TOYOTA
Technical Review

Special Feature

Continued: Toyota’s Role in a Circular Economy

Mobility Deep Dive
Potaro: an automated delivery robot designed to coexist with people

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Preface

The special feature of this issue of the *Toyota Technical Review* (Volume 70-2) continues the same theme from the previous issue (Volume 70-1) and focuses on Toyota's role in a circular economy.

As awareness of the environment on a global scale continues to grow, we are experiencing an ongoing transition from a conventional 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. The previous issue of the *Toyota Technical Review* introduced several of Toyota's initiatives for helping to achieve a circular economy, including its design efforts to make end-of-life vehicles (ELVs) easier to dismantle, the recycling of materials such as aluminum, magnets, and plastics, and the proper disposal and cyclical use of automotive batteries.

Part 2 of this Special Feature focuses on some of the fundamental circular economy-related activities that will play an essential role in moving these initiatives forward. After an article that reiterates and emphasizes the importance of working to achieve a circular economy, this issue of the *Toyota Technical Review* describes a proposal for a defining circular economy indicator for vehicles and explains the company's thoughts about public acceptance of the adoption of used parts and recycled materials in vehicles that are in service for an extended period of time.

The purpose of this Special Feature is to deepen understanding of what Toyota is doing to help achieve a circular economy as we remain dedicated to innovation and taking on the challenges involved in creating a sustainable future.

This issue also includes a deep dive into a new form of mobility via a case study describing the use of robots to improve internal logistics within a hospital. As Toyota transforms itself into a mobility company, the company is expanding its development activities to include robots and other forms of mobility, as well as just vehicles. This article describes the development of a hospital delivery robot as an example of this approach. We hope that you will continue to read the *Toyota Technical Review* to learn about how Toyota is working to apply its technologies across a wide range of fields.

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Initiatives for a Circular Economy

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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 materials and products has started to take place on a global scale. The previous issue of the *Toyota Technical Review* discussed several of Toyota's initiatives for helping to achieve a circular economy, including an overview of these initiatives, material recycling, the methodology behind the company's design efforts to make end-of-life vehicles (ELVs) easier to dismantle, and the proper disposal and optimal use of automotive batteries. After reviewing why these initiatives for a circular economy are necessary, this issue covers Toyota's approach in more depth from two perspectives covering the company's fundamental activities for supporting a circular economy.

Keywords: *circular economy, material circulation, adoption of indicators, social acceptance, behavioral transformation*

1. Introduction

The previous issue of the *Toyota Technical Review* (Vol. 70-1) discussed several of Toyota's initiatives for helping to achieve a circular economy (CE), including an overview of these initiatives, material recycling, the methodology behind the company's design efforts to make end-of-life vehicles (ELVs) easier to dismantle, and the proper disposal and optimal use of automotive batteries. After reviewing why these initiatives for a circular economy are necessary, this issue summarizes Toyota's approach from two perspectives covering the company's fundamental activities for supporting a circular economy.

The first perspective is a discussion about how best to assess initiatives for a circular economy. There are currently no indicators capable of unambiguously defining the achievement of a circular economy in the same way as greenhouse gas emissions are used to define carbon neutrality. For this reason, Toyota is studying the necessary elements for assessing circular economy initiatives and is carrying out research into CE indicators capable of expressing these results.

The second is a report on research carried out into the social acceptability of products manufactured incorporating circular economy concepts. More specifically, this means gauging how products developed based on the concept of a circular economy might be received by consumers. This report presents some of these research results, and considers how to facilitate deeper discussions about the acceptability of the circular economy.

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2. Background to Initiatives for a Circular Economy

2.1 Significance of circular economy initiatives

The previous issue of the *Toyota Technical Review* outlined the environment surrounding the concept of a circular economy focusing on regulatory trends and the obligation to disclose various information. This issue reviews the significance of circular economy initiatives from the following two perspectives.

The first perspective is the impact of the extraction of natural resources on the global environment. Mineral ore is extracted from the ground and converted into metals and other materials for industrial uses by various preparation and refining processes. Vehicles are manufactured using a wide range of these materials, which are obtained by the excavation of land in resource-rich countries. The size of the land transformation area (i.e., the area of land affected by resource extraction) depends on the method of extraction. In some cases, only the necessary minerals are extracted from the excavated ore, generating leftover material that is jettisoned at the excavation site. In addition, the extraction of some resources may result in a loss of natural biodiversity if the producing region is notably biodiverse. For example, lithium production sites use large volumes of water that may cause shortages for agriculture and local residents.(1) Similarly, nickel extraction is having an impact on highly biodiverse forests in countries producing this mineral (**Fig. 1**). Since mineral extraction affects the residents and land of material producers, it must not be forgotten that vehicles are ultimately manufactured using extracted natural resources. Therefore, it is important to ensure that such resources remain in a valuable state after extraction and that the circular use of these resources is maintained.

The second perspective relates to business continuity, specifically the risk that various materials may become more difficult to procure. Imbalances in the distribution of producing countries and the geographical concentration of refining processes within overall manufacturing process must be urgently addressed from the standpoint of economic stability, assuming the fact that these materials must be exported to the point of manufacture. Attention must also be paid to the risk of material depletion. To help mitigate these risks, it is important to regard waste as a resource in its own right and target achieving the circular use of such resources on a global level. For resource-poor countries like Japan, circularity must be promoted from the standpoint of material autonomy. The following sections describe the current situation regarding these issues and the relationship between these issues and the circular economy.

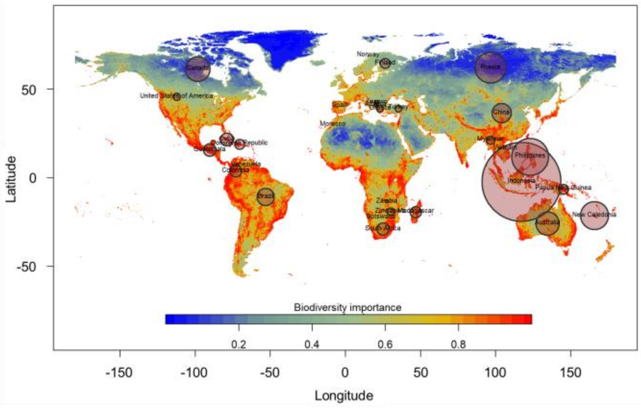

Fig. 1 Priority Biodiversity Preservation Areas Overlaid on Regions of Nickel Production

Source: Map created by Professor Kubota at the University of the Ryukyus from biodiversity data provided by Think Nature Inc.[2] and nickel production data described in Nickel Statistics and Information (collated by the U.S. Geological Survey (USGS))[3].

2.2 Resource depletion risk

Currently, the global population consumes 1.75 times more natural resources than the Earth's ecological system is capable of regenerating.[4] Demand for these resources has increased dramatically due to population increase and economic growth since the Industrial Revolution. Assuming that the trend of rising resource demand in accordance with economic growth continues in the future, there is the risk that some resources may become depleted. **Fig. 2** shows the results of research carried out by Harada et al. that was announced by the National Institute for Materials Science (NIMS) in 2007.[5][6] These results show estimates for cumulative resource demand up to 2050 compared to existing resource reserves. The term "current resource reserves" refers to the amount of a resource that can be extracted economically. "Reserve base" refers to the total amount of a resource that is considered to be feasibly accessible. This research assumed that resource demand would increase in a linear fashion in line with economic growth and that the rate of demand increase with respect to economic growth would start to plateau once a certain economic scale is reached. In many cases, cumulative demand up to 2050 exceeds the current material reserves. Furthermore, demand for zinc, copper, nickel, lead, tin, antimony, silver, indium, gold, and palladium all exceed the reserve base.

This research by Harada et al. estimates future resource demand based on resource consumption figures up to 2004. However, changes in industrial structures and the types of products being manufactured are likely to cause fluctuations in demand for particular resource types. Consequently, even when the cumulative demand for a resource does not exceed the reserve base according to this research, the situation must be carefully considered based on future trends. From the standpoint of the automotive industry, the progress of electrification is a major transformation point and representative of a change in the type of product being manufactured. According to a scenario put forward by the International Energy Agency (IEA), the market share of electrified vehicles is projected to exceed at least 50% by 2050.[7] Advances in electrification, particularly in the case of battery electric vehicles (BEVs), are likely to result in higher demand for copper, lithium, and cobalt. **Fig. 3** compares the amount of lithium and cobalt used in several vehicle powertrains. Due to differences in battery capacity and the specifications, a BEV uses at least eight times more of these resources than an HEV. Factoring in this change in product, it is possible that cumulative demand for lithium and cobalt will also exceed the reserve base.

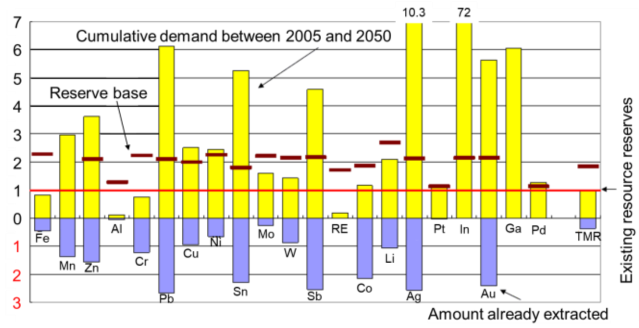

Fig. 2 Cumulative Demand Compared to Existing Resource Reserves until 2050

Source: Duplicated from materials prepared by NIMS[6]

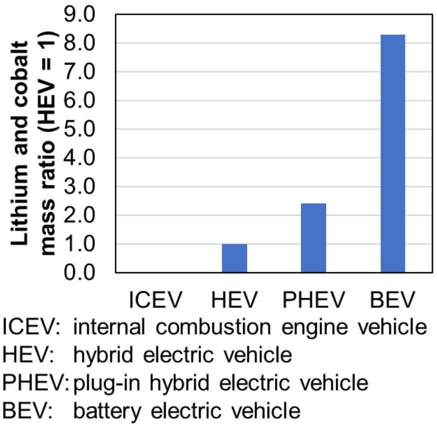

Fig. 3 Mass Ratio of Lithium and Cobalt Usage

2.3 Perspectives of CE initiatives

As described in the previous section, the impact of resource extraction on the global environment from extraction to vehicle manufacturing must be considered. At the same time, it is necessary to ensure the thorough circularity of extracted resources. In other words, the automotive industry must focus on the principle that "quality" is the key concept for material recycling and that material circularity must be achieved without lowering the value of the extracted resources throughout its lifecycle.

Toyota is a firm believer in this principle and has conducted research into assessment indicators for the circular economy as well as social acceptance related to material circularity. The following sections outline global trends up to the present day with regard to these two topics.

3. Global Trends Related to the Adoption of Circular Economy Indicators

3.1 Circular economy indicators around the world

This section summarizes the current circular economy indicators using a review paper as a reference.(8) Different circular economy indicators are based on different assumptions related to the range of impact of the circular economy. This impact can also be expressed using the term "scope." In general terms, the impact of the circular economy can be categorized by range into scope 0, scope 1, and scope 2. Scope 0 indicators cover only the internal environment of a manufacturing plant. Scope 1 indicators cover the overall lifecycle including manufacturing, product usage, recycling, and material recovery. Scope 2 indicators cover the product lifecycle as well as the relationship of that product with the environment, economy, and society. It is difficult to use a single indicator to assess a circular economy strategy in its entirety. Circular economy strategies can be categorized into function-related strategies affecting lease, rental, and sharing, product-related strategies affecting the reuse, refurbishment, and re-manufacturing of products, part-related strategies affecting the reuse and repurposing of parts, and material-related strategies affecting recycling and energy recovery. For these reasons, separate indicators have been proposed for functions, products, parts, and materials. In addition, the scope of these circular economy indicators also differs. For example, some cover single products, while others cover whole countries. It is difficult to define a single indicator capable of covering every possible scope.

If the aim is to assess automotive products, a circular economy indicator that covers the impact of a product over its lifecycle (i.e., a scope 1 indicator) would be most appropriate. It would also be better to adopt an indicator capable of covering a circular economy strategy over a wide range. However, if the coverage is extended in this way, the indicator value starts to lose objective meaning and becomes more abstract. As a result, even if an indicator is used to successfully quantify the concept of a circular economy, the meaning conveyed by the indicator value becomes more difficult to understand. After looking into various groups of indicators, Toyota decided to focus initially on two indicators that are capable of covering a circular economy strategy over a wide range and that use values with transparent and objective meanings. These indicators, the Material Circularity Indicator (MCI) and the Circular Transition Indicators (CTI), include many points that need to be reflected in circular economy initiatives.

The MCI can be expressed as a single formula based on abstract parameters, and factors in material circularity, the product lifetime, and product functional units. The lifecycle and functional units of a product are incorporated into the indicator in comparison with the same aspects of similar types of product. The CTI cover various aspects of circularity. The meanings of the parameters used to create each individual indicator are transparent and objective, and are easy to quantify. **Fig. 4** illustrates the process of international standardization (under ISO 59020) for measuring and assessing circularity performance with respect to these indicators and the circular economy. Various versions of the CTI have been released to expand the assessment scope. In the future, it is likely that discussions about the CTI will focus on individual sectors of the economy such as vehicles.

