid energy storage system went into operation in 2022.(2)

To realize the same type of parallel connection adopted by conventional large-capacity stationary energy storage systems that feature combinations of new batteries, this system addressed the issues of the sorting costs involved in aligning the performance of used batteries and making use of the full battery capacity. Specifically, these issues were resolved by the development of the sweep function by Toyota Central R&D Labs., Inc., which allows the connection of different types of used batteries and batteries with different levels of degradation (**Fig. 8**).[3] The sweep function allows the flow of electricity in series-connected batteries to be switched on and off in microseconds, enabling the system to control charge-discharge in accordance with the battery level and making full use of the battery capacity. With this function, used batteries that malfunction can be disconnected to maintain system performance. In addition, the capability of the batteries to directly output alternating current (AC) helps to reduce cost by eliminating the need for power conditioners (PCS) and raises energy usage efficiency by minimizing the power loss that occurs when AC is converted into direct current (DC).

Power grid energy storage systems are a technology that can help make full use of naturally fluctuating renewable energy, which has become more prevalent in Japan in recent years, as well as lowering CO_2 emissions. Furthermore, power grid energy storage systems consisting of used batteries have the potential to contribute to the achievement of both a circular economy and carbon neutrality.

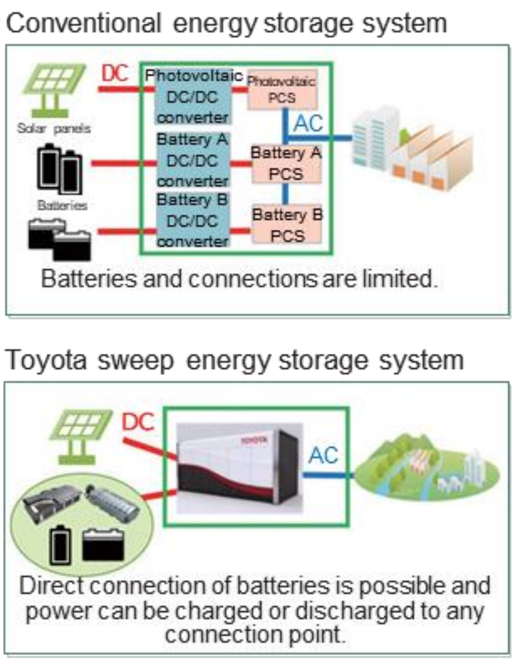


Fig. 7 Features of Sweep Energy Storage System

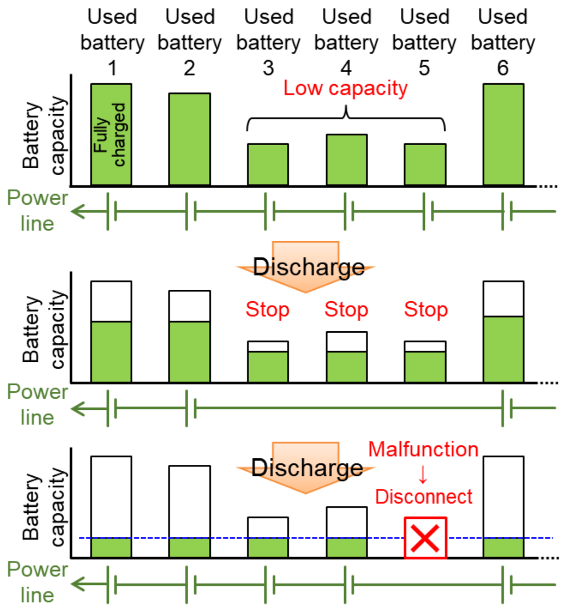


Fig. 8 Sweep Function

Source: Toyota Central R&D Labs., Inc.[3]

4.3 Non-incineration battery recycling

The conventional LiB recycling process involves the crushing and incineration of battery cells, followed by the sorting and recovery of fragments containing materials such as aluminum and copper, as well as powder with a high rare metal content known as “black mass” from the incinerated ash. Rare metals are recovered from this black mass using a wet process. In the conventional process, the combustible electrolyte in battery cells is incinerated together with the cells or battery pack. This process releases CO_2 and results in the loss of some battery materials. Therefore, a process has been developed that dismantles used batteries (**Fig. 9**) and recovers the combustible electrolyte from the battery cells (**Fig. 10**) before the empty cells are crushed. This process enables the separation of different resources from the batteries (**Fig. 11**). In addition to reducing CO_2 emissions, this technology helps to recover resources that are lost under conventional recycling processes.

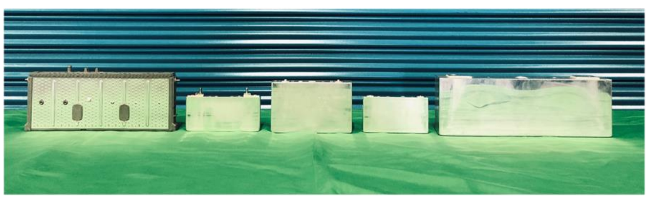


Fig. 9 Various Types of Used Batteries

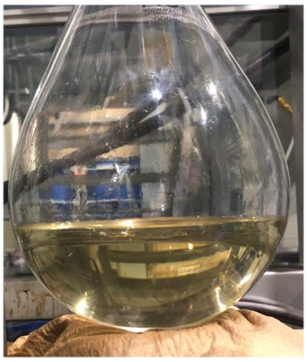


Fig. 10　Extracted Electrolyte

Fig. 11　Battery after Crushing and Separation

5. Conclusion

Toyota is a pioneer of the mass production of electrified vehicles and started its initiatives for battery recycling in 2010. In addition to expanding the production and sale of electrified vehicles, the first step for the future is to develop technology to make use of leftover materials in the battery manufacturing process. This must be followed by the development of technology to utilize batteries from ELVs. To help realize these objectives, Toyota is taking on the challenge of recycling the Earth's limited resources through a full range of initiatives, including designing vehicles that facilitate battery removal, establishing a system to recover batteries, and enabling the reuse, rebuilding, and recovery of resources from recycled batteries.

References

(1) Japan Automobile Manufacturers Association. *Initiatives of Automakers (JAMA)* (in Japanese). Material submitted by the Vehicle Recycling Working Group, Resource Circulation Economy Subcommittee, Committee on Industrial Science and Technology Policy and Environment, 58th Industrial Structure Council (January 2024).

(2) *Construction and Launch of a Large-Capacity Sweep Energy Storage System from Reused Electrified Vehicle Batteries Connected to the Electrical Power Grid.* Toyota Global Newsroom. https://global.toyota/en/newsroom/corporate/38149071.html (2022).

(3) Toyota Central R&D Labs., Inc. News Release. *Development of Waste-Free Technology to Maximize Utility of Used Batteries: Power Storage and Supply Using Renewable Energy* (in Japanese). https://www.tytlabs.co.jp/cms/news/news-20221027-2429.html (2022).

The Toyota Land Cruiser 250 Series

Lead authors:
Keita Moritsu*1
Takuma Ono*2
Masato Nakamura*3
Shunnosuke Naruoka*4
Shinya Kitai*5
Yoshito Watanabe*6
Tomohiko Iwashita*7

Abstract

The Land Cruiser has supported the lives and livelihoods of people in places that only it can reach, a vehicle that allows people to go anywhere and everywhere and return safely. It has been developed and refined over more than seventy years as one of Toyota's signature models, based on the actual usage conditions of customers all around the world. The 250 series is a core model in the Land Cruiser lineup and was developed by going back to its origin as a simple and sturdy vehicle that helps to fulfill both the lifestyle choices and practical needs of its customers. This article outlines the objectives of the 250 series and the technologies developed to realize these objectives.

Keywords: *Land Cruiser, 250 series, going back to the origin, TNGA, GA-F platform, reliability, durability, off-road performance, go and return safely, lifestyle choices and practical needs*

1. Introduction

The new Land Cruiser 250 series was created as a core model in the Land Cruiser lineup with the role and mission of supporting people's lives by providing ease of handling and operation based on strong off-road performance. This article describes how the development team went back to the original role and mission of the Land Cruiser 250 series and outlines the technology developed to realize a simple and sturdy vehicle that can be trusted by customers to fulfill their lifestyle choices and practical needs.

2. Development Target

2.1 History and role of the Land Cruiser

Launched originally as the Toyota BJ on August 1, 1951, the Land Cruiser series has now celebrated its 73rd birthday. Immediately after its launch, it became the first vehicle to climb to the sixth station of Mount Fuji. From that time, the Land Cruiser has fulfilled its mission of delivering safety and security to all types of people in places that only it can reach. Developed and refined based on the actual usage conditions of customers all around the world, it provides the level of reliability, durability, and off-road performance that allows people to go anywhere and everywhere and return safely. This concept has been passed down and continuously evolved since its launch. With cumulative sales of about 11.51 million units in approximately 170 countries and regions, it continues to support the lives and livelihoods of people everywhere. Historically, the Land Cruiser lineup has been divided into three different series: a station wagon that always showcases the latest technologies and has evolved into the flagship model (currently the 300 series), a heavy-duty model with outstanding durability and off-road driving performance (the 70 series), and a light-duty model that provides ease of handling and comfort based on off-road performance to fulfill the lifestyle choices and practical needs of customers (Prado).

2.2 Significance of going back to the origins of the Land Cruiser

The light-duty series has tended to shift toward high-end and luxury models as the generations have evolved. In developing the 250 series, then-President Akio Toyoda, who had the ultimate responsibility for product development, explained his basic approach as follows. "The Land Cruiser should be a vehicle that supports people's lives and local communities, so the light-duty model must return to the true form that customers are looking for."

In response, the development team defined going back to the origin of the Land Cruiser as the development concept. Motivated by the challenge of rebuilding the model, the team created a simple and sturdy vehicle that can be trusted by customers to fulfill their lifestyle choices and practical needs. The 250 series is a core model in the Land Cruiser lineup. It uses the same Global Architecture-F (GA-F) platform as the 300 series to dramatically improve its basic performance as an off-roader. On top of that, the development team also achieved dramatic improvements in the ease of handling and operation, with the 250 series being the first Land

*1 MSZ, Mid-size Vehicle Company
*2 MS Platform Development Div., Mid-size Vehicle Company
*3 MS Vehicle Development Div. No. 1, Mid-size Vehicle Company
*4 MS Vehicle Control Development Div., Mid-size Vehicle Company
*5 Powertrain Product Planning Div., Vehicle Development Center
*6 Advanced Design Development Dept., Advanced R&D and Engineering Company
*7 Final Assembly Div., Tahara Plant, Production Group

Cruiser to be equipped with electric power steering (EPS) and the Stabilizer Disconnect Mechanism (SDM). The EPS system reduces kickback during off-road driving, ensuring ease of handling both on and off the road, while the SDM allows the driver to lock or unlock the front stabilizer at the touch of a button, ensuring driving performance and ride comfort off the road and stable handling on the road.

The 250 series also adopts various powertrains to achieve excellent driving and environmental performance worthy of a Land Cruiser. It was created in pursuit of the unique Land Cruiser characteristics, incorporating interior and exterior design that fuses traditional and modern in a functional package. The aim was to create a next-generation Land Cruiser with improved ease of handling and comfort for both on- and off-road driving, while also delivering class-leading advanced safety performance.

2.3 Packaging

The 250 series has body dimensions of 4,925 mm in length and 1,980 mm in width. Its wheelbase is 2,850 mm, which is the ideal length to realize both the off-road performance and comfort required by a three-row sport utility vehicle (SUV). The couple distance between the second- and third-row seats and the luggage space were also expanded (**Fig. 1**). The development team also placed a particular focus on the ease of handling, creating shorter a front overhang than the Prado 150 series while still satisfying the stringent crash safety performance requirements of every country and region around the world. The structure around the front of the vehicle was updated using new welding technology to create non-linear curved tailor welded blanks that increase rigidity and reduce weight. At the rear of the vehicle, the rear ends of the rails were brought forward to help realize a chamfered body shape and enhance maneuverability.

