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Development of New Fuel Cell System for Mass Production

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Abstract

Regarding electricity and hydrogen as promising means to help resolve issues related to the environment and energy, Toyota Motor Corporation is developing fuel cell vehicles (FCVs) for mass production. This paper describes the developmental approach for a new mass production fuel cell system.

Keywords: PEM fuel cell (proton exchange membrane), passenger car, cost, commercial

1 Introduction

In response to growing concerns about energy issues, global warming, and air pollution, governments, energy corporations, and major automakers in countries such as Germany and Japan recently agreed on a scenario aiming to begin the popularization of fuel cell vehicles (FCVs) from 2015 [1]. Toyota Motor Corporation is developing various environmentally friendly vehicles to meet the needs of a wide range of customers and to help society live in harmony with the global environment. Of these, the FCV has great potential as a clean, efficient, and quiet source of transportation. Then, Toyota was the first automaker in the world to start sales of an FCV on a limited lease basis in December 2002.

Figure 1: Toyota FCHV-adv

Subsequently, after incorporating a number of incremental advances and making progress toward the resolution of the main technical issues of cruising range and cold start capability, lease sales of the FCHV-adv (Fig. 1) began in 2008 [2]-[6]. The key to achieving mass-production of FCVs in 2015 as a viable product is to greatly reduce costs (Fig. 2).

This paper describes the developmental approach for a new mass production fuel cell (FC) system based on the following items:

- Cost factors of FC systems and general cost reduction approach (Section 2)
- Examples of cost reduction activities:
  - Motor system cost reduction activities (Section 3)

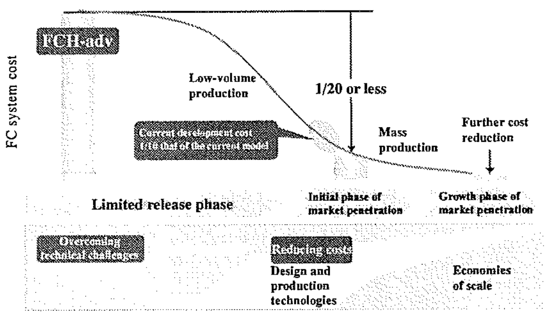

Figure 2: Cost reduction of FC system

- FC system cost reduction activities (Section 5)
- FC stack cost reduction activities (Section 6)

2 Cost Factors of FC Systems and Cost Reduction Approach

Table 1 lists the cost factors of FCVs. These include the small production scale, the complexity of dedicated FCV systems (i.e., the large numbers of parts), and the high cost of special materials required for FCVs. These factors are discussed below.

Table 1: FCV cost analysis

Factor	Countermeasures
1. Small production scale	Carry over mass production parts from other vehicles Carry over production lines from other vehicles Unify mass production specifications between OEMs
2. Complexity of dedicated FCV systems	Consolidate parts Optimize part requirement specifications (market feedback, regulations, etc.) Revise part configurations
3. High cost of special FCV materials	Reduce material amounts Use or develop alternative materials

2.1 Effect of mass-production

Although there may be a certain cost reduction effect from mass production at the initial stage of FCV introduction, establishment of the necessary hydrogen supply infrastructure for ensuring greater market penetration is likely to proceed only gradually in accordance with the spread of FCVs. For this reason, in the initial period, the FCV production volume is unlikely to reach the same level or to achieve the same cost reduction effect as with conventional gasoline vehicles. Therefore, reducing costs with small-scale production remains a critical element.

The main mass-production parts that can be carried over from other vehicles are in the motor system and the systems for operating the fuel cell. The scope of part carryover can have a major cost reduction effect from the standpoints of both components and the production line.

Part carryovers require changing system specifications to match those of the original vehicle. The approach for carrying over parts in the motor system is described in Section 3 (motor system cost reduction activities) below.

Figure 3 shows the system diagram of the Toyota FCHV-adv. Table 2 describes whether similar parts exist in other vehicles and the key requirements for those parts from the standpoint of the feasibility of carrying over mass-production parts for the main component units.

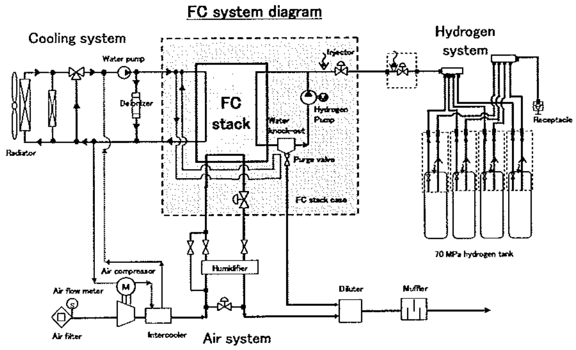

Figure 3: FCHV-adv system diagram

Table 2: Component unit analysis

		Similar part	Key requirements
Air system	Air compressor	Yes	Large flow High pressure
	Humidifier	No	
	Valves	Yes	Freezing resistance
Hydrogen system	Injector	Yes	Large flow
	Hydrogen pump	Yes	Large flow
	Purge valve	Yes	Freezing resistance
Cooling system	Radiator	Yes	Large heat dissipation
	Water pump	Yes	Large flow
	Deionizer	Yes	Wide temperature range

As the table demonstrates, these systems have many similar mass-production parts in other vehicles. However, many cannot be carried over because the requirements for parts to operate the FC stack exceed the usage parameters of the mass-production parts. For example, to carry over the air compressor, the characteristics of the FC would have to be improved to factor in the system part specifications, such as enabling FC operation with low air flow.