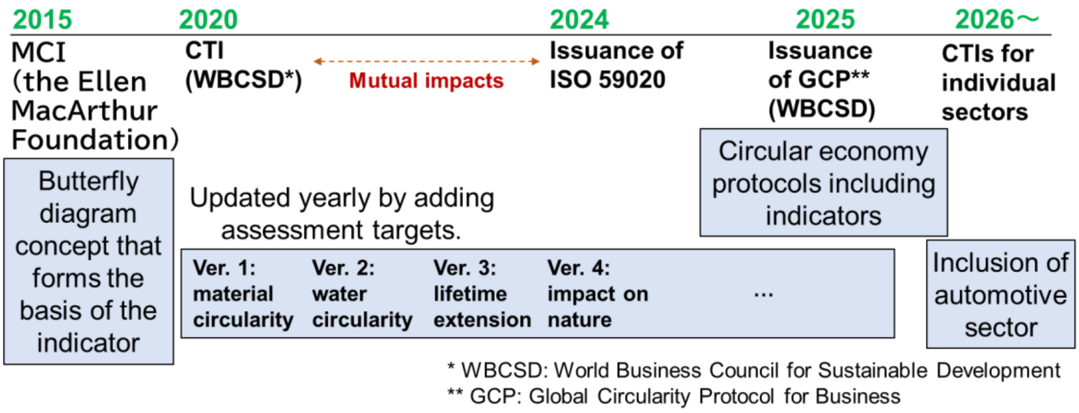

Fig. 4 Global Trends Related to the Adoption of Circular Economy Indicators

3.2 Relationship between CTI and ISO

Fig. 5 shows the relationship between the CTI and ISO 59020, which was published in May 2024. The main focus of ISO 59020 is the assessment of the extent and efficiency of circularity in material usage. Most of the relevant principles are also included in the CTI. In addition to these principles, the scope of the CTI has been expanded to cover the relationship with corporate revenue and other issues affecting corporations.

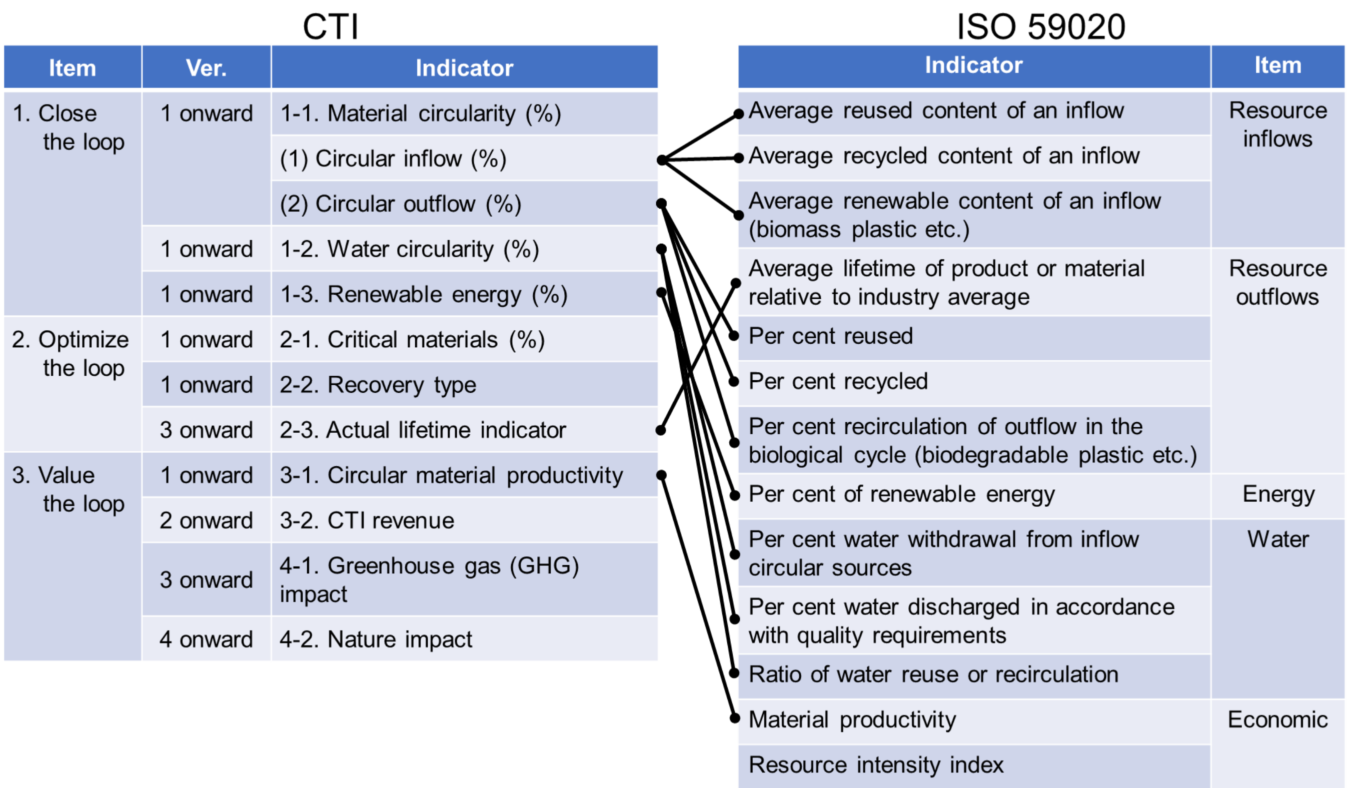

Fig. 5 Relationship between CTI and ISO 59020

3.3 Studies into new circular economy indicators

This section focuses on global circular economy indicator adoption trends and the history of the MCI and CTI as representative indicators. The MCI is regarded as the foundation of the thinking behind circular economy indicator adoption. In contrast, the CTI quantify various aspects of a circular economy transparently and objectively. However, to apply these indicators to a vehicle that consists of various materials, it is necessary to reflect different environmental impacts based on the materials in question. Therefore, Toyota decided to look into the Total Material Requirement (TMR) as a methodology capable of quantitatively measuring the different environmental impacts of materials. With the aim of constructing an indicator suitable for application to vehicles, trials are being conducted into using the TMR to carry out integrated assessments of the different environmental impacts of materials, the quality of circularity, and the value delivered to the customer. The details are described in ***Proposal of a Circular Economy Indicator for Vehicles*** starting on page 9 of this issue.

4. Activities toward Social Acceptance and Behavioral Transformation

Since the 1990s, the reduce, reuse, and recycle (3R) approach has been promoted both inside and outside Japan. From 2013, this approach began to be widened to integrate the idea of the circular economy. The establishment of the Ellen MacArthur Foundation (EMF) and wider awareness of the Sustainable Development Goals (SDGs) adopted by the United Nations in 2015 are playing particularly important roles in this process. In addition, the Circular Economy and Resource Efficiency Principles (CEREP) that were adopted at the G7 summit in Hiroshima in 2022 are acting as guidelines for encouraging positive behavior by private companies. These events have influenced consumer preferences and purchasing behavior (**Fig. 6**).

Year	1992	1993	1995	1996	2000	2001	2005	2013	2015	2018	2020	2022	2023	2024
International	1992 Rio Earth Summit		eBay established		MDGs* adopted				SDGs adopted EMF established		WBCSD CTI issued	CEREP adopted at G7 Hiroshima summit	European ELV directive	ISO 59020 issued
Japan General consumable goods		Basic Environment Act established		3R approach established	Act on the Promotion of Sorted Collection and Recycling of Containers and Packaging	Ministry of the Environment established		Japanese flea market app Mercari starts		Mercari listed on stock market				5th Fundamental Plan for Establishing a Sound Material-Cycle Society
Durable consumable goods					Act on Recycling of End-of-Life Automobiles		JARC** established							
				1997: Prius HEV launched			--------------------------------			Cumulative sales of 15 million units by 2020				

* MDGs: Millenium Development Goals
** JARC: Japan Automobile Recycling Promotion Center

Fig. 6 Global Trends Related to Social Acceptance

The 5th Fundamental Plan for Establishing a Sound Material-Cycle Society, which was adopted by the Cabinet in August 2024, is also evidence of increasing consumer awareness about the environment and consumption.(9) In addition, to a certain extent, wider use of flea market apps in the U.S. and Japan has helped to disseminate the concepts of recycling and reusing general consumable goods such as daily necessities and foodstuffs.(10)(11)

However, it is not clear whether customers hold the same motivations with respect to durable consumable goods such as domestic appliances and vehicles that are used over a number of years, and whether a change in consumption behavior can be expected for these products as well. Although a stable used vehicle market already exists, the market for reused parts appears to be limited to certain items only. For this reason, in 2022, Toyota teamed up with the National Institute of Advanced Industrial Science and Technology (AIST) and Toyota Central R&D Labs., Inc. to carry out a survey of vehicles to examine consumer acceptance with respect to the circularity of durable consumable goods. The details are described in ***Social Acceptance of a Circular Economy for Vehicles*** starting on page 14 of this issue.

5. Conclusion

This article has presented a fresh overview of Toyota's initiatives for a circular economy, focusing on the necessity to transform the linear consumption of materials to circular use to help address the issues of resource extraction and depletion. The article went on to outline trends related to the adoption of indicators for assessing circular economy initiatives and social acceptance of the circular economy as fundamental elements for realizing this transformation.

Toyota upholds the following two critical principles with respect to the circular economy: that manufacturing must use materials with a lower impact on the environment, and that, since "quality" is a key concept for material recycling, material circularity must be achieved without lowering the value of the extracted resources. Toyota will continue developing products that will help bring a smile to the face of as many people as possible through *monozukuri* (manufacturing) that reflects global realities.

Acknowledgments

The information related to circular economy indicators was obtained and interpreted thanks to the invaluable support and cooperation of everyone involved in writing this article, particularly Takamichi Iwata and Masashi Hara of Toyota Central R&D Labs., Inc. The author would like to take this opportunity to express his gratitude to everyone involved.

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Proposal of a Circular Economy Indicator for Vehicles

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Abstract

The assessment of items such as material circulation and economic viability will play an essential role in the realization of a circular economy for vehicles. Since vehicles use a wide range of different materials, assessments that only consider recycling rates based on mass are not sufficiently accurate. Therefore, to assess the performance of material circulation factoring in environmental impacts, Toyota is working on a circular economy assessment methodology based on the Total Material Requirement (TMR) concept, which also incorporates the impacts of material extraction. The TMR concept can be used to assess the importance of recycling material resources with a high environmental impact even if low volumes of those materials are used in a vehicle. This article describes several circular economy indicators and proposes an indicator capable of assessing the performance of material circulation factoring in environmental impacts.

Keywords: *circular economy, circular economy indicator, Total Material Requirement (TMR), environmental impact, quality of material circulation*

1. Introduction

Assessments of the extent of material circulation, its economic viability, and accompanying environmental impacts will play an essential role in the realization of a circular economy (CE). Many circular economy indicators have been proposed for this purpose.(1) The most representative type of indicator uses mass as the basis to calculate the usage rate of recycled materials. However, since vehicles use a wide range of different materials, assessments based simply on recycling rates are not sufficiently accurate. For example, if mass is adopted as the basis of assessment, the focus of the assessment will be biased toward steel, which makes up the biggest proportion of the mass of a vehicle. In contrast, compared to conventional vehicles, electrified vehicles use far more copper as well as larger amounts of cobalt and lithium in batteries. Despite making up a small proportion of the mass of the vehicle, these are materials with major environmental impacts that cannot be fully assessed using existing circular economy indicators. This article describes the details of ongoing research into a circular economy indicator that factors in environmental impacts.

2. Background of Circular Economy Indicator Research: International Trends Related to the SDGs and Environmental Consideration

Japan and Europe have inaugurated various initiatives to reduce environmental impacts through innovation and technological advancement. These initiatives are driven by the United Nations' Sustainable Development Goals (SDGs), regulations and restrictions imposed by the European Parliament, the frequent occurrence of natural disasters caused by climate change, geopolitical risks affecting key materials and supply chains, as well as the issue of waste disposal. To help address these issues, people have started to become aware of the necessity to achieve the transition to a circular economy that realizes the circular use of products and materials in an economic fashion.

Requirements for promoting a circular economy include the adoption of standards and rules to ensure that these limited materials are cared for and used fairly. As described in ***Initiatives for the Circular Economy*** starting on page 3 of this issue of the *Toyota Technical Review*, the circular economy technical committee (ISO/TC 323) of the International Organization for Standardization (ISO) and the World Business Council for Sustainable Development (WBCSD) that works to promote sustainability in the business world have cooperated to formulate a standardized protocol. Furthermore, the WBCSD has also issued the Circular Transition Indicators (CTI) as a set of circular economy indicators.

In partnership with the National Institute of Advanced Industrial Science and Technology (AIST) and Toyota Central R&D Labs., Inc., Toyota has studied a large number of proposed circular economy indicators, including the CTI, and has begun to carry out research to identify whether these indicators omit any factors requiring further consideration.

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3. Characteristics of Current Main Circular Economy Indicators

3.1 Characteristics of the Material Circularity Indicator (MCI)

The MCI was proposed by the Ellen MacArthur Foundation in the UK.(2) This section introduces MCI_p, which is an MCI that focuses on products. This indicator uses **Equation (1)** to define the Linear Flow Index LFI based on the mass of virgin material V used in the product, the mass of unrecycled waste W attributed to the product, and the total mass of the product M.

$$LFI = \frac{V+W}{2M} \quad (1)$$

The LFI places the amount of virgin material on the inflow side and the amount of unrecycled material after use on the outflow side to express the ratio of material that makes no contribution to material circulation. Consequently, 1-LFI is the material ratio that contributes to material circulation. Although a description is omitted here for space, the LFI is also corrected by the amounts of non-recyclable and unrecoverable waste that occur in the recycling process.