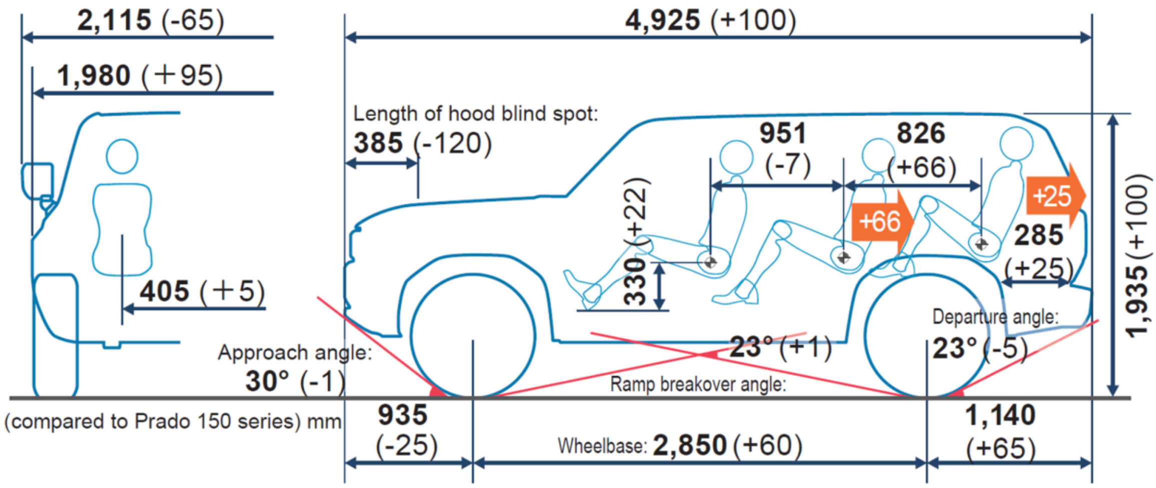


Fig. 1 Packaging

Ease of handling was also realized by widening the distance between the tires to dramatically enhance driving performance and the feeling that the vehicle is firmly planted on the road, and by restricting the width from door mirror to door mirror, which is a concern when driving on narrow roads, to just 2,115 mm, shorter than the Prado 150 series.

3. Dynamic Performance and Platform

3.1 GA-F platform

The 250 series uses the same robust ladder frame GA-F platform as the 300 series, allowing it to combine off-road performance with ease of handling, including on the road, to support the lifestyle choices of the customer.

In the event of a frontal impact, the force received by the frame is distributed to the body, helping to mitigating the need to reinforce the frame. In the event of a side impact, the structural members between the rockers and frame distribute the force received by the rockers, optimizing the strength of the body (**Fig. 2**). This structure that transmits force mutually between the frame and the body helps to achieve both collision safety and lightweight construction.

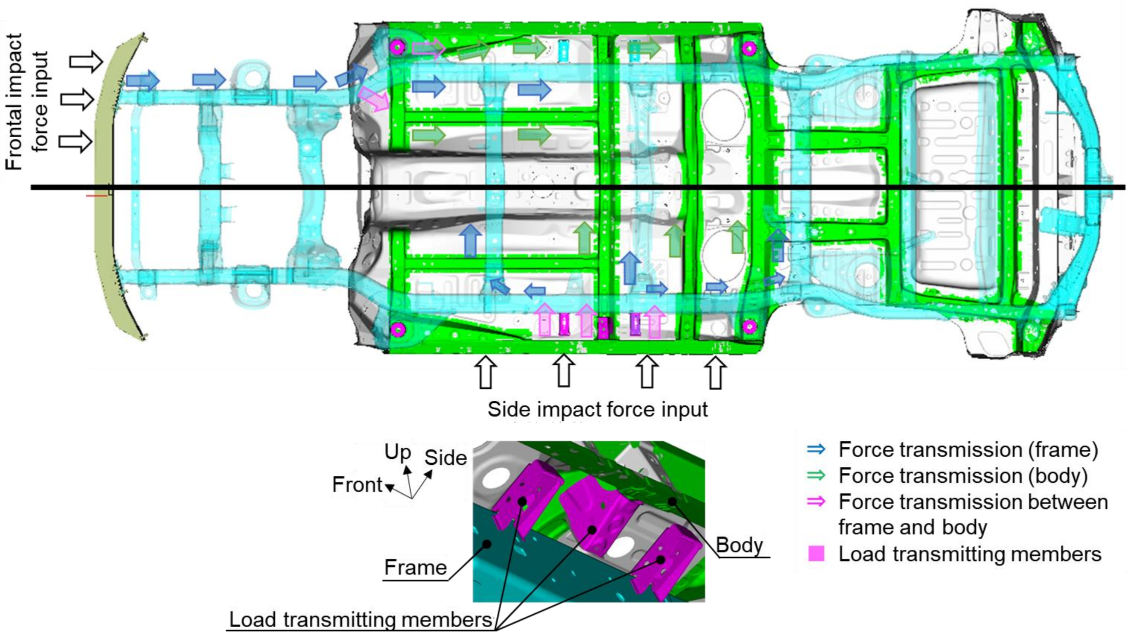


Fig. 2 Frame Layout

3.1.1 Ladder frame structure

The ladder frame combines the optimum cross member layout of the GA-F platform with the latest non-linear (curved) tailor welded blank (TWB) technology and ultra-high tensile strength steel plates in the ideal locations (**Fig. 3**), helping to increase the torsional rigidity of the frame by 50% compared to the Prado 150 series. The normal reinforcing structure that overlays reinforcements onto steel sheets (**Fig. 4**) was replaced by a non-linear TWB structure (**Fig. 5**). This structure helps to realize a significant reduction in weight (compared to the structure of the Prado 150 series) while retaining the signature reliability and durability of the Land Cruiser. In addition, by adopting the GA-F frame, which is compatible with a wide range of vehicle specifications, a ladder frame was developed that delivers a diverse range of choices in line with the multi-pathway strategy.

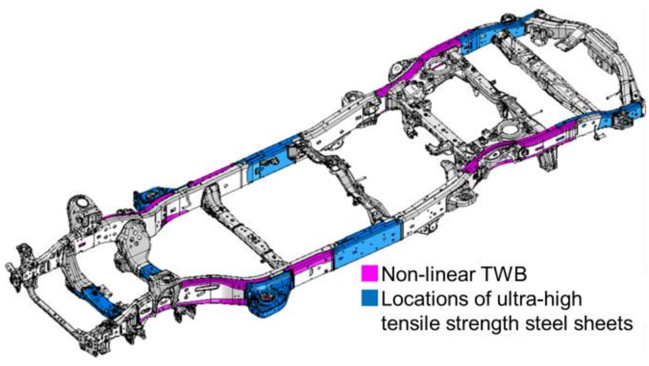


Fig. 3 Ladder Frame Adopted by the 250 Series

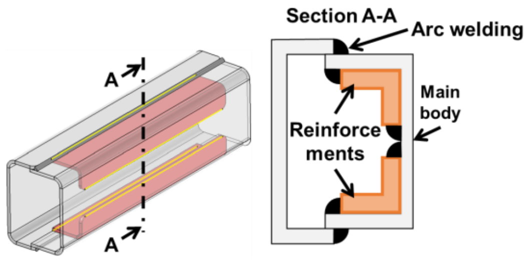


Fig. 4 Structure of the Prado 150 Series (Reinforcing Structure)

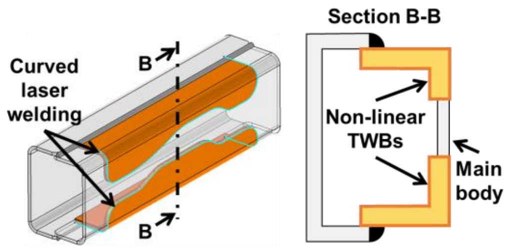


Fig. 5 Non-Linear TWB Structure

3.1.2 Body structure

Ultra-high tensile strength steel sheets were adopted in the optimum locations to help ensure reliability and durability, while also reducing weight (**Fig. 6**). In addition, the adoption of structural adhesive on the frame and direct tightening between the body frame and seat rails helps to realize superb ride comfort and handling (**Fig. 7**).

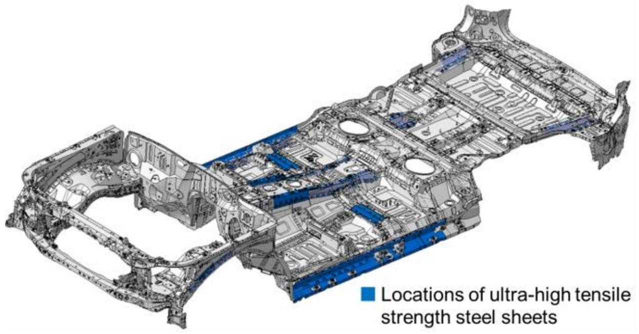


Fig. 6 Adoption of Ultra-High Tensile Strength Steel Sheets

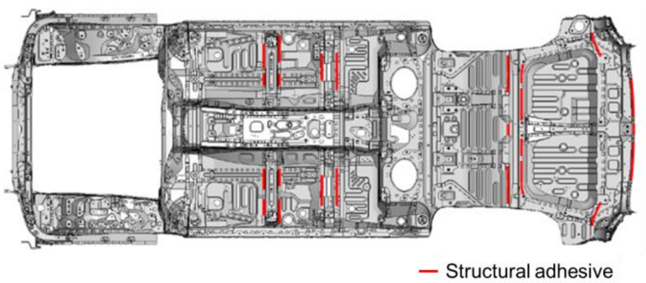


Fig. 7 Application Range of Structural Adhesive

3.2 Suspension types

The suspension combines a high-mount double wishbone at the front (**Fig. 8**) with a trailing link axle at the rear (**Fig. 9**). Excellent ride comfort and handling were ensured by adopting the same GA-F platform as the 300 series.

Fig. 8 High-Mount Double Wishbone Front Suspension

Fig. 9 Trailing Link Axle Rear Suspension

At the same time, the 250 series also incorporates a wide range of specially designed parts to achieve easy handling on any road surface to help support the lifestyle choices of the customer. A short front overhang was achieved by positioning the front stabilizer behind the front axle and optimizing the geometry. This approach helped to substantially improve both the maneuverability and design of the vehicle. At the same time, roll stiffness was increased efficiently by positioning the attachment point of the stabilizer directly below the highly rigid cross member and adopting a pillow ball as the stabilizer link, resulting in an agile driving feel.

The suspension stroke and longitudinal stabilizer balance were optimized to ensure sufficiently high wheel articulation (an indicator of off-road performance that describes the ability of a tire to stay on the ground). These measures helped to improve both off- and on-road performance.

3.3 EPS

The 250 series features a newly developed rack assist type EPS that provides easy handling and fun-to-drive performance both off-road and on-road. This system reduces the steering movement caused by kickback (i.e., shock generated by irregular road surfaces), making it easier for the driver to handle the vehicle during off-road driving. The EPS was repeatedly tuned to provide optimal steering torque and stability in response to driver operation, resulting in an easy steering feel at low speeds, as well as a comfortable and reassuring experience during long drives on the highway, similar to that of a passenger car. In addition, initial steering response was improved by adopting rigid mounts for two of the three EPS mounts (i.e., direct fastening to the cross member without rubber bushes). The EPS supports the mode select and multi-terrain select functions to achieve the optimal steering feel. Additionally, this system is also compatible with driving assistance functions such as Lane Tracing Assist (LTA), which makes driving easier during long trips.

3.4 Stabilizer with Disconnection Mechanism (SDM)

The SDM is applied to the front stabilizer, allowing excellent performance and ride comfort under harsh off-road conditions, while also ensuring on-road performance (**Fig. 10**).