In addition, parameter X can be defined as shown in **Equation (2)** based on the potential lifecycle of a product L, the industry-average lifecycle of a similar product L_{av}, the number of functional units of the product U, and the average number of functional units of the same industrial product U_{av}.

$$X = \left(\frac{L}{L_{av}}\right) \cdot \left(\frac{U}{U_{av}}\right) \quad (2)$$

Parameter X expresses whether the product lifetime and number of functional units are superior to the average values for similar types of products. A higher X value indicates a longer product lifecycle and a higher number of functional units. The product-focused MCI_p is defined using **Equations (3) and (4)**.

$$MCI_p^* = 1 - LFI \cdot F(X) \quad (3)$$

$$MCI_p = max\left(0, MCI_p^*\right) \quad (4)$$

where, $F(X)$ is a function of parameter X and MCI_p^* is calculated by subtracting LFI multiplied by $F(X)$ from 1. The resulting value expresses the ratio of materials that contribute to material circulation factoring in the lifecycle and number of functional units of the product. **Equation (4)** expresses that $MCI_p = 0$ when MCI_p^* becomes a negative value.

The MCI can be expressed as a single formula based on the abstract parameters X and $F(X)$, and factors in material circulation, the product lifecycle, and product functionality.

3.2 Characteristics of the Circular Transition Indicators (CTI)

The CTI were proposed by the WBCSD at the United Nations Conference on Environment and Development (also known as the Earth Summit) in 1992 with the objective of explaining the position of the business community with regard to sustainable development. The purpose of the CTI is to provide an objective, quantitative, and flexible framework, identify risks and opportunities to determine circular priorities, and set targets.(3)

As shown in **Fig. 1**, the CTI define the rates of material circularity in terms of both circular inflows and circular outflows. The CTI also focus on the consumption rate of critical materials, recovery type, and actual lifetime to assess the optimality of material circularity. This indicator also combines material circularity with corporate revenue as a measure of effectiveness. The main indicators within the CTI are shown in the figure below. This section extracts some of these indicators and describes the specific defining formulas.

Material circularity on the inflow and outflow sides are defined as shown in **Equations (5) and (6)**.

$$\text{Circular inflow} = \frac{\text{Mass of recycled materials used} + \text{mass of renewable materials used}}{\text{Total mass of materials used}} \quad (5)$$

$$\text{Circular outflow} = \frac{\text{Actual mass of materials reused out of the mass of renewable materials used}}{\text{Total mass of materials used}} \quad (6)$$

To measure the optimality of circularity, the consumption of critical materials is defined by **Equation (7)**.

$$\text{Consumption of critical material resource} = \frac{\text{Mass of inflow defined as critical}}{\text{Total mass of linear inflow}} \quad (7)$$

Among the indicators that combine material circulation with company revenue, material productivity is defined by **Equation (8)**.

Circular material productivity =

$$\frac{\text{Company revenue}}{\text{Total mass of linear inflow}} \quad \cdots\cdots (8)$$

The CTI cover various aspects of circularity. The meanings of the parameters used to create each individual indicator are transparent and objective, and are easy to quantify.

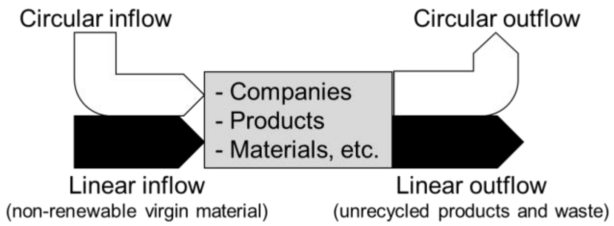

Fig. 1 Outline of the CTI

Source: Created based on reference materials from the WBCSD[3]

4. Discussion of Circular Economy Indicators

4.1 Elements required for a circular economy indicator

One issue with the MCI is its abstract nature, which makes it unsuitable for expressing tangible values. In addition, the CTI are composed of individual indicators representing various perspectives, which makes it difficult to establish a correlation between separate items. Therefore, after re-examining which elements are necessary for a circular economy indicator, the following two focus points were selected. The first point is that vehicles use a wide range of materials that all have different environmental impacts. Therefore, when considering vehicle manufacturing, environmental impact must be incorporated into the indicator rather than using mass alone. The second point is the quality of material circularity. Recycling can take place in various ways. Examples include horizontal recycling, in which the quality and grade of a material is maintained and returned in the form of the original product. Another example is cascade recycling, in which a material cannot be returned to the form of the original product due to impurities or the like becoming mixed into the material during the recycling process, affecting the quality or grade of the material. Repeated cascade recycling ultimately eliminates potential applications of the material, resulting in its disposal and the dissipation of its inherent value. Consequently, from the perspective of value retention, it is preferable to target horizontal recycling rather than cascade recycling. In other words, preventing the dissipation of the material value is regarded as extremely important.[4]

4.2 The environmental impacts of materials

As described above, it is important to factor in environmental impacts when considering material circularity. If an indicator uses only material mass, it is impossible to understand the extent of the impact on the environment when obtaining that material. For this reason, Toyota decided to focus on using the Total Material Requirement (TMR) coefficient to visualize these impacts.[5] Since this coefficient expresses the extent of natural resources (such as how many kilograms of soil or water) required to obtain 1 kg of a certain material, this indicator can be used to identify the environmental impact of a material. **Table 1** shows the TMR coefficient of the main materials used in vehicles.[6] A higher TMR coefficient means that more of the surrounding area has to be excavated to obtain the material, implying a higher environmental impact. As the table shows, lithium has a TMR coefficient approximately 200 times higher than the coefficient for iron. This means that the environmental impact of obtaining 1,000 kg of iron is the same as the impact of obtaining 5 kg of lithium. **Fig. 2** compares the environmental impacts of materials in a normal electric vehicle when measured in terms of mass (left pie chart) with the impacts when measured in terms of the TMR (right pie chart) coefficient. Although iron is responsible for around half of the environmental impact in terms of mass, this value falls to 20% when evaluated by the TMR coefficient. This is because copper, lithium, and cobalt have higher TMR coefficients. In this way, it is possible to use the TMR coefficient to evaluate material circularity factoring in environmental impacts. These results demonstrate why it is necessary to promote material circularity for elements other than iron.

Table 1 TMR Coefficients

Element	TMR coefficient (kg-TMR/kg)
Fe	8
Al	48
Cu	360
Li	1,500
Co	600
Ni	260

Source: Created based on resource extraction volume[6]

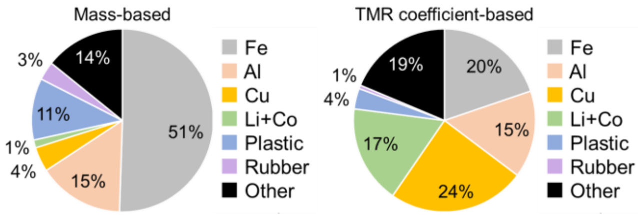

Fig. 2 Comparison of Environmental Impacts of Materials in Electric Vehicle Measured in Terms of Mass and TMR Coefficients

4.3 Quality of material circularity

As described in Section 4.1, it is preferable to target horizontal recycling rather than cascade recycling. Therefore, the quality of material circularity was assessed by using the type of recycling (either horizontal or cascade recycling) to define the material coefficient. A scenario in which the quality and grade of the material is maintained and recycled back to the same part or product is defined as having a value of 1. In contrast, a scenario in which the material is discarded into a landfill or the like and not recycled is defined as having a value of 0. Consequently, under this system, a scenario in which a material is recycled to a different application due to the mixing of multiple materials or the like is defined as having a value between 0 and 1. Thorough discussion will be required to fix the value for each material.

4.4 Proposal of a circular economy indicator

Focusing on the two factors of the environmental impacts of a material and the quality of material circularity, the TMR approach was adopted to measure the former and coefficients determined in accordance with the type of recycling to measure the latter. **Equations (9) and (10)** show two of the formulas presented at the JSAE Annual Autumn Congress 2024 for use as part of a circular economy indicator incorporating these two factors.[7] *InFlowTMR* refers to the TMR on the inflow side of the product and *OutFlowTMR* refer to the TMR on the outflow side of the product. $Mass'_t$ and $Mass''_t$ refer to the mass of the material, and $MatValue'_t$ and $MatValue''_t$ are the coefficients expressing the quality of material circularity.

InFlowTMR=

$$\sum_{t=1}^{n} TMR_t \times Mass'_t \times MatValue'_t \quad \text{(9)}$$

OutFlowTMR=

$$\sum_{t=1}^{n} TMR_t \times Mass''_t \times MatValue''_t \quad \text{(10)}$$

A lower *InFlowTMR* value indicates that a lower volume of material was newly extracted and used in the product. In other words, this shows that the product was manufactured using recycled materials. To maintain the *OutFlowTMR* value, more of the product's materials must be recycled and used for the next product, upholding the principle of horizontal recycling.

5. Conclusion

This article proposed a circular economy indicator that adopts material requirement coefficients in accordance with the method of recycling to assess the environmental impacts related to material extraction and the quality necessary to maintain material circularity. Remaining issues include how to assess other environmental impacts and how to fix the coefficients used to measure the quality of recycling.

The use of indicators such as these to assess circular economy initiatives can help to identify cases in which the transition to material circularity is more preferable than procuring materials by extraction. As the scale of material circularity expands, the circular economy will also grow. Assessing the relevant value when the approximately 30,000 parts that make up a vehicle are reused or processed to recover their materials is the basis for the appropriate application of recycling, reuse, or material recovery. This is likely to have a transformational effect on the ecosystem of the whole automotive industry.

Acknowledgments

This research was accomplished thanks to the invaluable support and cooperation of everyone involved, particularly Takamichi Iwata and Masashi Hara of Toyota Central R&D Labs., Inc., as well as Kiyotaka Tahara and Mitsutaka Matsumoto of the National Institute of Advanced Industrial Science and Technology (AIST). The authors would like to take this opportunity to express their gratitude to everyone involved.

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Social Acceptance of a Circular Economy for Vehicles

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Takayuki Nagai*1

Abstract

Toyota is promoting efforts to achieve a circular economy with the aim of breaking away from conventional linear economic practices. As part of these efforts, in 2022, Toyota teamed up with the National Institute of Advanced Industrial Science and Technology (AIST) and Toyota Central R&D Labs., Inc. to carry out research identifying the extent of the social acceptance of used parts and recycled materials in vehicles and other durable consumable goods with a long service life. This article presents the initial results obtained through this research.

Keywords: *circular economy, adoption of used parts and recycled materials, social acceptance, Purity Orientation-Pollution Avoidance scale*

1. Introduction

Progress is being made on a global basis toward the transition to a circular economy (CE) by encouraging the circularity of materials, parts, and the like. Toyota is also working toward a circular economy through efforts promoting the adoption of used parts and recycled materials. As part of these efforts, Toyota teamed up with the National Institute of Advanced Industrial Science and Technology (AIST) and Toyota Central R&D Labs., Inc. in 2022 to carry out research identifying the extent of the social acceptance of used parts and recycled materials in vehicles and other durable consumable goods with a long service life.

2. Objectives and Outline of Surveys 1 and 2

To enable the widespread acceptance of used parts and recycled materials by consumers, measures will probably be necessary to identify and mitigate the psychologically inhibiting factors that have an adverse effect on social acceptance, and to identify and promote the psychologically facilitating factors that have a positive effect. Through a series of surveys, this research attempted to extract the inhibiting and facilitating factors pertaining to the adoption of used parts and recycled materials. Survey 1 aimed to identify the extent to which consumers might accept the adoption of used car parts. This was carried out by comparing the acceptance of used items across 102 different categories including car parts, books, personal computers, bedding, washing machines, writing materials, accessories, and the like. Subsequently, the same survey investigated the impact of the adoption of 35 types of used parts on consumer perception of a vehicle's newness. In contrast, survey 2 aimed to ascertain the value of used parts and recycled materials and to identify which factors might facilitate the acceptance of cars that adopt these items. This was carried out by comparing consumer impressions of cars adopting used parts or recycled materials with new cars as well as conventional certified used cars. The methods and results of surveys 1 and 2 are described below.

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3. Survey 1: Acceptance of Used Car Parts and Effects of Adopting Used Parts on Perception of Vehicle Newness

3.1 Survey method

Responses were received from a total of 1,600 men and women resident in Japan (ages: 20s to 70s, responses received from roughly equal proportions of ages and genders) via an Internet-based survey in February 2022.

To measure the social acceptance of used parts, the survey listed 102 items (including vehicle steering wheels, personal computers, bedding, washing machines, writing materials, accessories, and the like) and asked the respondents to describe their purchasing preferences over five levels (1: Would only consider new items, 2: Would give priority to new items, 3: Would give roughly equal priority to both new and used items, 4: Would give priority to used items, and 5: Would only consider used items). Additionally, to calculate consumer perception of vehicle newness, the survey also listed 35 used car parts and components (including the engine, mirrors, doors, navigation system, and the like) and asked the respondents to state how far the adoption of these parts in a new car would lower their perception of that car's newness, again over five levels. (1: Substantially lower perception, 2: Somewhat lower perception, 3: Hard to say, 4: Slightly lower perception, 5: Absolutely no change in perception). This survey also asked questions examining people's need for mental and physical purity as well as their tendency to avoid pollution and uncleanliness by calculating a score based on the Purity Orientation-Pollution Avoidance (POPA) scale.[1] Higher scores indicate a higher need for purity and a stronger tendency to avoid pollution or uncleanliness. It should be noted that this survey did not examine the price of new and used parts.

3.2 Survey results

3.2.1 Acceptance of used items in each category

Factor analysis carried out for the used item acceptance scores identified seven categories of items with similar acceptance trends (**Fig. 1**). These categories can be ranked in descending order of used part acceptance scores as follows: leisure items (books, computer games, etc.) = mean used item acceptance score of 2.33 points, car parts (steering wheel, brakes, etc.) = 1.81 points, fashion items (bags, accessories, etc.) = 1.73 points, daily items (writing materials, clocks, etc.) = 1.70 points, IT-related items (personal computers, smart phones, etc.) = 1.63 points, household appliances (refrigerators, washing machines, etc.) = 1.50 points, items that come into contact with the skin (underwear, bedding, etc.) = 1.36 points. Although not ranked as high as leisure items, used car parts seem to be relatively more acceptable to consumers. In addition, when the correlation between the used item acceptance scores and POPA scale scores was analyzed for each category, a close correlation was identified in almost every category, including car parts (correlation coefficient *r*: -0.11 to -0.22). This correlation indicates that the acceptance of used items decreases as people’s tendency to avoid pollution or uncleanliness increases.

These results suggest that the acceptance of used car parts decrease in accordance with people’s need for purity and desire to avoid pollution.

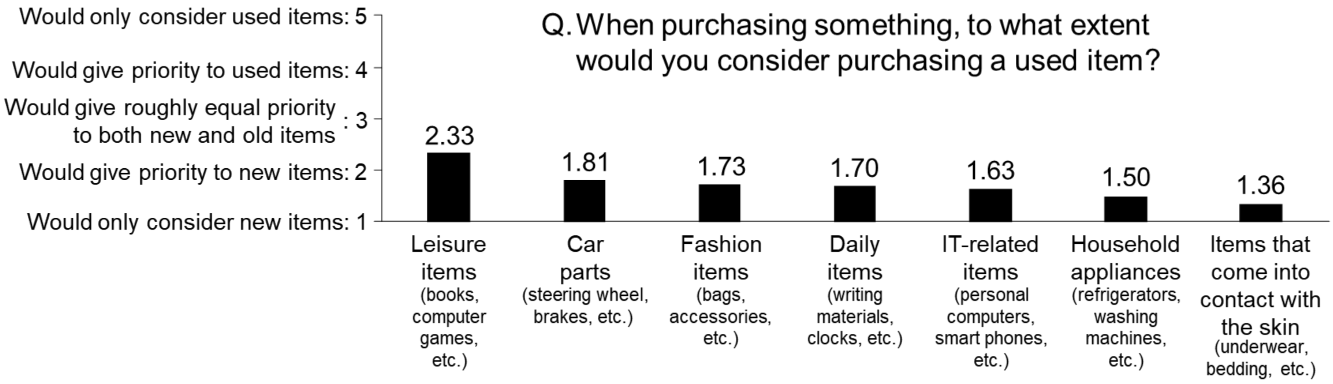


Fig. 1 Acceptance of Used Parts in each Category (N = 1,600)

3.2.2 Effects of adopting used parts on perception of vehicle newness

Factor analysis carried out for the perception of vehicle newness scores identified four categories of used parts with a similar tendency to lower the perception of vehicle newness (**Fig. 2**). These categories can be ranked in ascending order from the largest reduction in the perception of vehicle newness as follows (i.e., from lower to higher scores for the perception of newness): brakes, gears, etc. (mean perception of vehicle newness score = 2.19 points), seats, doors, etc. = 2.28 points, navigation systems, drive recorders, etc. = 2.42 points, mirrors, lights, etc. = 2.57 points. Brakes, gears, seats, and doors can probably be regarded as core elements of a vehicle. In contrast, navigation systems, drive recorders, mirrors, and lights can probably be regarded as accessories. This suggests that adopting used parts for the core components of a vehicle (i.e., its brakes, gears, seats, or doors) would have a negative impact on people’s perception of a vehicle’s newness.

When the correlation between the perception of vehicle newness scores and POPA scale scores was analyzed for each category, a close correlation was identified between the perception of the newness of the brakes, gears, seats, and doors and the scores describing people’s pollution avoidance tendency (correlation coefficient *r*: -0.18 to -0.15). This suggests that adopting used parts for the core components of a vehicle (i.e., its brakes, gears, seats, or doors) would be more likely to reduce the perception of vehicle newness for people with a stronger pollution avoidance tendency (i.e., people with no desire to engage with anything potentially negative). In addition, these results recognized a close correlation between the perception of vehicle newness scores and the scores describing people’s uncleanliness avoidance tendency across all categories of parts (correlation coefficient *r*: -0.11 to -0.12). This suggests that people with a stronger uncleanliness avoidance tendency (i.e., people with no desire to touch something dirty) tend to have a lower perception of a vehicle’s newness, no matter which used parts are adopted.

In summary, these results demonstrate that the acceptance of used car parts decreases in accordance with people's need for purity and desire to avoid pollution when used parts are adopted for essential vehicle functions.

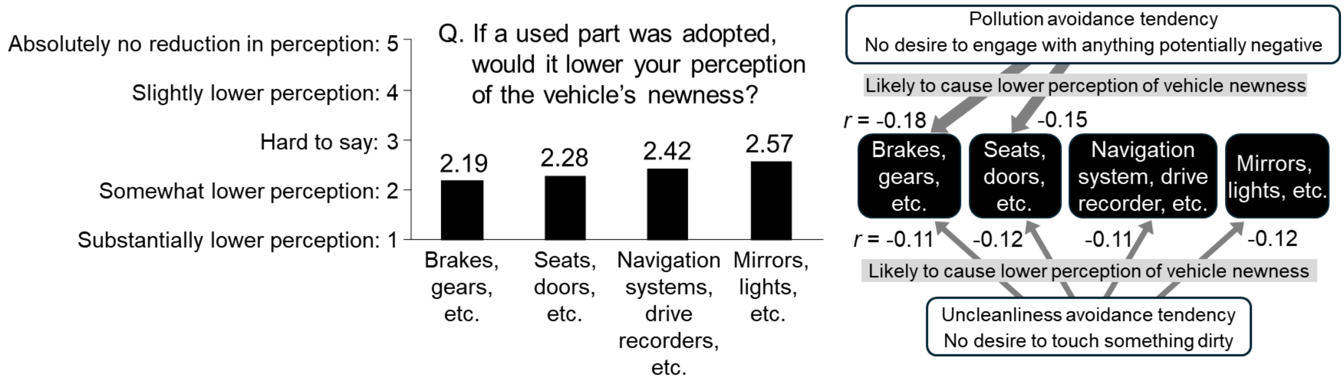


Fig. 2 Effects of Used Parts on Perception of Vehicle Newness and Relationship with Pollution Avoidance Tendency (N = 1,600)

4. Survey 2: Impression of Adoption of Used Parts and Recycled Materials – Comparison with Conventional Certified Used Cars and New Cars –

4.1 Survey method

Responses were received from a total of 1,800 male and female car owners (ages: 20s to 70s, responses received from roughly equal proportion of ages and genders) via an Internet-based survey in November 2022.

The respondents rated their impressions of two types of vehicles: cars adopting used parts and cars adopting recycled materials. The former type of vehicle was defined as a car adopting used parts in the interior (e.g., the seats) or the exterior (e.g., the body). The latter type of vehicle was defined as a car adopting materials recycled from used parts. However, because no vehicles adopting used parts or recycled materials have been released anywhere in the world, it is not possible to obtain an absolute impression of these cars. Instead, the respondents were asked to provide relative impressions based on conventional new or certified used cars.

In the survey, the 1,800 respondents were divided into groups of 300 people based on the following conditions (1) to (6) (each group contained roughly equal proportions of ages and genders).

(1) Respondents asked to give their impression of cars adopting used parts compared to conventional new cars after reading an illustrated explanation about cars adopting used parts.
(2) Respondents asked to give their impression of cars adopting used parts compared to conventional certified used cars after reading an illustrated explanation about cars adopting used parts.
(3) Respondents asked to give their impression of cars adopting recycled materials compared to conventional new cars after reading an illustrated explanation about cars adopting recycled materials.
(4) Respondents asked to give their impression of cars adopting recycled materials compared to conventional certified used cars after reading an illustrated explanation about cars adopting recycled materials.
(5) Respondents asked to give their impression of conventional certified used cars compared to conventional new cars.
(6) Respondents asked to give their impression of conventional new cars compared to conventional certified used cars.

The semantic difference (SD) method was adopted as the impression response method. In other words, the respondents were presented with opposing pairs of adjectives (e.g., 1: Plain – 7: Ostentatious) and asked to rate the target vehicle on a seven-step scale between the adjective pair. These responses were defined as the impression rating values. Impression rating values for 86 adjective pairs were obtained from all of the respondents. The adjective pairs used for evaluation included words related to perception and the senses (e.g., 1: Plain – 7: Ostentatious), words with a cognitive or conceptual basis (e.g., 1: Commonplace – 7: Individualistic), and words related to emotional or attitude (e.g., 1: Uninteresting – 7: Interesting).

4.2 Survey results

4.2.1 Adjective categories

Factor analysis carried out for the impression rating values identified six categories of adjectives that generated similar impressions (**Table 1**). These six adjective categories can be defined as follows: object with good appearance, interest in/desire to purchase an object, no impression of annoyance, innovation/ individualism, environmental friendliness/impression of being up-to-date, and sparkling/artistic. A mean impression score was calculated within each adjective category for each of the six groups of respondents.

Table 1 Adjective Categories and Examples of Adjective Pairs

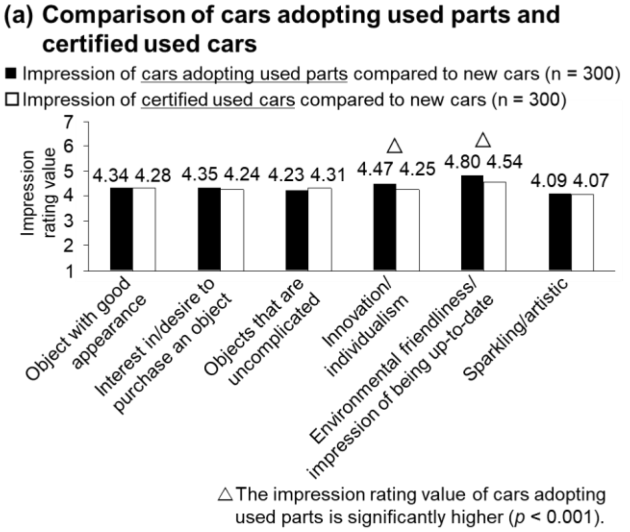
Adjective category	Examples of adjective pairs
Object with good appearance	Rough – Sophisticated Unpleasant – Pleasant
Interest in/desire to purchase an object	Uninteresting – Interesting No desire to purchase – Desire to purchase
No impression of annoyance	Awkward – Convenient Difficult – Simple
Innovation/individualism	Commonplace – Individualistic Predictable – Fresh
Environmental friendliness/impression of being up-to-date	Bad for the environment – Good for the environment Out of step with the times – In step with the times
Sparkling/artistic	Plain – Ostentatious Practical – Niche

4.2.2 Impression of cars adopting used parts

The *t*-test method was applied to analyze the survey results. In this method, the means of two samples are compared and the difference between the two determined to be either random or statistically significant. First, to extract the difference between impressions of cars adopting used parts and conventional certified used cars, the *t*-test method was applied to compare the rated impression for each adjective category obtained under condition 1 (cars adopting used parts rated in comparison with conventional new cars) with those obtained under condition 5 (certified used cars rated in comparison to conventional new cars). Since new cars are the baseline under both of these conditions, the differences in the impression rating values between each condition should depend on the differences in the object being rated. **Fig. 3 (a)** shows the results. The impression rating values for the categories of innovation/individualism and environmental friendliness/impression of being up-to-date were significantly higher for cars adopting used parts compared to certified used cars (△, $p < 0.001$).

Next, to extract the difference between impressions of cars adopting used parts and conventional new cars, the *t*-test method was applied to compare the impression rating values for each adjective category obtained under condition 2 (cars adopting used parts rated in comparison with conventional certified used cars) with those obtained under condition 6 (conventional new cars rated in comparison with certified used cars). **Fig. 3 (b)** shows the results. The impression rating value for the environmental friendliness/impression of being up-to-date category was significantly higher for cars adopting used parts compared to conventional new cars (△, $p < 0.01$). In contrast, the impression rating values for the object with good appearance, interest in/desire to purchase an object, no impression of annoyance, and sparkling/artistic categories were significantly lower for cars adopting used parts compared to conventional new cars (▼, $p < 0.01$).

Based on the results described above, cars adopting used parts were given an overall positive rating compared to conventional certified used cars. Particularly high ratings were awarded to these cars in terms of their innovation/individualism as well as their environmental friendliness/impression of being up-to-date. However, despite a higher rating in the environmental friendliness/impression of being up-to-date category, cars adopting used parts were given an overall negative rating compared to conventional new cars.