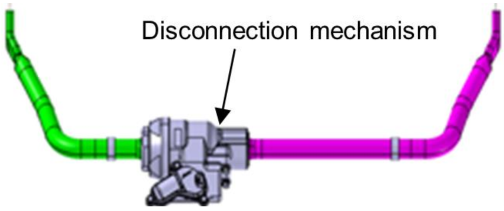


Fig. 10 SDM

The stabilizer connects the left and right wheels to enhance on-road handling. However, if the left and right wheels are connected off-road, this will inhibit the ability of the suspension to expand and contract, and have a negative impact on the road-holding performance of the tires. The SDM allows the front stabilizer to be unlocked at the touch of a button, helping the tires to stay on the ground and enhancing off-road performance on severe rocky or undulating surfaces. Installing the SDM increases wheel articulation by approximately 10%.

Driving on unpaved surfaces may cause the heads of occupants to be shaken from side to side (a phenomenon called "head tossing"). With the SDM locked, the left and right sides of the front suspension operate independently, which improves the ability of the vehicle to follow the road surface profile more closely, reducing the head tossing amount. If the stabilizer is unlocked and the vehicle speed exceeds 30 km/h, the system will judge that the vehicle is on a road and automatically lock the stabilizer, thereby ensuring excellent on-road handling.

3.5 Off-road driving support

To support the lifestyle choices of customers in as many countries and regions as possible, the 250 series was developed to achieve excellent off-road performance assuming a wide variety of environments. The off-road driving support functions of the 250 series were tuned and evaluated under various conditions in a wide range of locations around the world.

3.5.1 Downhill Assist Control (DAC) and Crawl Control

DAC and Crawl Control are functions that maintain steady low speed vehicle motion without the driver having to think about operating the brake or accelerator pedal. As a result, the driver only has to steer the vehicle, helping to deliver almost stress-free off-road driving. DAC activates when the driver selects the transfer high range (H4) and prevents tire lock by automatically controlling the brakes at each of the four wheels. This function ensures stable descents on steep hills where engine braking alone may not deliver sufficient deceleration. Although the Prado 150 series is equipped with a similar function that fixes the vehicle speed to 4 km/h, the functional speed range was increased to between 4 and 30 km/h, making the vehicle easier to drive in practical off-road scenarios.

Crawl Control activates when the driver selects the transfer low range (L4). This function helps to deliver smooth performance in highly uneven off-road environments and on slippery road surfaces through integrated control of the accelerator and brakes. Five speed settings can be selecting depending on the driving conditions. The linear hydraulic pressure control and accuracy of wheel speed estimation of the brakes were improved to reduce operation noise and enhance the speed control feeling. In addition, this system also features a control that suppresses wheel spin and wheel lock, improving the capability of the vehicle to escape from situations where it becomes stuck.

3.5.2 MTS (Multi Terrain Select)

To achieve excellent off-road performance that is both stable and safe, the 250 series adopts the MTS system, which allows the driver to select from six off-road driving support modes based on the road surface conditions. In accordance with the selected mode, the system optimizes the driving force and braking controls to maximize off-road performance on that surface (**Fig. 11**).

MTS mode	H4					L4			
	AUTO	DIRT	SAND	MUD	DEEP SNOW	AUTO	SAND	MUD	ROCK
Driving/braking force characteristics	Automatically determines the road conditions and switches to the appropriate mode characteristics.	Designed for stable driving at speeds comparable to paved roads, balancing stability and sportiness.	Characteristics that help prevent the vehicle digging into sand and adjust slip to the appropriate amount for stable driving.	Characteristics that allow for some slip to maximize tire grip.	Characteristics that minimize starting slip, anticipating powerful traction in deep snow.	Automatically judges the road surface conditions and selects the appropriate mode.	Characteristics that help prevent the vehicle digging into sand and adjust slip to the appropriate amount for stable driving.	Characteristics that allow for more slip to maximize tire grip.	Characteristics that suppress tire spinning, making it easier to control walking speed on rocky terrain.
Starting gear position		1st gear	1st gear	1st gear	2nd gear		2nd gear	2nd gear	1st gear
Gear shift schedule		Exclusive to H4 MTS. Characteristics that effectively utilize the appropriate torque band for off-road driving.					Exclusive to L4. Characteristics that effectively utilize the appropriate torque band for off-road driving.		
EPS characteristics		Assist characteristics specifically tuned for off-road use.					Assist characteristics specifically tuned for off-road use.		

Fig. 11 Outline of MTS System

For the Land Cruiser 250 series, the MTS operational range was expanded from the transfer low range (L4) in the Land Cruiser Prado 150 to include the transfer high range (H4). This expansion allows for greater versatility in off-road conditions, including high-speed driving on unpaved roads. The traction control system enhances drivability by adjusting shifting characteristics and precisely controlling throttle opening in response to accelerator inputs. The braking control system supports off-road driving by managing wheel slip and effectively distributing driving force to all four wheels. In AUTO mode, the control system automatically maximizes performance based on real-time sensor data, enabling the driver to achieve optimal results across varying terrain without needing to manually change modes. The 250 series implements optimal control settings tailored to each powertrain unit in the line-up.

3.5.3 Multi Terrain Monitor (MTM)

The vehicle is equipped with four cameras at the front, both sides, and the rear. Images from these cameras are processed into optimized views to help the vehicle cross trackless regions by allowing the driver to confirm the surface conditions around the vehicle that might be in potential blind spots (**Fig. 12**). The conditions under the vehicle that cannot be viewed directly by a camera can be visualized by combining images of the area in front of the vehicle taken a short time ago with current images from around the vehicle. The driver can use the resulting images to check the conditions around the tires and gain an understanding of the distance to obstacles. Digital cameras are used to create fresher and smoother moving images. A closeup underfloor view around the rear wheels was added for when the vehicle is moving off or reversing. Off-road performance is enhanced by inclinometer icon displays so that the driver can better estimate the longitudinal and lateral gradients.

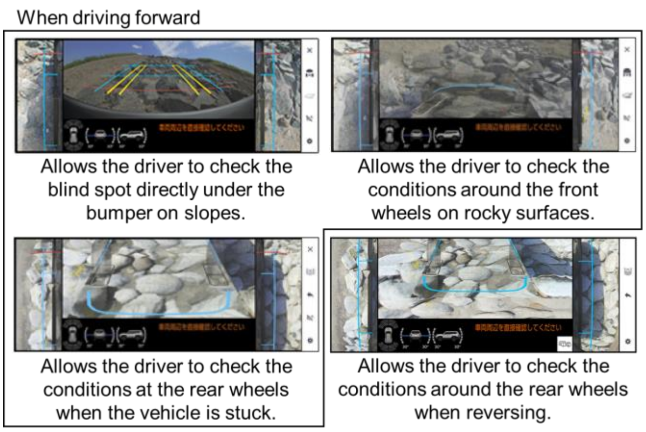


Fig. 12 MTM

4. Extensive Powertrain Lineup Worthy of a Land Cruiser

4.1 Combination of typical powerful driving and environmental performance

The 250 series inherits the Land Cruiser mission of supporting the lives and livelihoods of people everywhere, while realizing the reliability, durability, and off-road performance that is the DNA of the Land Cruiser. In line with Toyota's carbon neutrality initiatives that take a diverse multi-pathway approach, the 250 series has an extensive powertrain lineup, including the first hybrid system for a Land Cruiser. This powertrain lineup delivers powerful driving performance and environmental performance worthy of a Land Cruiser (**Table 1**).

Table 1 Powertrain Characteristics

Powertrain		Positioning	Destinations
T24A-FTS Gasoline 2.4-liter turbo Hybrid: Direct Shift 8-speed automatic transmission	Maximum power:* 243 kW (330 PS) Maximum torque: 630 Nm* *Maximum system value including MG	◇ High-end electric powertrain ◇ In addition to off-road capabilities, delivers greater acceleration and environmental performance across all power ranges, from initial acceleration to climbing and towing.	North America and China
T24A-FTS Gasoline 2.4-liter turbo Direct Shift 8-speed automatic transmission	Maximum power: 207 kW (281 PS) Maximum torque: 430 Nm	◇ Mass-market gasoline powertrain ◇ Delivers smooth and powerful driving performance, a quiet ride, and environmental performance through a newly developed TNGA powertrain.	The Middle East and Eastern Europe Other
1GD-FTV Diesel 2.8-liter turbo (48 V system) Direct Shift 8-speed automatic transmission	Maximum power: 150 kW (204 PS) (Europe only: 151 kW) Maximum torque: 500 Nm	◇ High-end diesel powertrain ◇ In addition to the characteristics of the 1GD engine, delivers improved actual fuel economy in urban settings and congestion. ◇ Delivers refined and quiet engine startup for smooth initial take-offs.	Australia and Western Europe
1GD-FTV Diesel 2.8-liter turbo Direct Shift 8-speed automatic transmission	Maximum power: 150 kW (204 PS) (Europe only: 151 kW) Maximum torque: 500 Nm	◇ Mass-market diesel powertrain ◇ Delivers improved ease of handling both on- and off-road through a combination of the 8-speed automatic transmission and the 1GD engine, which has a reputation for good fuel economy and powerful driving performance. *A 6-speed automatic transmission is still used in some countries and regions.	Western and Eastern Europe Japan and the Middle East Other
2TR-FE 2.7-liter gasoline 6 Super-ECT	Maximum power: 120 kW (163 PS) Maximum torque: 246 Nm	◇ High-quality, affordable basic powertrain ◇ Delivers improved ease of handling in normal driving conditions.	Eastern Europe and Japan Other

4.1.1 Fulltime four wheel drive system

To ensure off-road performance, all the powertrains are equipped with a fulltime four wheel drive (4WD) system provided with a center differential lock and Torsen® limited slip differential (LSD) on the center differential (depending on the grade, a differential lock or Torsen® LSD can also be added to the rear differential) (**Fig. 13**). Based on the components developed and refined for the Prado 150 series, development know-how from the 300 series (such as controls on models equipped with the 8-speed automatic transmission that realize dedicated acceleration settings for the transfer low range to enhance off-road performance when climbing rock slopes and the like) was incorporated for the first time into the 250 series 4WD system, enabling even greater reliability, durability, and off-road performance. In addition, the transfer high/low range selection actuator and rear differential lock selection actuator were improved to shorten the switching time, resulting in even greater user-friendliness.

* Torsen® is a registered trademark of JTEKT Corporation.

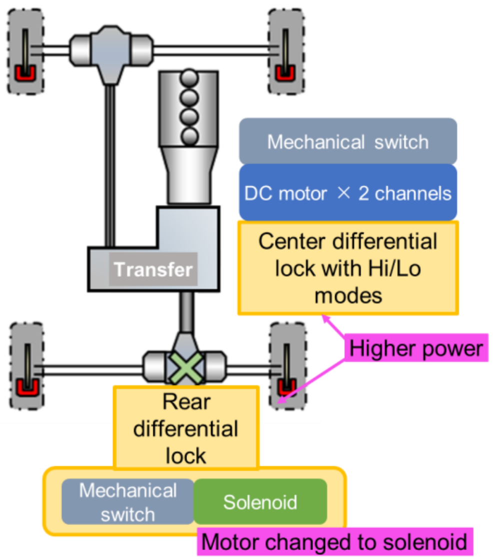


Fig. 13 Fulltime 4WD System

4.2 T24A-FTS engine × Direct Shift 8-speed automatic transmission (+ parallel hybrid system)

4.2.1 System outline

The 4.0-liter naturally aspirated engine and 6-speed automatic transmission combination adopted by the Prado 150 series was downsized into a newly developed 2.4-liter turbocharged gasoline engine created following the Toyota New Global Architecture (TNGA) design philosophy. This fuel-efficient and torqueful engine was then combined with newly developed high-performance dampers and a TNGA 8-speed automatic transmission (**Fig. 14**). This combination creates a feeling of endlessly linear and smooth acceleration, delivering powerful driving performance, a quiet ride, and environmental performance in all everyday driving scenarios both on and off the road. In addition, models returning to the North American and Chinese markets are also equipped with the first parallel hybrid system in a Land Cruiser. In addition to higher environmental performance, the system provides assistance from the motor/generator (MG) to realize the type of powerful standing start performance that only an electrified vehicle can deliver (**Fig. 15**).