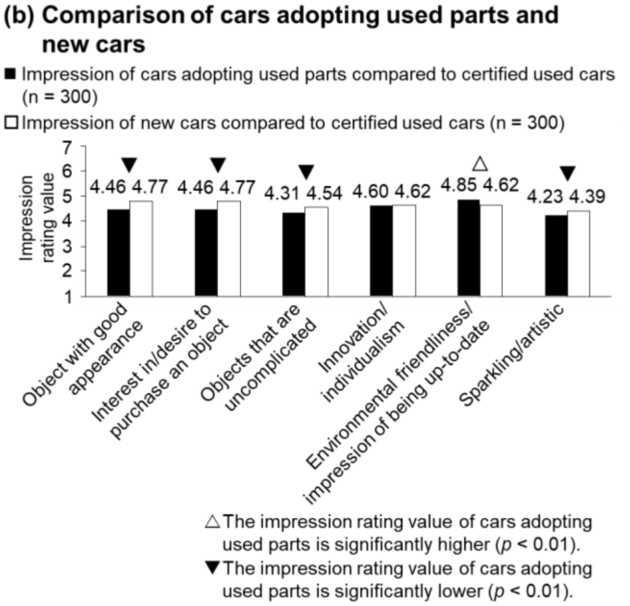


Fig. 3 Comparison of Impressions of Cars Adopting Used Parts and Conventional New Cars

4.2.3 Impression of cars using recycled materials

First, to extract the difference between impressions of cars adopting recycled materials and conventional certified used cars, the *t*-test method was applied to compare the impression rating values for each adjective category obtained under condition 3 (cars adopting recycled materials rated in comparison with conventional new cars) with those obtained under condition 5 (certified used cars rated in comparison to conventional new cars). **Fig. 4 (a)** shows the results. The impression rating values for the object with good appearance, innovation/individualism, environmental friendliness/impression of being up-to-date, and sparkling/artistic categories were significantly higher for cars adopting recycled materials compared to certified used cars (△, $p < 0.05$).

Next, to extract the difference between impressions of cars adopting recycled materials and conventional new cars, the *t*-test method was applied to compare the impression rating values for each adjective category obtained under condition 4 (cars adopting recycled materials rated in comparison with conventional certified used cars) with those obtained under condition 6 (conventional new cars rated in comparison with certified used cars). **Fig. 4 (b)** shows the results. The impression rating value for the environmental friendliness/impression of being up-to-date category is significantly higher for cars adopting recycled materials compared to conventional new cars (△, $p < 0.001$). In contrast, the impression rating values for the object with good appearance, interest in/desire to purchase an object, no impression of annoyance, and sparkling/artistic categories were significantly lower for cars adopting recycled materials compared to conventional new cars (▼, $p < 0.001$).

Based on the results described above, cars adopting recycled materials were given an overall positive rating compared to conventional certified used cars. Particularly high ratings were awarded to these cars in terms of the object with good appearance, innovation/individualism, environmental friendliness/ impression of being up-to-date, and sparkling/artistic categories. However, despite a higher rating in the environmental friendliness/impression of being up-to-date category, cars adopting used parts were given an overall negative rating compared to conventional new cars.

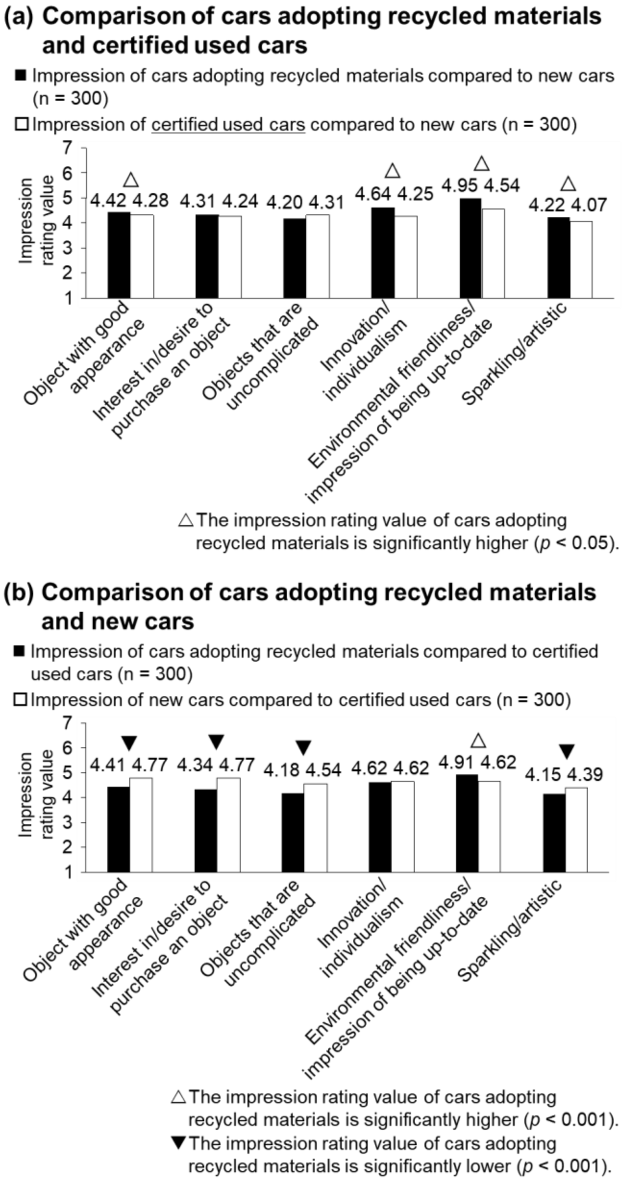


Fig. 4 Comparison of Impressions of Cars Adopting Recycled Materials and Conventional New Cars

5. Conclusion

Through a series of two surveys, this research extracted the inhibiting and facilitating factors pertaining to the adoption of used parts and recycled materials. The results of survey 1 demonstrated that the acceptance of used car parts decreases in accordance with people's need for purity and desire to avoid pollution when used parts are adopted for essential vehicle functions. The results of survey 2 demonstrated that cars adopting used parts or recycled materials are rated higher than conventional certified used cars and new cars from the perspectives of the conservation of the environment and the protection of materials. Therefore, to cultivate the acceptance of adopting used parts or recycled materials in vehicles, it will be necessary to address the concerns of consumers about used parts and communicate the contribution of used parts and recycled materials to environmental conservation and material protection.

Acknowledgments

The authors would like to express their sincere gratitude to everyone at the Human Informatics and Interaction Research Institute of the National Institute of Advanced Industrial Science and Technology (AIST) and Toyota Central R&D Labs., Inc. for their invaluable cooperation in obtaining and analyzing information related to the social acceptance of a circular economy and in writing this article. The authors would like to take this opportunity to express their gratitude to everyone involved.

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Achieving Lean Hospital Logistics Using Potaro (an Automated Delivery Robot Designed to Coexist with People) and a Multi-Robot Coordination System

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Abstract

Most cases of robots being used to carry out deliveries inside a hospital instead of people remain limited to the transportation of low-volume items either at night or during the day. The technology described in this article was used as the basis to review the logistics within a hospital from the perspective of the Toyota Production System (TPS). As a result, manual transportation within the hospital was replaced extensively by robot deliveries through the adoption of automated mobile technology and a multi-robot coordination system targeting four high-priority items. Currently, 24 of these robots are in service, handling approximately 170 delivery trips per day with an average successful delivery rate of 98%. In a year and a half since the opening of a new hospital building, a total of 100,000 deliveries have been made, which adds up to a distance of more than 10,000 km. In terms of labor costs, this is equivalent to savings of around 250 million yen per year.

Keywords: *automated mobile robot designed to coexist with people, multi-robot coordination system, delivery robot, TPS, mass produce happiness, lean hospital delivery system, task shifting, higher operational efficiency in medical workplaces*

1. Introduction

1.1 Issues of medical workplaces and the challenge of shifting tasks to robots

As Japan's working population continues to decline, a shortage of doctors and nursing staff is a serious issue faced by modern medical services. With the Japanese Ministry of Health, Labour and Welfare also promoting the reform of working practices for doctors, the shifting of tasks between different types of medical staff and raising the efficiency of work have become more important than ever. The Toyota Memorial Hospital located in Toyota City, Aichi Prefecture (**Fig. 1**), was originally established by Toyota Motor Corporation as a company clinic. With a capacity of 527 beds, the Toyota Memorial Hospital currently plays a core role in the local area and has been designated as a Regional Medical Care Support Hospital. However, from around 2016, the hospital started to experience an uptick in nursing staff attrition. Questionnaire surveys found that many nursing staff were becoming overwhelmed with cumbersome day-to-day tasks that hampered their ability to secure the ideal amount of direct contact with patients.

To help improve this situation, a project was launched with the aim of raising the efficiency of nursing work at the hospital. One particular finding of this project was the discovery that nursing staff were spending large amounts of time fetching items within the hospital. Taking the opportunity of the planned opening of a new hospital building in 2023, it was decided to target the use of robots to take over delivery services. In addition to medical staff, the project team consisted of people from production sites with expert knowledge of the Toyota Production System (TPS) as well as people involved in robot research and development. This team aimed to realize a lean hospital delivery system capable of eliminating waste. After a thorough investigation of the state of logistics within the hospital, the team started to address the challenge of introducing 24 large-scale delivery robots capable of taking on as many logistics-related tasks as possible.

Fig. 1 Exterior Appearance of the Toyota Memorial Hospital

[*1] R Frontier Div., Frontier Research Center

This article introduces the practical technologies developed by Toyota to realize both Potaro (an automated delivery robot designed to coexist with people) and a multi-robot coordination system, while factoring in the opinions of the hospital staff.

2. Outline of Practical Technologies

2.1 Potaro: an automated delivery robot designed to coexist with people

Fig. 2 shows various aspects of the developed Potaro robot after its adoption and **Table 1** lists its main specifications. Although a wide range of objects have to be transported in medical workplaces, items such as medication for injections and specimens have to be handed over within a set time. However, even if robots take over delivery tasks, it may remain difficult for nursing staff to receive items within these set times in coordination with the arrival time of the robots since the nursing staff need to prioritize medical care. Therefore, the robot specifications were defined with the aim of realizing automatic loading and unloading so that the nursing staff can pick up the items in the intervals between high-priority tasks. Each Potaro robot is equipped with a wagon (**Fig. 2 (b)**) capable of carrying, delivering, and leaving the volume of items required by eighteen specialty medical departments in the hospital within predetermined times. It can also individually carry, deliver, and leave smaller volumes of items whenever necessary (**Fig. 2 (d)**).[1]

Fig. 2 Exterior Appearance of Potaro Robot

Table 1 Main Potaro Robot Specifications

Item		Specifications
Transportation system		Separate wagon lift up system
Continuous operation time after charging		Approximately 4 hours
Maximum speed	Maximum power	1.0 m/s
	In operation	0.75 m/s
Dimensions (when wagon loaded)	L	970 mm
	W	840 mm
	H	1,170 mm
Maximum cargo weight		70 kg
Localization		2D LiDAR + 2D map
Object avoidance		2D LiDAR + 3D camera

The Potaro robots complete delivery tasks by following routes that pass through preset waypoints inside the building. Automated movement between these waypoints is accomplished using localization technology founded on sensor-based odometry and map-matching using 2D LiDAR. In a hospital, the transportation environment frequently changes due to the presence of large objects such as gurneys and carts used for treating patients. However, the robustness of localization was improved by incorporating the evaluation formula proposed by Akai et al.[2] into the likelihood model of the particle filter. Therefore, even when the robot encounters objects that do not exist on the pre-registered map, it can operate without losing its position. In addition, a robot simulator and search-based testing technologies were incorporated into localization accuracy evaluations to optimize parameters by enabling parameter searches that avoid localized solutions even after a low number of evaluation iterations.[3]

2.2 Multi-robot coordination system

Conventionally, medication for injections is transported around a hospital as follows. Daily doses of medication to be administered are collected together on the previous day, transported from the pharmacy to the wards, and, normally, mixed by the nursing staff immediately before administration to the patient. However, this creates two issues. First, for hygiene reasons, the pharmacy is the recommended location for mixing. Second, since the quantity of medication transported from the pharmacy is an estimated amount, changes in the condition of the patient mean that unused medication has to be returned to the pharmacy. To resolve these issues, it was decided to consolidate the mixing task at the pharmacy and deliver the medication in small batches based on the administration schedule at the ward by adopting a just-in-time approach (this is known as “central mixing”). As a result, 9 robots are assigned to deliver medication from the pharmacy to the wards over two round trips, with a maximum of 24 robots available depending on the time for other transportation tasks, including medical equipment, specimens, and the like. To satisfy the delivery requirements (i.e., that each delivery service must be completed within a predetermined time to preserve the freshness of the medication and that the robots must not impede the movement of people and goods around the hospital), a management system was developed to coordinate the movement of multiple robots.

High robot traffic flows occur around medication handling areas and elevators. If robots have to wait for extended periods to carry out specific tasks (such as unloading and entering or exiting an elevator), this will increase the risk of delays and congestion (**Fig. 3**). In response, technology was adopted to control the right-of-way at intersections in accordance with the tasks being implemented to reduce congestion in these areas. In addition, a system was adopted that determines which robots have priority for using elevators considering the status of congestion at the destination floor. The efficiency of elevator usage was also enhanced by identifying optimum pairs of robots requiring access to an elevator, even if those robots are on different floors. The adopted control logic allows up to two robots to use an elevator at the same time. The control system was designed to handle differences in the sequence and direction that robots enter or exit an elevator in accordance with the orientation of the elevator door on a particular floor. This series of control operations was verified in advance by multiple robot simulations.

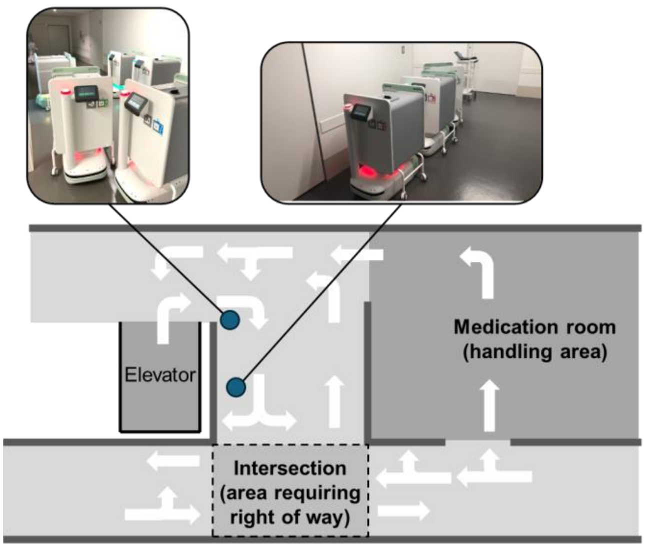

Fig. 3 Complex Route Intersections and Robot Congestion

In addition to robots, other large objects are moved within a hospital, including food delivery carts and beds (**Fig. 4 (a)**). Advance verifications found that, in some narrow corridors, the Potaro robots would run up against these objects and become stuck because the objects could not be bypassed. This issue was addressed by combining object recognition technology with the surveillance cameras inside the hospital. Control technology was developed that causes the robots to wait when specific objects are predicted to enter particular passages (**Fig. 4 (b)**).[4]

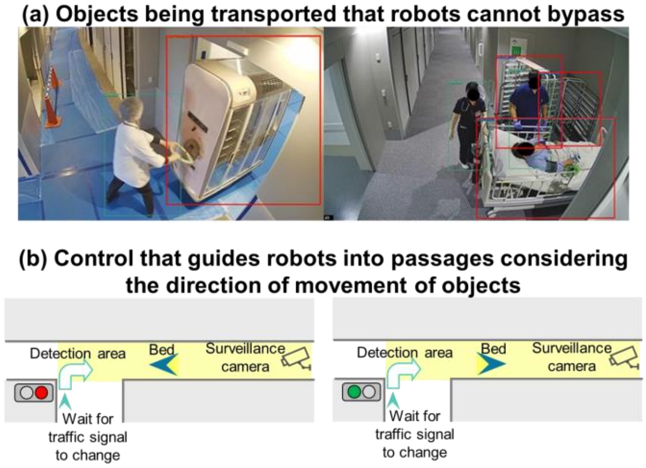

Fig. 4 Coordination with Surveillance Cameras

3. Operational Results

Medication delivery began when the new hospital building opened in May 2023 and was gradually expanded to include medical equipment and specimens. From November 2023, 24 Potaro robots were being used to carry out deliveries 24 hours a day, 365 days a year.[5]

Each day, this robot fleet carries out an average of 170 delivery tasks. As of December 2024, these robots had been used to perform a total of 100,000 tasks and had traveled a distance of more than 10,000 km. The current success rate of the adopted system is 99%. Remaining issues that cause the robots to stop include object detection sensor errors and marker recognition malfunctions caused by changes in sunlight conditions. If a robot stops due to one of these issues, a notification is sent from the monitoring web app to the system administrator in the hospital (**Fig. 5**), who then recovers the error.

Fig. 5　Potaro Robot Monitoring Web App

4. Target: Expansion of Robot Technologies throughout Medical Workplaces

Toyota is aiming to facilitate the development of medical workplace environments in which medical staff can concentrate even more fully on patient care by further improving the hospital delivery system adopted by the Toyota Memorial Hospital and expanding the services this system provides. After the adoption of this hospital delivery system, nursing staff commented that the system has helped to create more beneficial nurse-patient relationships by allowing closer and more varied conversations with patients concerned about their surgeries. Toyota intends to continue its efforts to mass produce happiness in medical workplaces on the frontline of Japan’s aging society through the development and social implementation of robots capable of working as partners with medical staff.

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The JSAE Asahara Prize Academic Encouragement Award (74th JSAE Awards)

Cabin Comfort Improvement and Heating Energy Reduction under Cold Conditions Using Radiative Heater

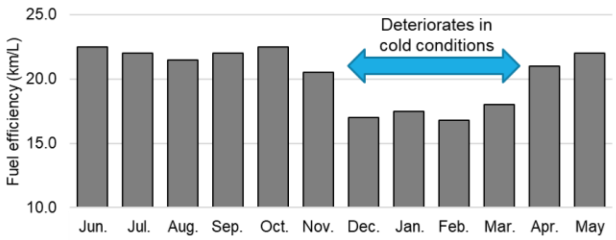
Hirotaka Sasaki*1

1. Introduction

Vehicle electrification is advancing in response to the introduction of increasingly stringent automotive CO_2 emissions regulations in countries and regions around the world. However, the consumption of energy for heating in cold conditions has a major negative impact on both the range and the fuel and power consumption efficiency of electrified vehicles, creating a trade-off effect between environmental friendliness and practicality. This article describes how existing devices designed to enhance the comfort of vehicle occupants (seat and steering wheel heaters) were redefined as energy-saving items and a new radiative heater was developed targeting the area around the knees, which is not efficiently warmed by conventional heating systems. This approach helped to improve the comfort of vehicle occupants immediately after entering the vehicle, while simultaneously lowering the energy required for heating.

2. Impact of Seasonal Conditions on Fuel Efficiency

In general terms, the real-world fuel efficiency and driving range of a vehicle tend to be lower than the certified test values of that model type due to the energy required for warming up the engine and motor or for climate control. This trend is particularly pronounced under cold conditions (**Fig. 1**).



Fig, 1 Seasonal Hybrid Electric Vehicle (HEV) Fuel Efficiency

Under real-world conditions, fuel is consumed to provide the energy for running the vehicle, warming up the vehicle due to the friction that occurs during a cold start-up, and operating the climate control system. Since the energy requirement of a climate control system is particularly high under cold conditions, it should be possible to raise fuel efficiency under these conditions by finding ways of improving occupant comfort more efficiently (**Fig. 2**).

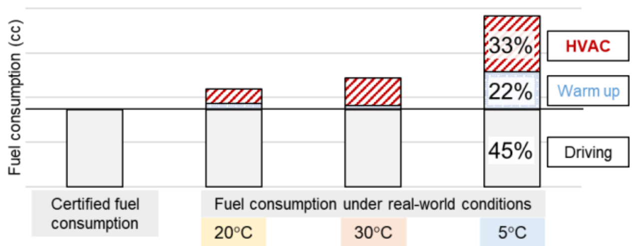


Fig. 2 Breakdown of Fuel Consumption

3. Approach for Saving Energy Used for Heating

3.1 Conventional heating system

Conventionally, a vehicle cabin is heated in two ways: by heating the air inside the whole occupant compartment using convective heat from the heating, ventilation and air-conditioning (HVAC) system (**top half of Fig. 3**), and by adopting devices such as seat and steering wheel heaters that use conductive heat to warm the occupants directly (**bottom half of Fig. 3**).

Evaluations of occupant comfort during driving under cold conditions show that areas of the body that are heated directly, such as the back and hands, warm up quickly. In contrast, the thermal sensation in areas such as the thighs and shins increases slowly. Since these areas can only be warmed by heating the air in the occupant compartment, there is a limitation on how much energy for heating can be reduced (**Fig. 4**).

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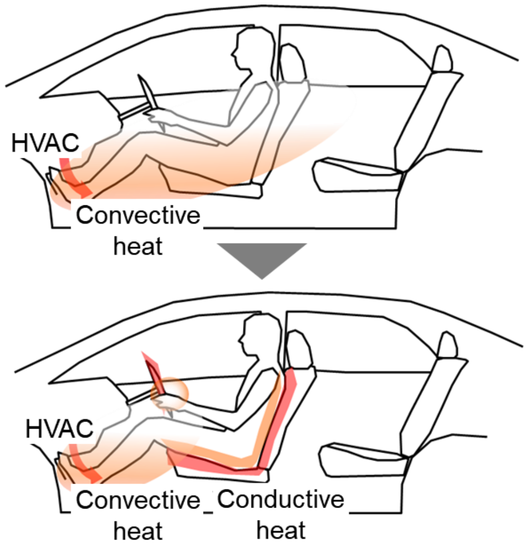

Fig. 3 Approaches for Warming Vehicle Occupants Using Conventional Heating Systems

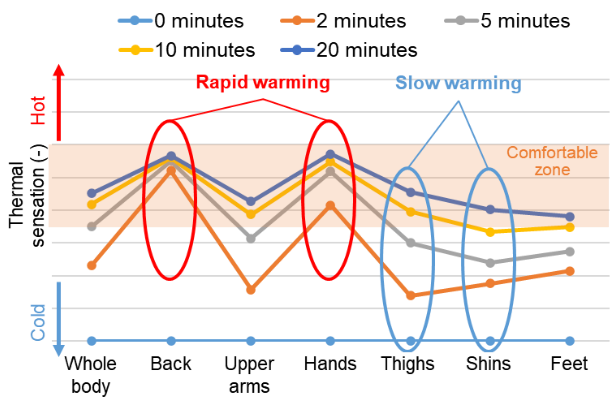

Fig. 4 Occupant Comfort Using Conventional Heating Systems

3.2 Heating system using radiative heater

This development focused on the thermal sensation of different parts of the body. The use of radiative heat to effectively warm the thighs and shins, which cannot be accomplished efficiently by convective or conductive heating, was proposed to further lower the energy required for convective heating (**Fig. 5**).

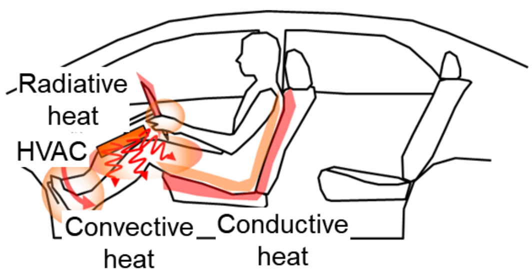

Fig. 5 Method of Warming Vehicle Occupants Using Radiative Heating System

3.2.1 Setting of performance targets

The necessary performance targets for ensuring occupant comfort were set as part of the process to design the radiative heater for the vehicle. To satisfy a wide range of requirements in the regions where the vehicle might be driven, the development team analyzed the likely ambient temperatures of those regions and aimed to achieve the necessary degree of warmth in the defined environments. Although the performance of a heater is determined by its size and temperature, the heat flux around the knees of the occupant, which differs depending on the conditions, was set as the performance indicator. This indicator was then used to evaluate the impact on the thermal sensation when the conditions were varied. As a result, the necessary heat flux around the knees was defined as 200 W/m^2 (**Fig. 6**).

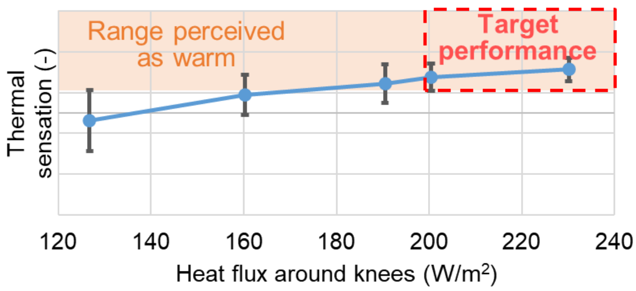

Fig. 6 Target Radiative Heater Performance

3.2.2 Radiative heater design

Computer aided engineering (CAE) simulations were carried out using the size and temperature (output) of the heater as parameters. The vehicle installation space and temperatures with the potential to harm the body were defined as constraining conditions. Heater specifications that satisfy the heat flux requirements were then studied under these constraints. The results found that a heater with a size of 200 cm^2 and an output power of 150 W could provide the necessary performance under the defined constraints. The heater is located between a top layer designed considering external appearance and an insulation layer on the back to prevent heat transfer to the installation area. An internal thermistor measures the temperature, which is adjusted precisely by a controller (**Fig. 7**).

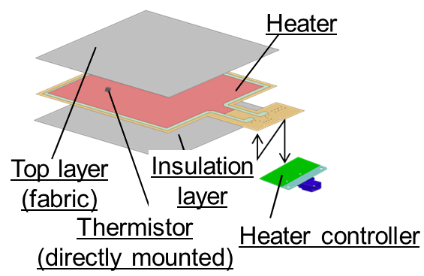

Fig. 7 Radiative Heater Structure

4. Vehicle Installation and Development of Synchronized HVAC Control

4.1 Development of synchronized HVAC control

The objective of this radiative heater is to reduce the energy required for convective heating. An efficient method of reducing this energy while maintaining or improving the level of comfort was studied. The two main elements involved in adjusting the convective heat provided by the HVAC system are the temperature and flow rate of the air discharged from the HVAC vents. Actual vehicle evaluations found that lowering the flow rate had a minimal impact on comfort and lowered the energy required more efficiently. Therefore, a new control was developed to ensure comfort while saving energy by adjusting the flow rate of the HVAC system in accordance with the operational status of the radiative heater (**Fig. 8**).