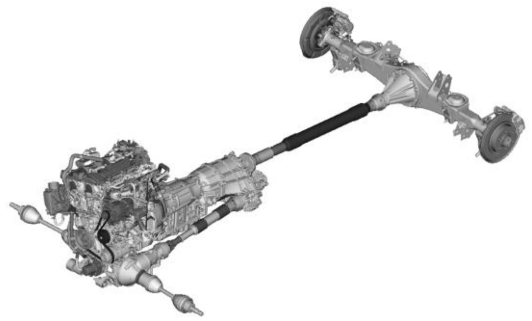


Fig. 14 T24A-FTS Engine × Direct Shift 8-Speed Automatic Transmission

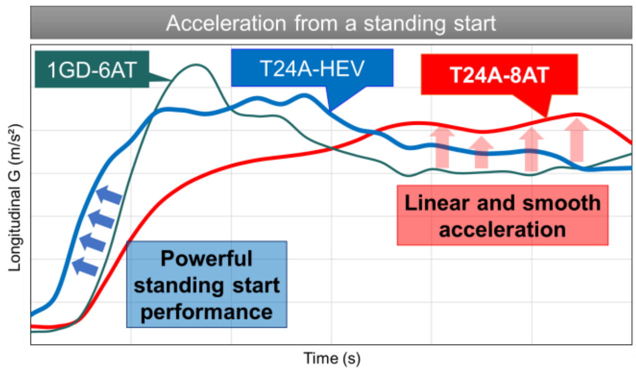


Fig. 15 Longitudinal Acceleration (G) from a Standing Start

4.2.2 T24A-FTS 2.4-liter turbocharged gasoline engine

The T24A-FTS engine, which is at the heart of the transverse engine packaging of Toyota's mid-size SUVs, has been developed and nurtured to delivery high efficiency, clean environmental performance, and satisfying driving performance. In addition to these three central features, a new transverse engine package optimized for the Land Cruiser was designed under the development concept of delivering comfort and reassurance on any surface, which are attributes customers look for in an off-road vehicle (**Fig. 16**). In addition to technologies such as the high tumble port designed to achieve high-speed combustion under the TNGA engine philosophy, spray guide combustion system, and the like, components such as a newly designed turbocharger and air-cooled intercooler were added to enhance efficiency in a wide range of engine operating regions including when carrying loads, and towing. The Land Cruiser is expected to ensure excellent engine lubrication on all types of gradients. The oil pan and lubrication system were designed to satisfy these expectations, and the whole powertrain was designed and evaluated for durability and reliability assuming driving over long distances and for extended periods.

Fig. 16　T24A-FTS Engine

4.2.3　Direct Shift 8-Speed automatic transmission

As a TNGA transmission designed to realize both driving performance and fuel efficiency, the Direct Shift 8-speed automatic transmission features a number of the latest technologies. These include a wider gear range and cross ratios, an expanded lock-up area due to the adoption of a multi-plate lock up clutch and high-performance dampers, a highly responsive hydraulic system, and other technologies for raising efficiency. The transmission was specifically developed with the aim of delivering a fun-to-handle vehicle by enhancing low-speed off-road controllability, and combining direct and powerful driving performance with easy handling through optimized gear selection (**Fig. 17**). Compared to a 6-speed automatic transmission, the 1st gear ratio was lowered and the lock-up area expanded to reduce the total heat generated by the torque converter, which also helps to enhance off-road performance. Assuming that the vehicle will be driven off-road on steep gradients and rocky surfaces, to ford rivers, and in desert environments, the oil level inside the transmission was optimized, the oil pan was designed with a high ground clearance, and a high breather position was adopted, among other measures.

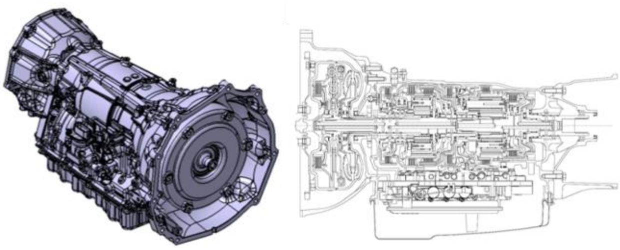


Fig. 17　Direct Shift 8-Speed Automatic Transmission

4.2.4　Parallel hybrid system

Assuming use in harsh environments such as off the road, carrying loads, towing, and the like, the 250 series is equipped with the first parallel hybrid system in a Land Cruiser. This parallel hybrid system combines a mechanical fulltime 4WD system and a torque converter (**Fig. 18**). The system includes a front module (F/M) located between the engine and torque converter-equipped automatic transmission. The F/M features a K0 clutch, which functions to engage and disengage the engine and drivetrain, and an MG. This layout enables the direct transmission of engine torque, ensuring high reliability and the delivery of the necessary driving force for off-road driving through the torque converter. In addition, combining this system with a multi-speed automatic transmission helps to realize a direct and rhythmical acceleration feeling. At the same time, the operating points of the engine and motor were optimized for compliance with stringent environmental regulations in North America and China.

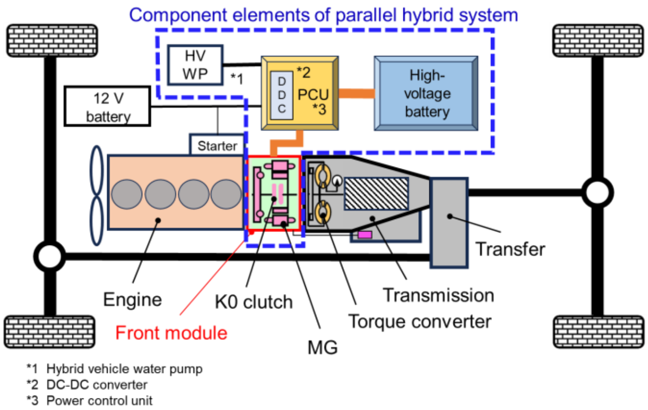


Fig. 18　Parallel Hybrid System

4.3　1GD-FTV engine × Direct Shift 8-speed automatic transmission (+ 48 V system)

4.3.1　System outline

This powertrain combines the distinctive power and high-torque characteristics of a diesel engine with a newly developed TNGA 8-speed automatic transmission (**Fig. 19**), and also features a newly developed compact and highly efficient compact turbocharger (**Fig. 20**). The combination of a multi-speed automatic transmission and multi-plate lock up clutch improves driveability and helps to deliver high-level acceleration control in line with the driver's intentions through direct and refined driving performance, similar to that of a manual transmission both off the road and in on-road scenarios from urban settings to highways (**Fig. 21**). In addition, to comply with corporate average fuel efficiency (CAFE) regulations in Australia and Western Europe, the 250 series is equipped with the first 48 V system in a Land Cruiser assuming operation under harsh off-road environments. Combined with a clean diesel system, this powertrain delivers superb environmental performance through improved actual fuel economy under frequent stop-starts in urban settings and congestion, as well as highly responsive, refined, and quiet engine starts, and smooth take offs.

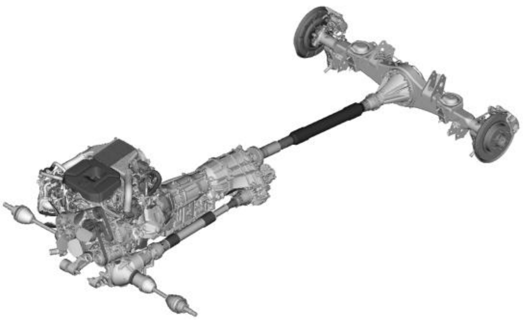


Fig. 19 1GD-FTV Engine × Direct Shift 8-Speed Automatic Transmission

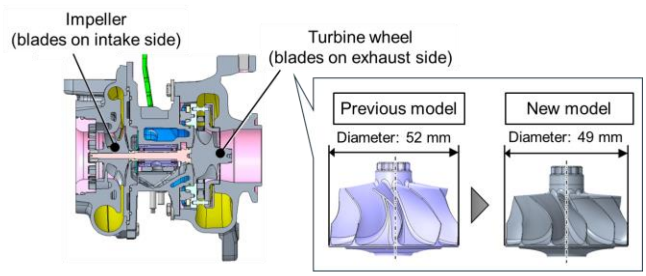


Fig. 20 Newly Developed Compact Highly Efficient Turbocharger

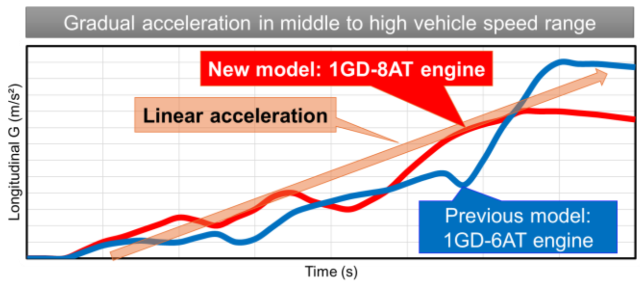


Fig. 21 Longitudinal Acceleration (G) under Gradual Acceleration in the Middle to High Vehicle Speed Range

4.3.2 48 V system

As described above, the 250 series is equipped with the first 48 V diesel electric system to comply with CASE regulations in Australia and Western Europe. Instead of an alternator, this system is equipped with a 48 V MG that connects a 48 V battery with the DC-DC converter (**Fig. 22**). This 48 V MG allows highly responsive, smooth, refined , and silent engine starts when the Stop & Start (S&S) system operates in congestion. When the vehicle decelerates, energy is recovered by the MG and used to create a driver-friendly and natural deceleration feeling in combination with engine braking. At the same time, the recovered energy is used to provide assistance via the MG in low-efficiency engine operating regions. This reduces the burden on the engine and helps to improve fuel efficiency in combination with the engine stop control. In addition, the layout of the MG and anti-slip performance were designed factoring in the assumption that the vehicle will be used in severe off-road environments such as fording rivers and the like.

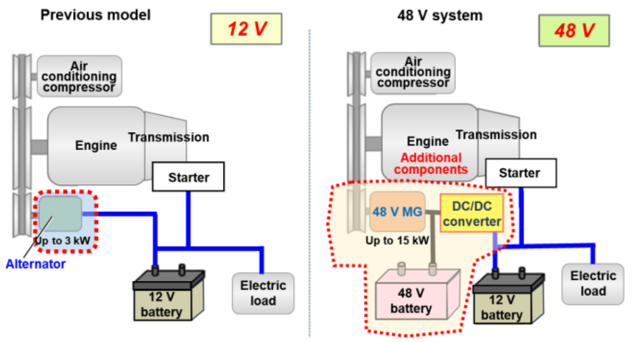


Fig. 22 48 V System

4.4 2TR-FE engine × 6-speed Super Electronically Controlled Transmission (6 Super-ECT)

4.4.1 System outline

This powertrain uses the components developed and refined for the Prado 150 series and takes advantage of the agile revving characteristics and responsiveness of a naturally aspirated engine. It also incorporates the software-based know-how derived from the development of the 300 series in the form of advanced safety features and cybersecurity measures to update the electronic control units (ECUs) and powertrain controls. These features were used to optimize gear selections to help prevent fatigue in everyday driving scenarios, resulting in a Land Cruiser that satisfies the practical needs of the customer through smooth performance in frequently occurring scenarios from take-off to low speeds and improved vehicle speed control when driving down hills.

5. Design

5.1 Design suitable for a genuine practical off-roader

The light-duty model in the Land Cruiser series is the most widely adopted by customers around the world. The development team reassessed the fundamental mission of this model, and guided its design toward off-road functionality under the keyword of going back to the origin of the Land Cruiser. While upholding the knowledge and innovations of past design teams over the past seventy years and more, the role of the vehicle was re-defined in accordance with the diverse values and more sophisticated expectations of the modern age, clarifying just what the Land Cruiser means today. The team aimed to create a vehicle that would connect the historic Land Cruisers of the past with the future still to come.