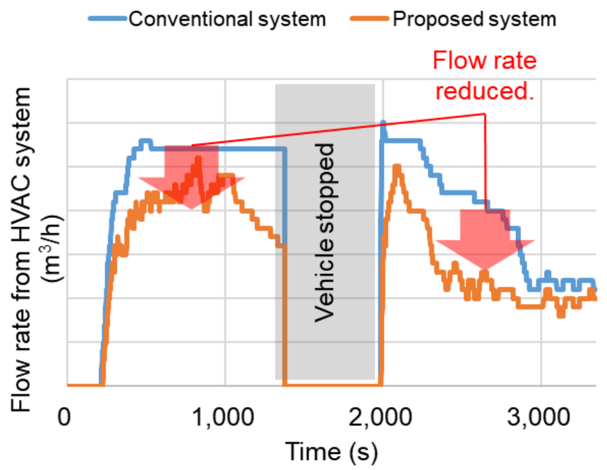

Fig. 8 HVAC Control Synchronized with Radiative Heater Operation

4.2 Vehicle installation and actual vehicle evaluations

To verify the effectiveness of the proposed system, the radiative heater was installed in a Prius PHEV. Evaluations were then carried out to assess occupant comfort and the effect of the system on fuel efficiency under cold conditions. Adopting the radiative heater had a major improvement effect on comfort by warming the thighs and shins of the vehicle occupants immediately after entering the vehicle (**top graph in Fig. 9**), resulting in a comfort level equivalent to or higher than the conventional system even under steady-state conditions (**bottom graph in Fig. 9**).

In addition, the developed system lowered the energy required by the HVAC system by a total of 16.4% during cold and hot start-ups (**top graph in Fig. 10**), helping to lower fuel consumption by 5.3% (**bottom graph in Fig. 10**).

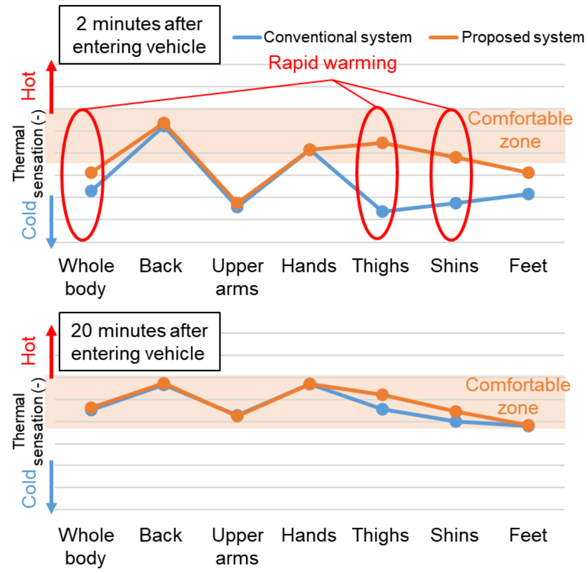

Fig. 9 Comparison of Thermal Sensation between Conventional and Developed Systems

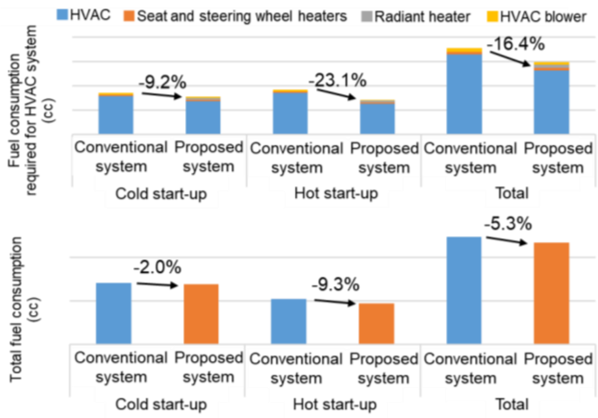

Fig. 10 Fuel Consumption Comparison between Conventional and Developed Systems

5. Conclusion

Focusing on how vehicle occupants perceive warmth at different parts of the body led to the development of a new type of radiative heater that helps to enhance occupant comfort while saving energy. In addition to contributing to carbon neutrality by improving fuel and power consumption efficiency, the developed heater also helps to extend driving range under cold conditions, something that is regarded as a weakness of electrified vehicles and that might help to promote vehicle electrification. In the future, Toyota intends to continue listening closely to its customers to provide ever better products while striving vigorously toward achieving carbon neutrality. Finally, the author would like to take this opportunity to express his sincere gratitude to Denso Corporation and everyone that supported this development for their invaluable contribution to its success.

The JSAE Technological Development Award (74th JSAE Awards)

Proposal of Data-Based Preview Controller for Active Vehicle Suspension

Hiroki Furuta[*1] Jin Hozumi[*2] Shuta Yokota[*1]

1. Introduction

As autonomous vehicles and Mobility as a Service (MaaS) become more widely adopted, demand for better ride comfort and the capability to carry out secondary activities inside the vehicle such as smartphone or computer operation (**Fig. 1**) more easily is likely to increase. As shown in **Fig. 2**, to reduce motion sickness and make such secondary activities easier to carry out, smaller low-frequency (below 1 Hz) body motion and better secondary ride (around 2 to 8 Hz) are required. However, conventional suspension controls used to address road inputs are less capable of reducing vibration and body motion in the frequency bands required for secondary activities due to the accuracy of state value estimation and the effects of phase shifts created by filters. Therefore, with the aim of achieving major improvements in the reduction of vibration in these frequency bands, this article proposes a data-based preview (DBP) controller as a new means of providing feed-forward control for an active vehicle suspension.

Fig. 1 Examples of Secondary Activities inside Vehicle

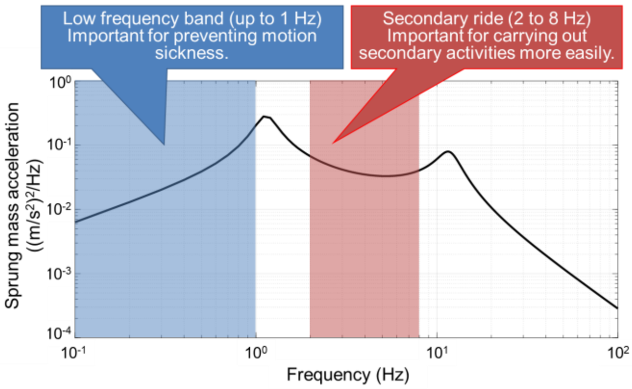

Fig. 2 Power Spectrum Density (PSD) of Sprung Mass Acceleration Calculated by Simulation

2. Outline of Technology

Fig. 3 shows the concept of the DBP controller, which functions by performing the following two steps.

Step 1 involves map generation. In step 1-1, positioning information (e.g., positioning data obtained from satellite signals or the like) and sensor values (e.g., from sprung mass accelerometers and suspension stroke sensors) is acquired from the cloud or elsewhere. In step 1-2, highly accurate unsprung mass vertical displacement values and the like (referred to below as "unsprung mass state values") are estimated from the raw sensor values by offline integration and using zero-phase filters. An unsprung mass state value map is then generated by combining these estimated values with the positioning information.

In step 2, the map generated in step 1 is used to implement the preview control. Highly accurate unsprung mass state values can be estimated by downloading these maps from the cloud or elsewhere and using the positioning information to read the estimated future position map, which has the potential to realize high vibration-reduction performance.

*1 Chassis Development Div. No. 1, Vehicle Development Center
*2 Advanced Mobility System Development Div., Advanced R&D and Engineering Company

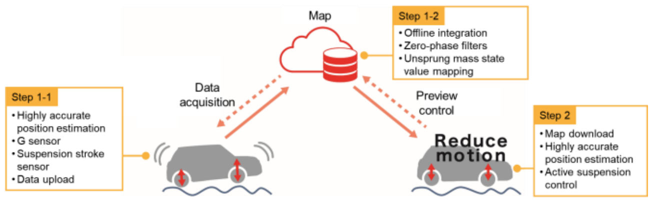

Fig. 3 Outline of DBP Controller

3. Accuracy of State Value Estimation

Fig. 4 shows the system configuration. A cloud-based environment was constructed. Measured data uploading and map data downloading is carried out by LTE/5G communication, and RTK GNSS is used to perform highly accurate position estimation. Using the sprung mass accelerometer and suspension stroke sensor, the unsprung mass displacement is estimated by offline integration and the zero-phase filters. This result is then combined with the positioning information and used to generate the map (in this example, the map is generated in the cloud). In this example, DBP control is carried out during driving by downloading the map data from the cloud based on the positioning information, determining the look-ahead time factoring in the delay of the system and the like, and reading the future position map after the estimated look-ahead time.

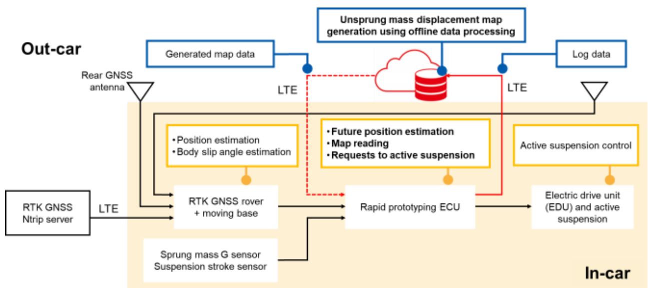

Fig. 4 Configuration of On-Road Testing System

Although the test road surfaces applied different amounts of displacement to the right and left wheels, the displacement applied to the wheels at right angles to the direction of movement remained constant. Consequently, the unsprung mass displacement should demonstrate the same characteristics. **Fig. 5** confirms these characteristics and indicates that the generated map correct reflects the correlation between the unsprung mass displacement and position.

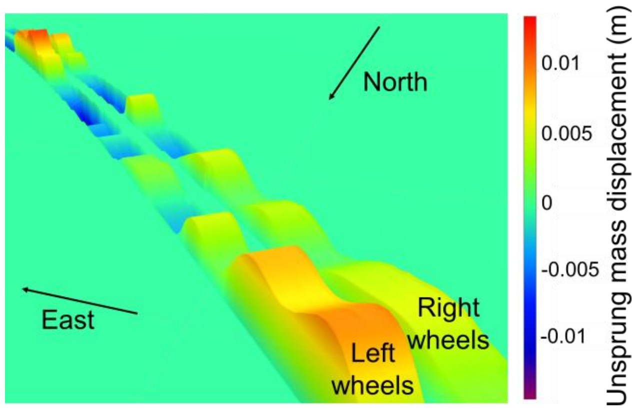

Fig. 5 Contour Chart of Generated Unsprung Mass Displacement Map

Figs. 6 and 7 show the results of state value estimation accuracy confirmation. **Fig. 6** confirms that accurate estimation was possible in the order of millimeters, even with an unsprung mass displacement of approximately ±10 mm. This indicates that the DBP controller is capable of highly accurate state value estimation. In addition, **Fig. 7** shows that a gain of 0 dB and a phase of 0 deg can be achieved in the target frequency band when the system is able to estimate the anticipated unsprung mass state values ideally. Since the actual results are also roughly 0 dB and 0 deg, this confirms that state values processed offline can be used in online controls, which is impossible with conventional systems.

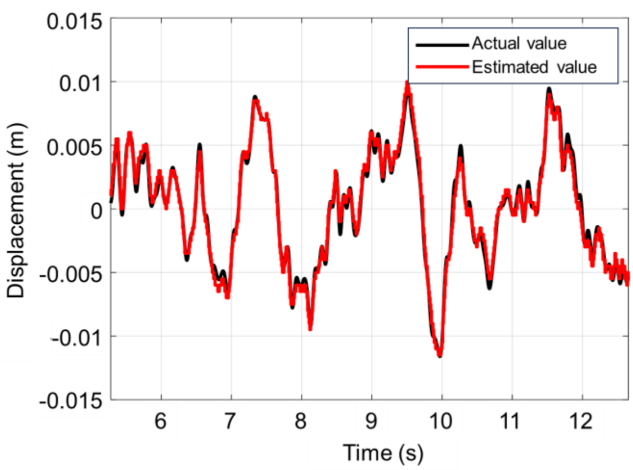

Fig. 6 Unsprung Mass Displacement Time Series

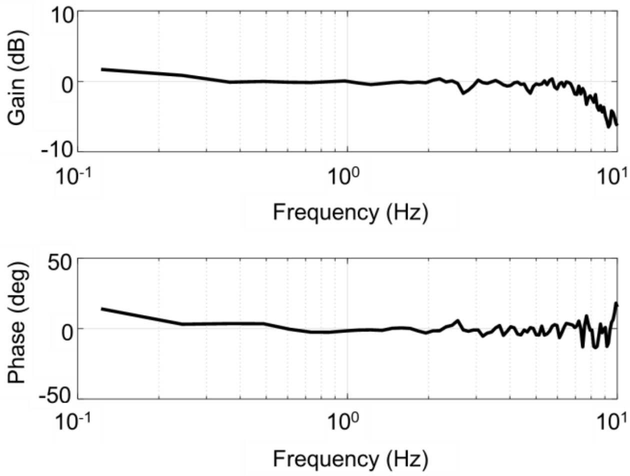

Fig. 7　Transfer Function of Estimated/Actual Unsprung Mass Displacement in Actual Driving

4. Vibration Reduction Performance

Fig. 8 shows the vibration reduction performance of the controller in an actual vehicle. As intended, major improvements in low-frequency body motion and secondary ride were achieved. A control effect in a range between approximately 10 and 20 dB was identified, which is equivalent to a difference of around 2 to 3 ranks as defined by the road surface profiles in ISO 8608. This means, for example, when driving on a class D (poor) surface, the system is capable of suppressing the vibration level to the equivalent of a class A (very good) or class B (good) surface. Consequently, the system is capable of reducing motion sickness and making secondary activities easier to carry out by an amount equivalent to the difference in these road surface classes.