5.2 Exterior design

The GA-F platform was adopted with the aim of dramatically improving off-road performance up to the level of the 300 series while creating easy handling through a compact body design that appeals to a wide range of customers. More specifically, using the GA-F platform, the rugged footprint of the longer and wider 300 series was retained. In contrast, any hint of waste in the body was eliminated by shortening the front and rear overhangs and cutting down the four corners of the body to create a door-to-door distance equal to the 150 Prado series. The design team focused on creating a signature silhouette by studying the package alongside major changes in the component layout from the 300 series, such as altering the position of the stabilizer.

While maximizing the characteristics of the package with its compact body and wide stance, a design proposal combining a modern freshness with an instantly recognizable Land Cruiser appearance was adopted (**Fig. 23**). This section describes specific examples of the various innovations that were adopted to achieve design that combines both functionality and beauty.

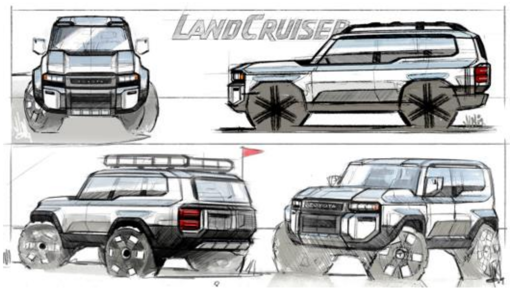


Fig. 23 Sketch Proposals

The body was given over-fender-like features supported by firmly planted large-diameter times that protrude out from the left and right of a boxy body with horizontal lines running parallel to the ground. This creates a visual appearance that expresses the vehicle’s inherent quality as a practical off-roader and creates the impression of stability, dynamism, and robustness (**Fig. 24**).

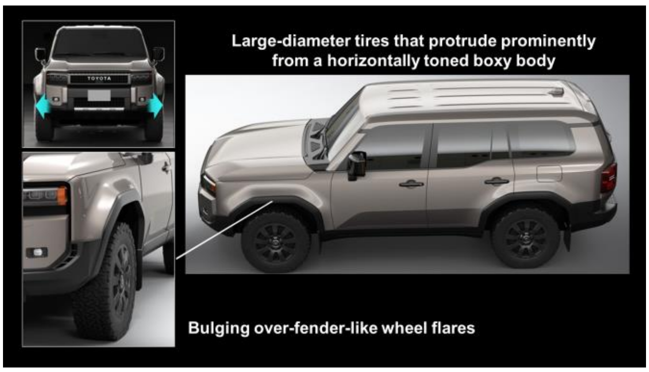


Fig. 24 Exterior Design Utilizing the Body-on-Frame Underpinnings

The corners of the box-like body were severely cut down to create a chamfered design and emphasize maneuverability. The chamfered surfaces around the body were joined over wide-ranging continuous areas to create a modern box-like design with a strong block effect. The aim was to create a set of lean and tight body surfaces with sweeping curves carved into sharply defined edges (**Fig. 25**).

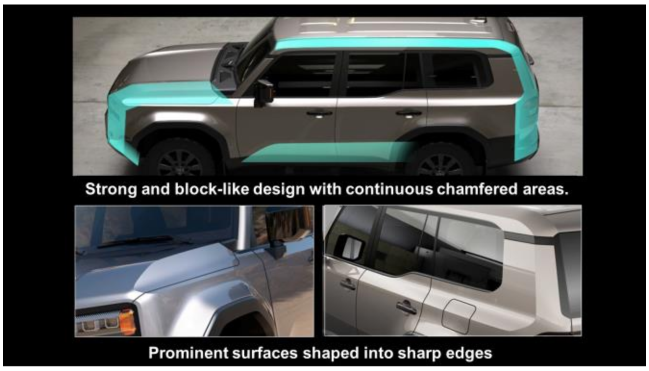


Fig. 25 Chamfered Body Surfaces

Good visibility in harsh driving environments is an important way of providing reassurance and safety to the driver. For this purpose, the forward visibility of the driver was improved by adopting an upright windshield and narrow A pillars. Likewise, the rearward visibility was improved by lowering the side windows by approximately 30 mm compared to the Prado 150 series. These measures help to form a unique silhouette perfectly suited for a powerful and practical off-roader that also expresses the maneuverability of the vehicle (**Fig. 26**).

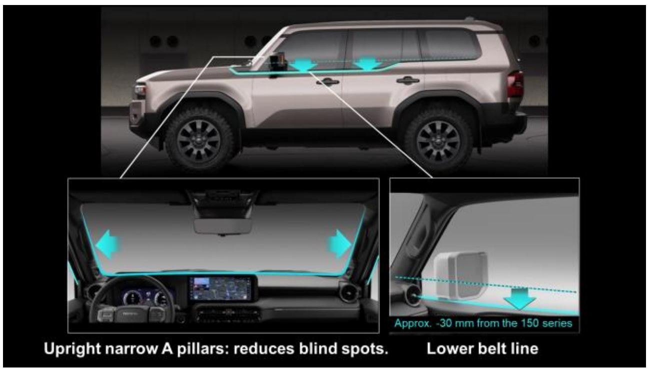


Fig. 26 Design Innovations for Visibility Prioritizing Safety

The front face follows the concept introduced from the 40 series. The headlamps are laid out high and toward the center of the front in a low-risk layout, reflecting the potential issues of driving at night over rough ground with damaged lights. Combined with the “TOYOTA” emblem, this creates an iconic and typical Land Cruiser design for the front face (**Fig. 27**).

Fig. 27　Front Face

The front bumper has a split structure that allows just easy-to-damage portions of the bumper to be replaced. This demonstrates Toyota's dedication to achieving the sustainable development goals (SDGs). The layout of this area was also designed to allow partial customization, such as changing from square to round headlamps, reflecting the diverse tastes of customers (**Fig. 28**).

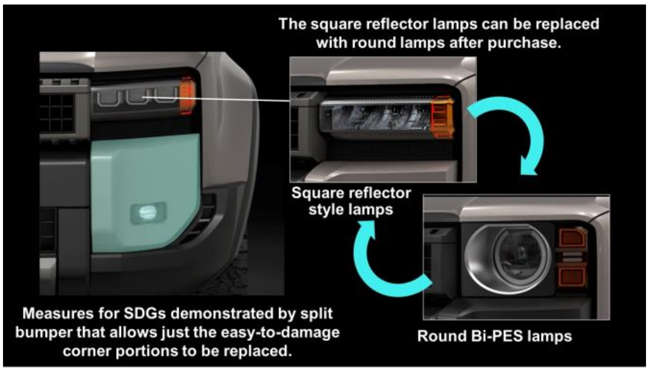


Fig. 28　Aims of Split Structure

5.3　Interior design

The aim of the interior design was to create a secure and fatigue-preventing interior space even during extended off-road driving. The fundamental elements of this space are created by a bathtub configuration that combines wide visibility through the windows and a positive sense of occupant protection. All aspects of the interior were designed for functionality and refinement. In particular, the cockpit functions were laid out to allow the driver to carry out the recognition, judgment, and operation processes of driving rapidly and without hesitation. A design mock-up was used to allow the rally driver Akira Miura to evaluate the position of these functions. Combined with actual off-road evaluation by the designers, the development of the interior design was carried out through a real, experience-based approach.

The instrument panel has a flat horizontal design to help the driver understand the angle of the vehicle based on the external field of view. The meter cluster and center display play important roles in the recognition process of driving. These elements were laid out in the optimum positions, high up in highly visible locations but below the cowl line so that the forward visibility of the driver is not impeded.

Electronic and compact system switches were adopted and laid out within the driver's reach on the driver's side of the vehicle (**Fig. 29**). In addition, fairly large physical switches were adopted that can be used even while wearing gloves. At the same time, for driving systems in particular, a wide range of operating methods including dials, toggles, and push switches were deliberately combined considering the fact that the driver might not be able to look at the switches while driving off-road (**Fig. 30**).

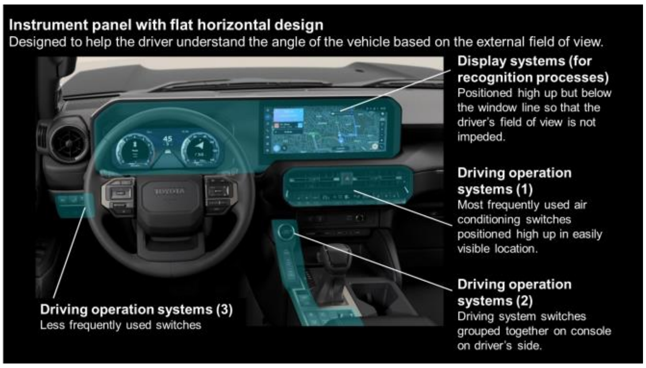


Fig. 29　Optimum Layout of Interior Parts

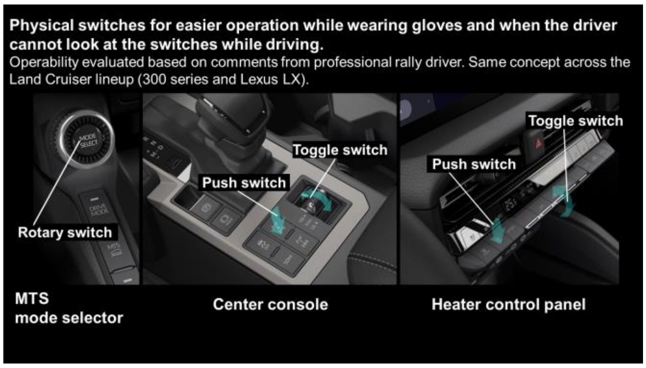


Fig. 30　Improvement of Off-Road Operability

Experience of off-road driving shows that shaking of the vehicle in the vertical and horizontal directions makes it difficult to maintain a stable driving posture and operate switches. This was addressed by providing knee and arm pads on the center console and door trim. In addition, the view monitor switch was moved to a more prominent location so that it can be found more easily even during off-road driving. A palm rest was also created to anchor the hand and enable stable operation of the center display and heater controls (**Fig. 31**).

Fig. 31 Feedback from Driving Experience

5.4 Color design

Reflecting diversify customer preferences, the exterior color lineup was designed to express two major common values. The first value expresses the capability of the Land Cruiser as a professional tool, emphasizing genuine impressions of texture and precision, as represented by the Avant-Garde Bronze color option (**Fig. 32**). The other value expresses the heritage of the Land Cruiser through exterior colors that evoke historic 40 and 60 series models, as represented by the Sand (newly developed color) and Smoky Blue color options (**Fig. 33**).

Fig. 32 Colors Expressing Professional Values

Fig. 33 Colors Expressing Heritage Values

These color options appeal to a wide range of customer values, from to die-hard Land Cruiser fans and younger new customers with an active lifestyle.

The interior colors create a calming impression using black and dark chestnut brown. A beige option is also available in some regions, giving a full lineup of three distinct colors (**Fig. 34**).

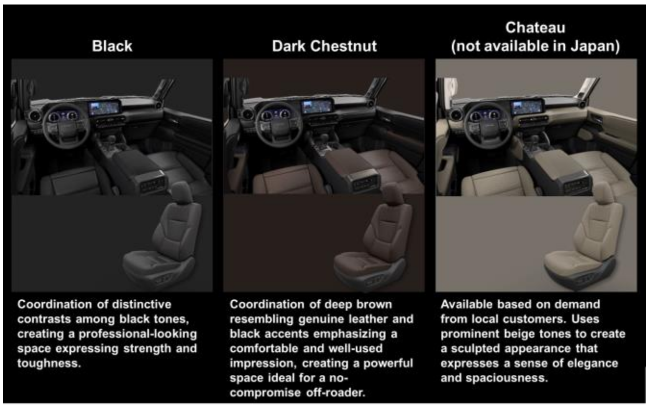


Fig. 34 Interior Colors

The internal ornamentation uses non-flashy titanium toned coloring or deep matte black inspired by the color of a cast iron skillet, combined with molded instrument panel piping overlaid with a film resembling a mountain climbing rope, enhancing the impression of a professional-grade tool.

6. Creating Land Cruiser Quality

6.1 Frame manufacturing processes

6.1.1 Non-linear TWB technology

To enable the adoption of the non-linear TWBs introduced in Section 3.1.1, a welding system compatible with non-linear shapes using a robot with high path accuracy was constructed.

Tailor welded blanking is a welding technology that sets two materials together in a butt joint. To ensure frame strength, it is necessary to control the sheet thickness at the weld bead (**Fig. 35**). This process is inhibited by the size of the gap between blanks. Compared to linear TWBs, non-linear TWBs feature wider variations in material gaps (**Fig. 36**). This requires a welding method with a large tolerance to cover the gap. Laser-arc hybrid welding was adopted for this process. This technology is appropriate for non-linear TWBs because it carries out arc welding first to create a wide melt pool that fits itself to the variations in the gap, followed by laser welding that creates a clear keyhole through the melt pool (**Fig. 37**).

After the welding process is completed, the quality of the weld is assured by measuring cross sections of the weld bead from both the front and back surfaces. Every weld bead is inspected from all directions by comparison with reference materials for each cross section.

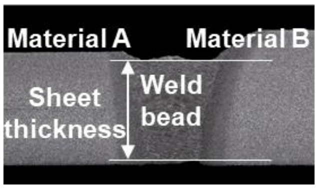


Fig. 35 Cross-Sectional View of TWB

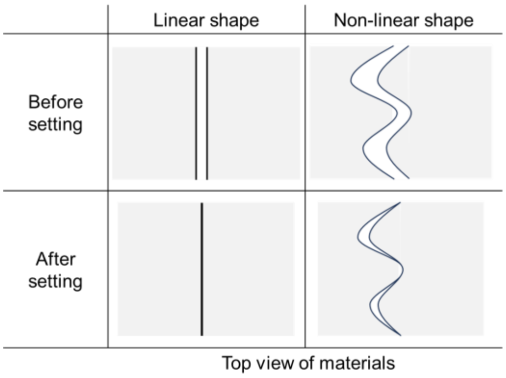


Fig. 36 Material Shapes and Sheet Gaps

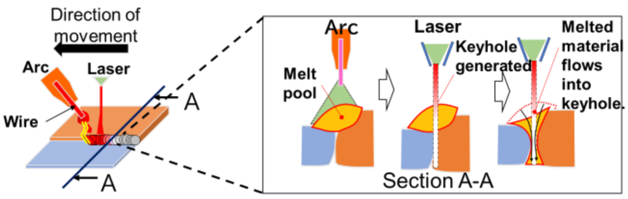


Fig. 37 Laser-Arc Hybrid Welding

6.1.2 Frame welding technology

Frame parts are primarily joined by arc welding. However, the heat of the arc may cause distortion that results in quality variations. On the new production line for the 250 series, the heat input from arc welding is controlled to produce frames with stable accuracy. To reduce variations in accuracy and the thermal distortion variation generated between processes, a high number of welds are carried out in a single process using multiple robots (**Fig. 38**).

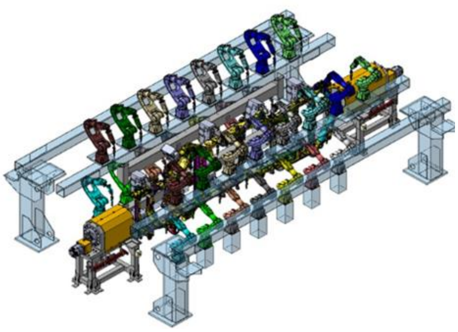


Fig. 38 Welding by Multiple Robots

New compact robots were developed to realize this multiple robot process. The welding line for the 250 series is capable of utilizing three times as many robots in a single process than the process for the Prado 150 series. This helps to reduce the number of frame welding steps from thirteen to six, halving the footprint of the process. If welding stops during production for some reason, the generated welding heat input will differ compared to normal and cause accuracy variations. Welding distortion was improved by maintaining the same in-process lead time for each process. This was accomplished by adopting a welding sequence that is less susceptible to distortion and controlling the number of work pieces entering the process.

Conventional frames have commonly used a box-type side rail structure. In a box structure, U-shaped steel sheets are overlapped and joined by fillet welding. By changing these overlapping areas (approximately 5 mm) used for side rail welding to butt joints, the portion of steel sheets that form the overlapping areas can be eliminated, thereby reducing the weight of the frame (**Fig. 39**).

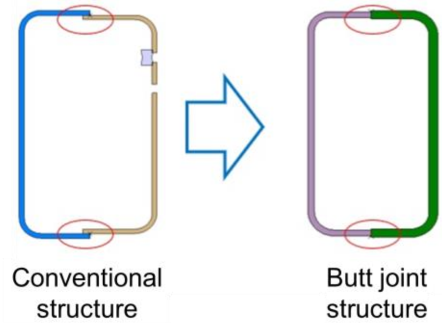


Fig. 39 Butt Joint Structure

A butt joint structure is an effective way of reducing the distortion caused by arc welding. In addition to the gap between the steel sheets being joined, another key element in butt joint welding is creating a level difference between the steel sheets. As manufacturing control items, innovations were incorporated into both the management of the steel sheets, as well as the equipment and welding conditions. In addition, from the perspective of quality assurance, every butt joint arc weld bead is inspected automatically using the laser- and camera-based light section method (**Fig. 40**).

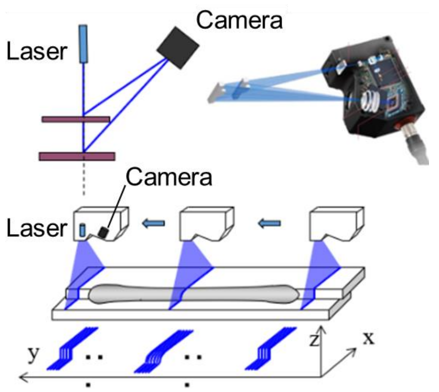


Fig. 40 External Inspection of Every Arc Weld

6.1.3 Frame electrodeposition technology

Long-life anti-corrosion performance is necessary to ensure the strength and durability of the chassis frame. The anti-corrosion performance of the vehicle is determined based on the anti-corrosion quality requirements of each country and region, changes in the usage environment (such as the spreading of salt-based snow melting agents), competitor trends, and changes in the vehicle environment that affect long-term use.

As part of the new chassis frame design adopted for the 250 series, an optimized water drainage structure, waterproofing by adopting electrodeposition coatings on parts, and expanded use of corrosion-resistance steel sheets were adopted alongside improved welding methods and materials. This was complemented by efforts to raise the quality of electrodeposition, which plays the most important role in ensuring anti-corrosion performance from a manufacturing perspective. Although electrodeposition dip coatings have excellent corrosion resistance, air on the internal surfaces of the object being coated must be bled off during the dipping process otherwise air pockets may form that prevent the formation of the coating film. These pockets may then react with moisture, causing rust and accelerating corrosion. This issue was addressed and anti-corrosion quality ensured as follows. First, the orientation of the electrodeposition process was changed to the same orientation as the completed vehicle so that the locations of air pockets on internal surfaces that do not collect water entering the frame during driving are facing up (**Fig. 41**). Then, simulation technology was adopted to determine the optimal dipping orientation, rocking angle, and air bleeding positions (**Fig. 42**).

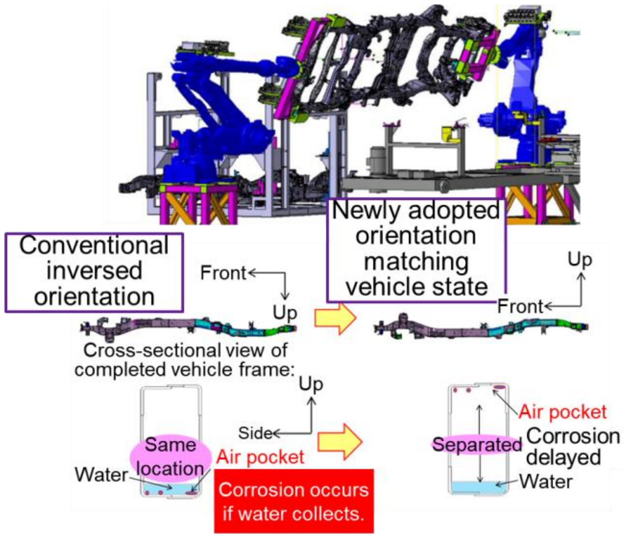


Fig. 41 Frame Rotating System and Electrodeposition Orientation

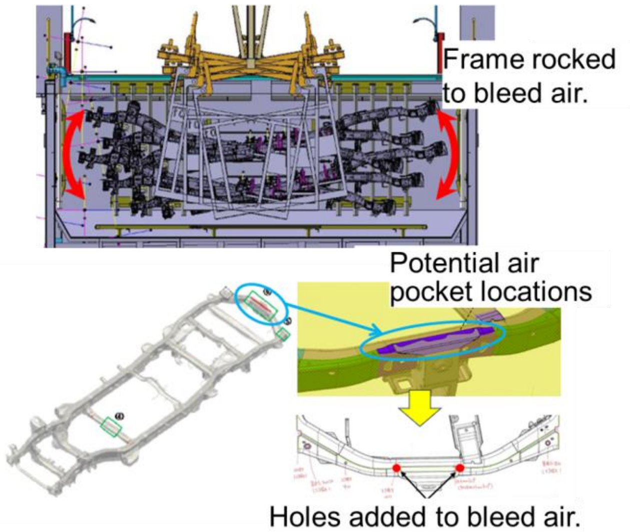


Fig. 42 Air Bleeding by Rocking and Air Pocket Simulation Technology

6.2 Quality-building evaluations in actual driving environments

The development team was strongly focused on achieving reliability and durability worthy of the Land Cruiser name. Therefore, from the initial stages of development, members of Toyota's rally team drove the vehicle over rally courses in the Middle East, Australia, and other regions to carry out quality-building evaluations in actual driving environments (**Fig. 43**). The main purpose of these evaluations was to identify weak spots and failure modes, and to assess repairability. In addition, the development team also prioritized creating an intuitive instrument layout that can be operated without looking and safe visibility even when driving on rally courses. This was accomplished using models to realize the ideal functional layout.

Fig. 43 Quality-Building Evaluations in Actual Driving Environments

7. Conclusion

Backed by the resolve to go back to the origins of the Land Cruiser as a vehicle that carries out the true role and mission of supporting people's lives, and to place the 250 series in the center of the Land Cruiser brand, the development team followed a concept called simply "The Land Cruiser." Under the Prado sub-name, the team succeeded in achieving the rebirth of the model as the Land Cruiser 250.

Under the spirit of going back to the origins of the Land Cruiser, in other words developing a vehicle that can support the lifestyle choices of as many people as possible, the direction chosen by the development team was to focus single-mindedly on eliminating waste and building a simple and sturdy vehicle that combines the fundamental performance of an off-roader with easy handling and operation.

The new Land Cruiser 250 carries on the traditional heritage of the Land Cruiser while evolving the model in impressive ways.

The authors would like to express their sincere gratitude to everyone involved in the development, from the people who helped the team overcome a wide range of issues to the customers and dealers around the world who have supported the Land Cruiser over more than seventy years.

It is hoped that the Land Cruiser 250 will become a vitally important model that connects the Land Cruiser brand with the future as its 100th anniversary approaches. The Land Cruiser truly goes beyond roads and beyond time.