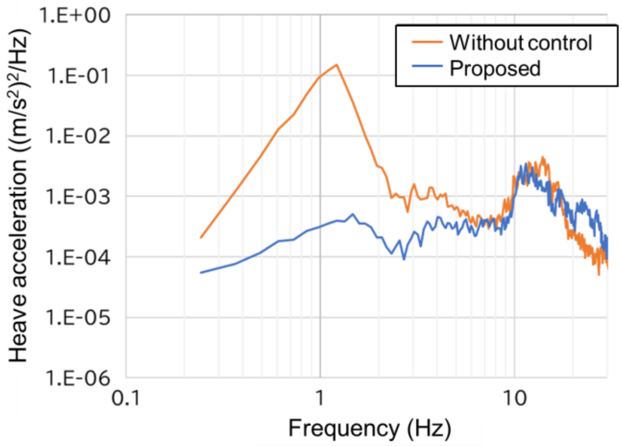

Fig. 8　PSD of Heave Acceleration in Actual Driving

5. Conclusion

This controller transforms the concept of using ideal state values processed offline in online controls, and provides a breakthrough toward resolving the long-running issues of filter phase shifts and state value estimation accuracy. As a result, the developed controller is capable of reducing the vibration encountered when driving over a rough road to the equivalent of a smooth road, an unprecedented level of vibration-suppression performance that helps to improve both motion sickness and the comfort of carrying out secondary activities in the vehicle. Therefore, since this technology enables more effective use of journey times, it has the potential to facilitate the provision of new value capable of transforming the concept of time spent in vehicles as the era of autonomous driving and MaaS arrives.

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IEEE Milestone Certification

The Toyota Prius, the World’s First Mass-Produced Hybrid Vehicle, 1997

1. Introduction

The Institute of Electrical and Electronics Engineers (IEEE), the world’s largest professional association in the field of electrical and electronics engineering, runs the IEEE Milestones program to commemorate significant technical achievements that completed development at least twenty-five years ago. Under this program, the IEEE has decided to honor the first-generation Prius, which debuted in 1997 as the world’s first mass-produced hybrid vehicle (**Figs. 1 and 2**).(1)

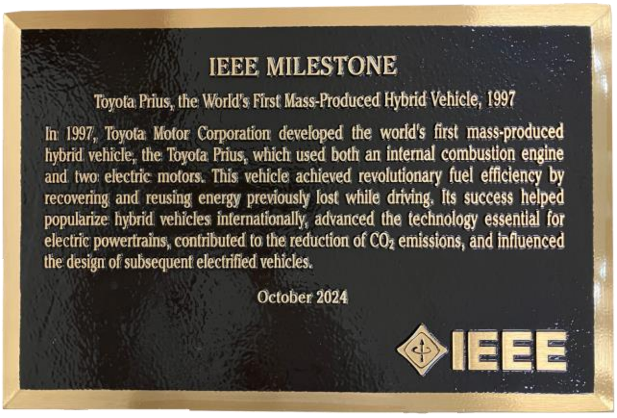

Fig. 1 Plaque Inscribed with the Commemorated Technical Achievements

* Displayed in the lobby of the Toyota Technical Center Headquarters (Toyota City, Aichi Prefecture).

Toyota Prius, the World’s First Mass-Produced Hybrid Vehicle, 1997
In 1997, Toyota Motor Corporation developed the world’s first mass-produced hybrid vehicle, the Toyota Prius, which used both an internal combustion engine and two electric motors. This vehicle achieved revolutionary fuel efficiency by recovering and reusing energy previously lost while driving. Its success helped popularize hybrid vehicles internationally, advanced the technology essential for electric powertrains, contributed to the reduction of CO_2 emissions, and influenced the design of subsequent electrified vehicles.

Fig. 2 Text of Plaque

The IEEE Milestones program was established in 1983. As of October 22, 2024, a total of 283 milestones from around the world had been honored, including the invention of Volta’s electrical battery and Maxwell's Equations. Of these milestones, 48 originated in Japan, including the Tokaido Shinkansen (bullet train) and the Quick Response (QR) Code.(2) This article outlines the significance of the first-generation Prius that was honored by the IEEE and the subsequent developments that this milestone pioneered.

2. The First-Generation Prius

Toyota Motor Corporation pioneered the world’s first mass-produced hybrid propulsion system in the 1997 Toyota Prius, combining both an internal combustion engine and an electric motor for propulsion.(3) At the time, cars powered by ICEs burning fossil fuels were the mainstream of vehicle technology. The hybrid drivetrain of the Prius was developed with the aim of achieving a clear improvement in energy efficiency compared to conventional vehicles, with the objective of addressing the issue of energy resource depletion. To achieve performance improvements outside the scope of that possible with a conventional ICE, the hybrid drivetrain in the Prius combined the advantages of both ICEs and electric motors. Although various types of hybrid systems were proposed at the time, the Prius adopted the series-parallel hybrid system (also known as the split hybrid system), which had the potential to achieve the highest improvement in fuel economy. The developed system featured a number of innovative functions. These included the capability to shut down the ICE and drive the vehicle on motor power alone, thereby allowing the ICE to be used at the most efficient speed ranges, as well as the capability to regenerate energy not used for driving and energy under braking, and storing it in the battery for reuse by the motor to drive the vehicle. As a result, this hybrid system helped the Prius realize fuel economy twice as high as a conventional ICE.

3. Developments since the First-Generation Prius

After the first-generation Prius was released in 1997, Toyota continued to enhance the performance of its basic attributes, resulting in the launch of four subsequent generations of the Prius (the second to the fifth generations),(4)-(7) as well as a wide range of other models equipped with similar hybrid systems. The first-generation Prius was also the foundation of Toyota’s future plug-in hybrid and fuel cell electric vehicles, which used some of the basic elements of the developed hybrid system. Initiated by the Prius, Toyota's total sales of electrified vehicles had reached 27.01 million units by the end of March 2024.[8]

4. Conclusion

Since its debut in 1997, the technologies developed for the first-generation Prius have helped to create a critically important path toward sustainable mobility as awareness of environmental issues has continued to increase. Toyota would like to express its sincere gratitude to IEEE for this great honor.

Toyota intends to continue promoting technological innovation to help achieve a mobility society that is friendly to both people and the environment.

Midori Mori, Naoya Yasuda, Naho Senoo (editor: Midori Mori)
IEEE Milestones Office (R&D and Engineering Management Div.)

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List of Externally Published Papers for the first half of FY2024(From April 2024 to September 2024)

Publication Name	Title	Presenter	Affiliation
Transactions of the Society of Automotive Engineers of Japan	Convergent Construct Validity of Japanese Version of Karolinska Sleepiness Scale Conforming to European Union Law	Yuji Uchiyama Kiyofumi Nakajima	Toyota Central R&D Labs., Inc. Toyota Motor Corporation
	A Feasibility Study for Quantum Computing Methodologies in Automotive Advanced Material Investigation - Application for Functional Carbon Material Screening Problem with Quantum Inspired Methodologies -	Yoshinori Suga Akito Maruo Hideyuki Jippo	Toyota Motor Corporation Fujitsu Limited. (same as above)
	Influence and Countermeasure of Vehicle Electrification on Ride Comfort	Shingo Koumura Makoto Yamakado Masato Abe Masaki Yamamoto Tsuyoshi Yoshimi	Toyota Motor Corporation Kanagawa Institute of Technology (same as above) (same as above) Toyota Motor Corporation
	Development of New Injury Prediction Algorithms for Pedestrians and Cyclists Considering Minor injuries, Serious Injuries and Fatalities	Tetsuya Nishimoto Kosuke Nagai Yasushi Nagaoka Masayuki Shirakawa	Nihon University Nihon University, Graduate School Toyota Motor Corporation (same as above)
	Study of the Growth Forecast of Zinc Whisker in the Market	Jun Muto Yasufumi Shibata Hisao Nishimori Yasuyuki Takai Takashi Tokuda	Toyota Motor Corporation (same as above) (same as above) (same as above) (same as above)
	Traversability Estimation Based on Occupancy Grid for Autonomous Driving in Extreme Environments	Yukiya Fukuda Yuya Mii Yuga Yano Hidenari Iwai Shintaro Inoue Hakaru Tamukoh	Kyushu Institute of Technology, Graduate School (same as above) (same as above) Toyota Motor Corporation (same as above) Kyushu Institute of Technology, Graduate School
	Study on Objective Analysis of Tire Performance in Mud Off-Road and Correspondence between Subjective Evaluation and Objective Evaluation	Koshi Nishikawa Takeo Atsumi	Toyota Motor Corporation (same as above)
	Pressure Pulsation Prediction Model for Control Brake Actuator with Compound Pipeline	Yohei Koike Masashi Komada Masahiro Yano Nobuhiko Yoshioka	Toyota Motor Corporation (same as above) ADVICS CO., LTD. (same as above)
	Development of Non-noble-metal CO_2 Methanation Catalyst -Catalyst Improvement Focusing on Support Effect -	Yusaku Onochi Masahiko Takeuchi Akira Kato	Toyota Motor Corporation (same as above) (same as above)
International Journal of Automotive Engineering (IJAE)	A Study of Estimating Lane-level Traffic Conditions Using Smartphone Data	Yoshiaki Irie Masahiro Mochizuki Hiroaki Asao Junji Nishida	Toyota Motor Corporation Japan Research Institute for Social Systems (same as above) (same as above)
	Study of Dynamic Traffic Management Based on Automated Driving/ADAS with Connected System	Yoshiaki Irie Masahiko Sano Hiroaki Matsunaga Daisuke Akasaka Mototsugu Miura	Toyota Motor Corporation Regional & Transportation Planning Institute, Ltd. (same as above) MathWorks Japan PTV Group Japan Ltd.

Publication Name	Title	Presenter	Affiliation
SAE Technical Paper	Reduced Order Modeling of Engine Coolant Temperature Model in Plug-In Hybrid Electric Vehicles	Tomotaka Sugai	Toyota Motor Corporation
		Kohei Shintani	(same as above)
		Takumu Honda	(same as above)
		Hironobu Sakamoto	(same as above)
		Minoru Tsuchiyama	(same as above)
	The New Toyota 2.4L L4 Turbo Engine with 8AT and 1-Motor Hybrid Electric Powertrains for Midsize Pickup Trucks	Motoshiro Endo	Toyota Motor Corporation
		Alistair Bridge	(same as above)
		Akihiro Ikeda	(same as above)
		Koichi Miyamoto	(same as above)
		Terufumi Miyazaki	(same as above)
		Fuminori Hosoda	(same as above)
		Craig Herring	Toyota Motor North America
		James J. Wallace	(same as above)
		Mu Hu	(same as above)
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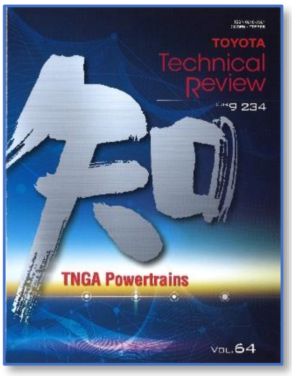

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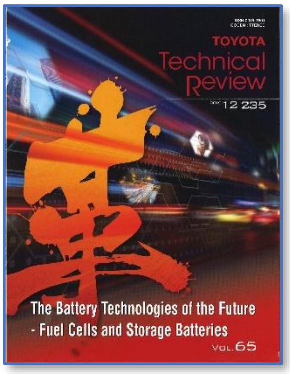

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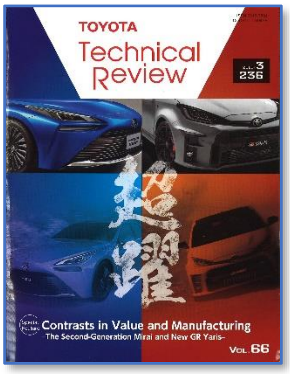

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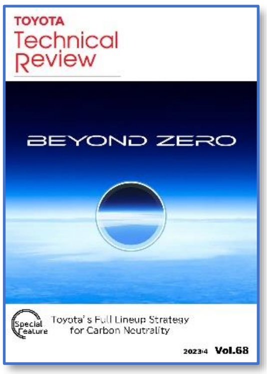

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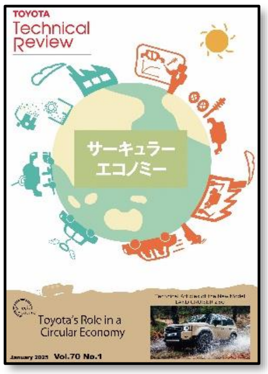

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