Authors

Section 1 Introduction
Section 2 Development Target
Section 7 Conclusion
MSZ, Mid-size Vehicle Company
Keita Moritsu
Minoru Takayama
Kohei Nohara

Section 3 Dynamic Performance and Platform
MS Platform Development Div., Mid-size Vehicle Company
Takuma Ono
Asaki Imai
Takashi Murakami
Takaya Komatsuzaki
MS Vehicle Development Div. No. 1, Mid-size Vehicle Company
Masato Nakamura
User Interaction Development Div., Software Development Center
Shinya Kodama
MS Vehicle Control Development Div., Mid-size Vehicle Company
Masataka Takahashi
Koshi Nishikawa
Shunnosuke Naruoka

Section 4 Extensive Powertrain Lineup Worthy of a Land Cruiser
Powertrain Product Planning Div., Vehicle Development Center
Shinya Kitai
Nobufusa Kobayashi
Masao Eto

Section 5 Design
Advanced Design Development Dept., Advanced R&D and Engineering Company
Yoshito Watanabe

Section 6 Creating Land Cruiser Quality
Final Assembly Div., Tahara Plant, Production Group
Tomohiko Iwashita
Body Manufacturing Engineering Div., Tsutsumi Plant, Production Group
Takehiro Hiraishi
Keisuke Nojiri
Hiroshi Uchiyama
Genta Tsujino
Surface Finishing & Plastics Manufacturing Engineering Div., Takaoka Plant, Production Group
Akihiro Shibata

2023 JSME Medal for Outstanding Paper

Coupling Analysis of Unsteady Aerodynamics and Vehicle Behavior with Road Input: Modeling and Verification in Road Tests

Kazuhiro Maeda[*1] Daisuke Tsubakino[*2] Susumu Hara[*2] Akihiro Sasoh[*2]

1. Introduction

Since aerodynamic forces have a major impact on vehicle running stability, various body shapes and aero-devices have been adopted to help improve performance. However, because the effectiveness of these devices is difficult to explain using conventional steady-state aerodynamic forces alone (i.e., lift or yaw moment under constant vehicle states or at constant wind velocities), analysis is required that focuses on unsteady aerodynamic characteristics such as fluctuations generated by vehicle motion and natural wind conditions. As one type of unsteady analysis, it is necessary to analyze the aerodynamic responses generated by vehicle pitch and heave motion due to road input and identify the effects of these responses on motion (**Fig. 1**).

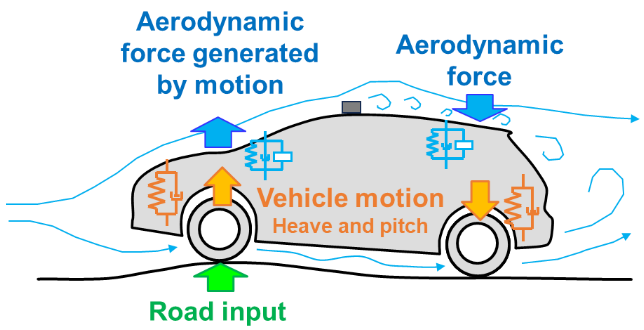
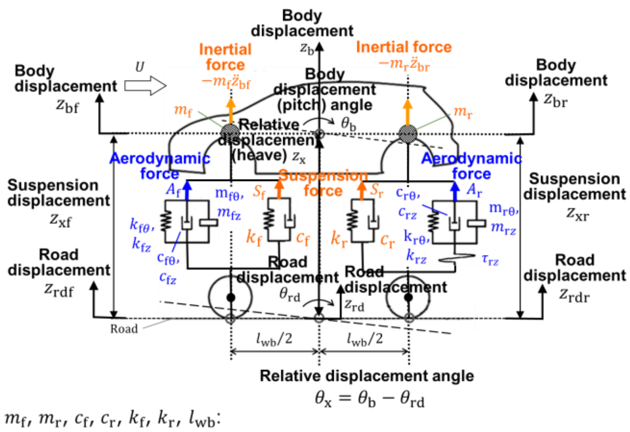


Fig. 1 Unsteady Aerodynamic Forces Generated by Motion Caused by Road Input

2. Outline of Technology

2.1 Coupling equation for vehicle motion and unsteady aerodynamic forces

An equation of motion that couples aerodynamic forces and vehicle motion was formulated to identify the effects of unsteady aerodynamic forces generated by motion on vehicle behavior. Focusing on longitudinal motion with two degrees of freedom (pitch and heave caused by road input), a vehicle motion model was created featuring mass acting at the front and rear axles, dampers and springs as suspension systems, and aerodynamic forces acting on the axles (**Fig. 2**).



m_f, m_r, c_f, c_r, k_f, k_r, l_{wb}:
body mass, damping/spring coefficients, wheelbase
$m_{f\theta}$, $m_{r\theta}$, $c_{f\theta}$, $c_{r\theta}$, $k_{f\theta}$, $k_{r\theta}$:
aerodynamic inerter/damping/spring coefficients with respect to pitch motion
m_{fz}, m_{rz}, c_{fz}, c_{rz}, k_{fz}, k_{rz}, τ_{rz}:
aerodynamic inerter/damping/spring/first-order lag coefficients with respect to heave motion
Subscripts f, r:
front, rear

Fig. 2 Coupled Vehicle Motion Model for Longitudinal Motion and Unsteady Aerodynamic Forces

These aerodynamic forces were defined as forces acting with respect to pitch and heave motion. Unsteady characteristics were incorporated via aerodynamic inerter, damping, and spring coefficients. **Equation (1)** shows the resulting equation of motion and **Fig. 2** illustrates the meaning of the terms and symbols in the form of a Laplace transformation. The equation is capable of expressing the longitudinal motion (i.e., the relative pitch angle θ_x and heave displacement z_x) response due to road input (z_{rdf}) in accordance with the action of the suspension and aerodynamic forces. In the suspension part of the model, the inertial, damping, and spring forces act in response to the relative displacement at the front and rear. Additionally, for the aerodynamic forces, aerodynamic inerter, damping, and spring forces

*1 Vehicle Engineering Development Div., Vehicle Development Center
*2 Nagoya University

act at both the front and rear in response to the relative pitch angle and heave displacement over the overall body. First-order lag (τ_{rz}) was only required at the rear in response to the heave displacement.

$$\hat{M}(s)\begin{bmatrix}\hat{\theta}_x(s)\\ \hat{z}_x(s)\end{bmatrix} = -\begin{bmatrix} m_f s^2 & -m_r s^2 \\ m_f s^2 & m_r s^2 \end{bmatrix}\begin{bmatrix} 1 \\ e^{-s\tau_{wb}} \end{bmatrix}\hat{z}_{rdf}(s) \quad ..(1)$$

$$\hat{M}(s) := \begin{bmatrix}\hat{M}_{11}(s) & \hat{M}_{12}(s)\\ \hat{M}_{21}(s) & \hat{M}_{22}(s)\end{bmatrix}$$

$$= \begin{bmatrix} m_f s^2 + 2c_f s + 2k_f & -m_r s^2 - 2c_r s - 2k_r \\ m_f s^2 + 2c_f s + 2k_f & m_r s^2 + 2c_r s + 2k_r \end{bmatrix}\begin{bmatrix} l_{wb}/2 & 1 \\ -l_{wb}/2 & 1 \end{bmatrix}$$

$$-\begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix}\begin{bmatrix} m_{f\theta} s^2 + c_{f\theta} s + k_{f\theta} & m_{fz} s^2 + c_{fz} s + k_{fz} \\ m_{r\theta} s^2 + c_{r\theta} s + k_{r\theta} & \frac{m_{rz} s^2 + c_{rz} s + k_{rz}}{\tau_{rz} s + 1} \end{bmatrix}$$

2.2 Measurement and modeling of unsteady aerodynamic forces

Excitation tests were carried out in a wind tunnel using a 1/4 scale vehicle model to obtain the unsteady aerodynamic forces. An excitation system was placed in the wind tunnel and the input force from this system was measured via load cells installed on the input applicators. The unsteady aerodynamic forces were identified by subtracting the difference between the input forces with and without the application of wind. Under pitch and heave inputs, two test cases (with and without an airflow-disturbing protrusion attached to the top surface of the roof) were carried out and the results compared (**Fig. 3**). Sine inputs were applied at six frequencies between 0.2 and 2 Hz. The gain and phase of the aerodynamic forces (A_f and A_r) were obtained in response to the vehicle motions (θ_x and z_x) at each frequency. Identification was then applied to these results using the least squares method in each frequency domain to calculate the response functions (**Fig. 4**).

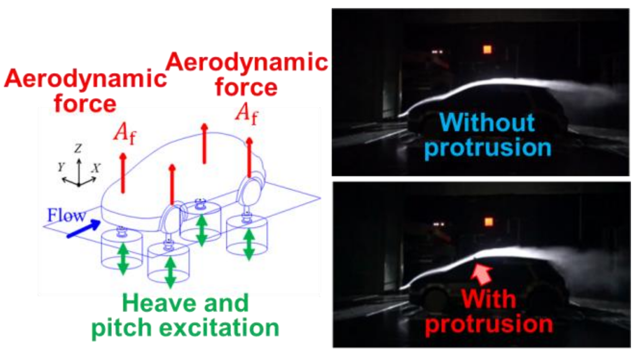


Fig. 3 Illustration of Scale Model Excitation Test and Outline of Study Cases

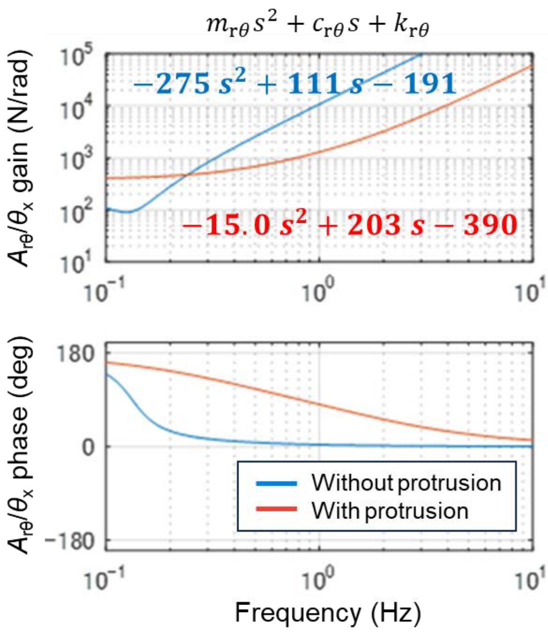


Fig. 4 Response Functions of Rear Aerodynamic Forces Due to Pitch Motion ($A_{r\theta}/\theta_x$)

As a result, the necessity for modeling aerodynamic forces considering the second-order terms and first-order lag in **Fig. 2** was realized and the existence of unsteady characteristics was confirmed. **Fig. 4** shows the rear heave motion aerodynamic force responses due to large differences in pitch motion as Bode plots and an identification equation. These plots show that, without a protrusion, the gain generated by the aerodynamic forces is large and the phase deviation is small.

2.3 Analysis and verification of effects of unsteady aerodynamic forces on motion

Vehicle motions due to road inputs can be calculated as response functions by substituting each coefficient of the calculated unsteady aerodynamic force response functions into **Equation (1)**. As a result, it was possible to verify the difference with and without a protrusion (**Fig. 5**: pitch motion). Then, in timeline simulations under uneven road surface inputs using those response functions (top graph in **Fig. 6**), it was also possible to verify the differences in motion response (middle graph in **Fig. 6**: pitch motion).

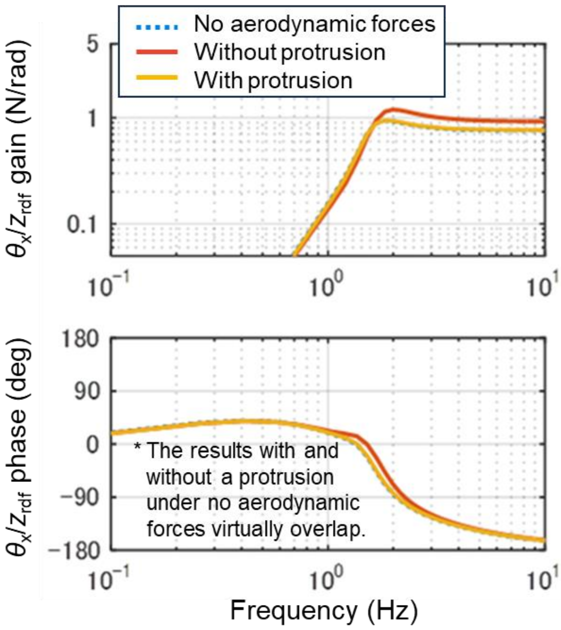


Fig. 5 Response Functions of Pitch Motion Due to Road Input (θ_x/z_{rdf})

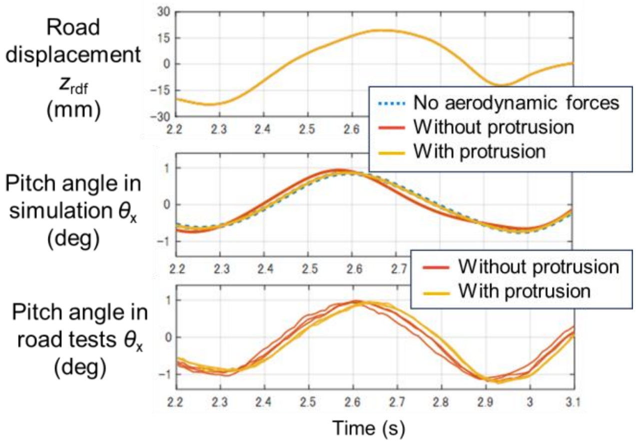


Fig. 6 Comparison of Results of Simulations and Road Tests of Pitch Motion Due to Road Input

In addition, these simulation results were compared and verified using measurement results from actual vehicle road tests (bottom graph in **Fig. 6**). This graph indicates that, without a protrusion, the vehicle responds strongly to the road surface (i.e., the amplitude is large and the lag is small). This result matched the driver evaluation results, which stated that, without a protrusion, the vehicle responded closely to the road surface and delivered a solid steering feeling.

Without a protrusion, aerodynamic forces were generated that increased the susceptibility to pitch motion. In contrast, vehicle motion was much lower with a protrusion. Without a protrusion, the airflow over the roof escaped to the sides. However, with a protrusion, disturbed airflow over the roof stagnated and provided resistance to motion. It is thought that the susceptibility of airflow to change differs in accordance with the differences in unsteady aerodynamic forces (**Fig. 7**).

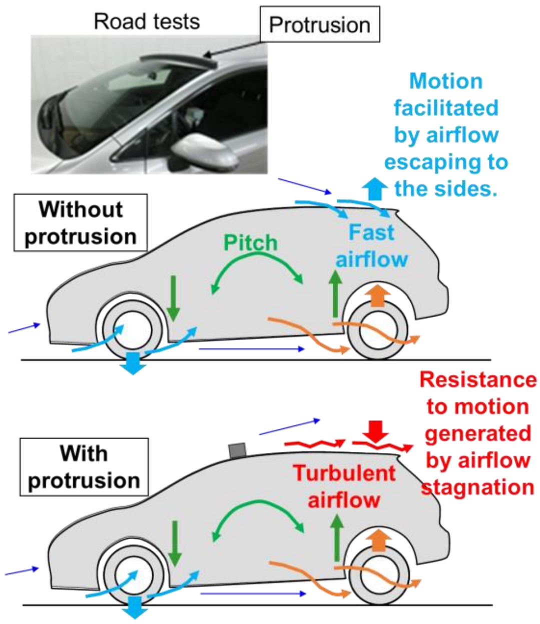


Fig. 7 Changes in Airflow Due to Protrusion Shape during Pitch Motion

3. Conclusion

Aerodynamic forces have a major impact on the running stability of vehicles. This research examined this impact by focusing on unsteady aerodynamic forces (i.e., the aerodynamic forces generated by motion) and quantitatively demonstrated the mechanism by which these forces act. In the future, the objective is to realize further improvements in performance using this developed analysis technique.

References

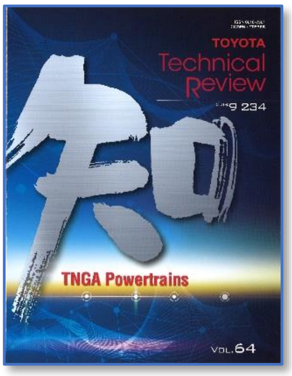
(1) K. Maeda, Tsubakino, Hara, Sasoh. "Coupling Analysis of Unsteady Aerodynamics and Vehicle Behavior with Road Input: Modeling and Verification in Road Tests." *Mechanical Engineering Journal* Vol. 8 No. 4 (2021) DOI: 10.1299/mej.21-00095.

(2) K. Maeda, Tsubakino, Hara, Sasoh. "Investigations of Unsteady Aerodynamic Effects Generated by Heave and Pitch Motion in Different Vehicle Body Shapes with Model Excitation Tests." *Mechanical Engineering Journal* Vol. 7 No. 5 (2020) DOI: 10.1299/mej.20-00276.

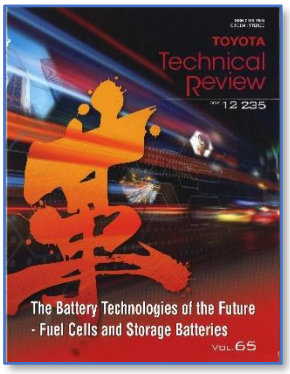
List of Externally Published Papers for the second half of FY2023(From October 2023 to March 2024)

Publication Name	Title	Presenter	Affiliation
Transactions of the Society of Automotive Engineers of Japan, Inc.	Suggest of Set-Based Design Method Based Differential Evolution and Application to Design of Suspension	Koji Nishikawa Kohei Shintani Motofumi Iwata Kohta Miyaki	Toyota Motor Corporation (same as above) (same as above) (same as above)
	A Simple Prediction Method for Tire Vibration Characteristics Used in the Early Stages of Road Noise Development	Masashi Komada Masanori Araki Masato Hashioka Hideki Murakami	Toyota Motor Corporation (same as above) (same as above) (same as above)
	Effects of Fuel Components on Thermal Efficiency in Super Lean Burn S.I. Engine	Kazuki Kaneko Naoyoshi Matsubara Koji Kitano Nozomi Yokoo Koichi Nakata Yuki Yasutake Taketora Naiki Ken Obata Manabu Watanabe	Toyota Motor Corporation (same as above) (same as above) (same as above) (same as above) ENEOS Corporation (same as above) (same as above) (same as above)
	Experimental Verification of a Large 3D Variable-Axis CFRP-Aluminum Unified Structure Targeting a Full-Scale Monocoque Frame	Yoshihiro Iwano Masaaki Tanaka Isao Ohashi Kazuhiko Umemoto Atsushi Kawamoto Tsuyoshi Nomura	Toyota Motor Corporation Toyota Customizing & Development Co., Ltd. TISM Co., Ltd. Toyota Central R & D Labs., Inc. (same as above) (same as above)
	Measuring Mechanical Properties in Simulated HAZ and Fracture Prediction Model for CMT Arc-welded Joints of Ultra-high-strength Steel	Ritsu Nishimura Ninshu Ma	Toyota Motor Corporation Joining and Welding Research Institute Osaka University
	Development of Pressure Pulsation 1D Model for Brake System using “2 pressures/2 systems” Method	Masahiro Yano Nobuhiko Yoshioka Yohei Koike Masashi Komada	ADVICS CORPORATION (same as above) Toyota Motor Corporation (same as above)
	A Validation of an EMF Exposure Simulation Using a Small Size Magnetic Field Sensor	Mikiko Suzuki Watari Toshio Kenichi Ichinose Keishi Miwa Masanori Ishii	Toyota Motor Corporation (same as above) (same as above) (same as above) National Institute of Advanced Industrial Science and Technorogy
	Experimental Study About Avoidance Behavior of the Driver Who Meets with the Dangerous Scenes During City Driving	Toru Kojima Yuki Manabe Koichi Kitada Kunihide Sano Ayumi Shinohara Nana Takahashi Tadashi Shima Yukihiro Ikeda	Automobile and Land Transport Technology (same as above) (same as above) (same as above) Ministry of Land, Infrastructure, Transport and Tourism (same as above) (same as above) Toyota Motor Corporation
	Evaluation of the Effect of Communication Latency on Drivability and Clarification of Communication Latency Requirements in Remote Driving System	Kosuke Akatsuka Rio Suda Hirofumi Momose	Toyota Motor Corporation (same as above) (same as above)
	Prediction Method of Compatibility between Ride Comfort and Load of Off-Road Vehicles using Bayesian Active Learning	Hiroaki Kawamura Misuzu Haruki Hiroyuki Toyoda Kohei Shintani	Toyota Motor Corporation (same as above) (same as above) (same as above)
	Establishment of Wind noise Prediction Method Caused by Flow of Vehicle Shape Using CFD.	Yuta Ito Mikio Wakamatsu Vinh Long Phan Shiro Yasuoka	Toyota Motor Corporation (same as above) (same as above) (same as above)
International Journal of Automotive Engineering (IJAE)	A Model for CAN Message Timestamp Fluctuations to Accurately Estimate Transmitter Clock Skews	Camille Gay Tsutomu Matsumoto	Yokohama National University Toyota Motor Corporation Yokohama National University
Mechanical Engineering Journal	Basic study on transmission error for gear made from different metals laminated in width direction to provide rigidity distribution	Fumitaka Yoshizumi Takayuki Aoyama Yoshikatsu Shibata	Toyota Central R&D Labs., Inc. (same as above) Toyota Motor Corporation
Journal of Fluid Science and Technology	Behaviors of charged air flow on the step surface with an electric potential	Noboru Maeda Kazuhiro Maeda	SOKEN, INC. Toyota Motor Corporation

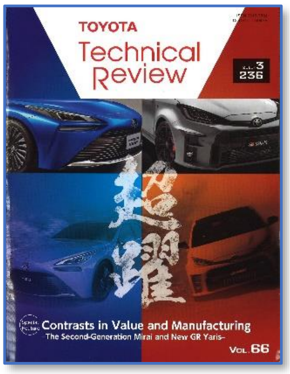
Back Number Index



Vol.64(Sep. 2018)
Special Feature:
TNGA Powertrains

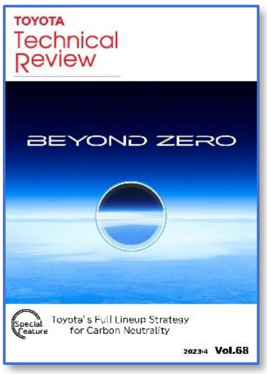


Vol.65(Dec. 2019)
Special Feature:
The Battery Technologies of the Future – Fuel Cells and Storage Batteries



Vol.66(Mar. 2021)
Special Feature:
Contrasts in Value and Manufacturing – The Second-Generation Mirai and New GR Yaris –

Vol.67(Mar. 2022)
Special Feature:
Toyota's initiatives for building a society through sports in which everyone can participate in peace and equality, and for realizing a sustainable society through mobility



Vol.68(Apr. 2023)
Special Feature:
Toyota's Full Lineup Strategy for Carbon Neutrality

Vol.69-1(Dec. 2023)
Special Feature:
Continued: Toyota's Full Lineup Strategy for Carbon Neutrality

Vol.69-2(Jul. 2024)
Special Feature:
Multi-Pathway Approach toward Carbon Neutrality

TOYOTA Technical Review Vol.70 No.1

Publisher's Office	R&D and Engineering management Div.
	TOYOTA MOTOR CORPORATION
	1 Toyota-cho, Toyota, Aichi, 471-8571 Japan
	81-565-28-2121 (Operator)
Publisher	Hideki Takamatsu
Planning	Midori Mori , Jun Tohyama , Mayuka Kubo
Editor	Shingo Kato
(Publishing Office)	Technical Area Administration Support Dept.
	Toyota Office
	TOYOTA ENTERPRISE INC.
Published	January 20, 2025