2.2 FCV system simplification

Disusing and consolidating parts is the most important aspect of system simplification. For example, although the Toyota FCHV-adv has four high-pressure hydrogen tanks, Section 4 (high-pressure tank system cost reduction activities) describes the study performed with the aim of reducing this number.

Dedicated functions of an FC system, which include external humidification of air and hydrogen circulation, are also potential targets for disuse. Although disusing either of these functions is extremely complex, Section 5 (FC system cost reduction activities) describes the approach toward scrapping the external humidification function.

2.3 Special FCV materials

An FC uses large amounts of high-cost materials, such as a platinum (Pt) catalyst and carbon fiber tanks. As shown in Fig. 4, the Toyota FCHV-adv FC system uses a high proportion of special materials.

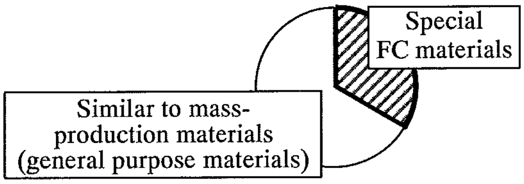

Figure 4: Cost breakdown

The key to reducing the amount of Pt is to improve its effective utilization rate. This issue is being addressed through the development of alloying and core-shell catalysts. In addition, Section 6 (FC stack cost reduction activities) describes how material usage is being reduced by improving the power density of the FC stack.

In addition, a new type of carbon fiber must be developed for the high-pressure hydrogen tanks. This is because the tanks of the Toyota FCHV-adv use high-cost aviation-grade carbon fiber instead of lower cost general-purpose carbon fiber due to the requirements of the tanks.

3 Motor System Cost Reduction Activities

Toyota has introduced the Prius, the world's first mass-production hybrid vehicle (HV), in 1997. Since then, the motor system used in the Toyota Hybrid System (THS) has been incrementally improved to reduce cost and enhance performance. Furthermore, different dedicated motor system were also developed for Toyota's FCVs. Adopting the mass-production motor system used in the THS would enable a substantial reduction in cost.

However, after optimization, the THS motor uses a 650 V high-voltage system compared to the 240 V rated voltage of the Toyota FCHV-adv. Consequently, one issue to be addressed is the voltage inconsistency between the HV and FCV systems. Possible ways of eliminating the voltage gap include boosting the FC output voltage or increasing the number of cell in the FC stack. Figure 5 shows typical FCV motor systems combining high and low motor system voltages with high and low FC voltages. Table 3 shows the merits and demerits of each plan.

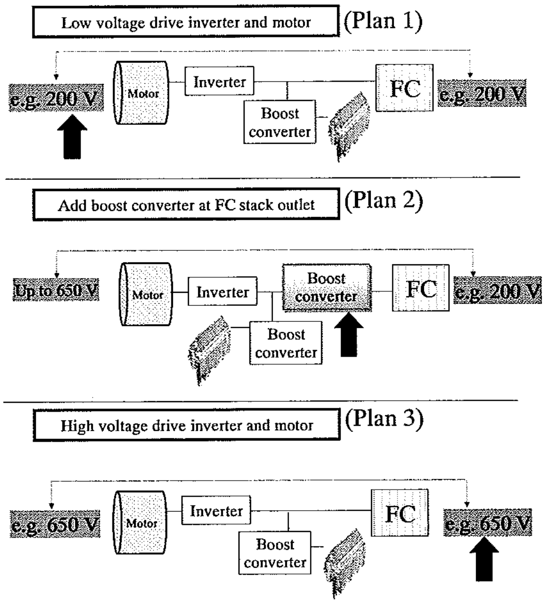

Figure 5: FCV motor systems

Table 3: Motor system characteristics

Plan	Merits	Demerits
1	Low number of FC cells	Requires dedicated FC motor system Losses due to large current
2	Possible to carryover mass-production motor Low number of FC cells Durability Easy to adopt in other models	Requires FC boost converter Losses due to FC boost converter
3	Possible to carryover mass-production motor	High number of FC cells

Of the methods above that allow the mass-produced motor system to be carried over, the plan that uses the FC boost converter is described in more detail below.

In addition to its compatibility with a lower cost mass-produced motor system, this plan also helps to reduce the cost of the FC stack by lowering the number of cells in the FC stack. Qualitatively, a smaller number of cells also helps to improve reliability by lowering the number of sealing portions between the FC cells. In addition, if the voltage of the FC falls over time to below the minimum motor operating voltage, then the load for maintaining the FC voltage will drop, causing the decrease in output to exceed the rate of the FC voltage drop. To counter this issue, Fig. 6 shows how the voltage is boosted to maintain the minimum motor operating voltage. This relaxes the conditions for meeting the targets for durability deterioration.

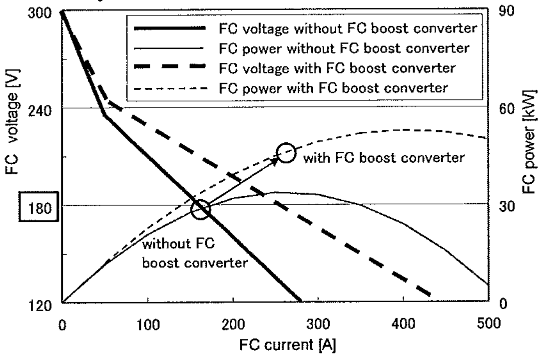

Figure 6: FC power with FC boost converter

This plan also facilitates the future adoption of the system in other models that require different FC outputs because the boost converter can be used to absorb differences between motor systems without having to develop new FC cells. In contrast, the demerits of this system include the need to develop a high-capacity FC boost converter and the energy loss of the converter. This energy loss of the converter can be mitigated by, for example, stopping boost converter switching when the FC voltage is higher than the motor system voltage at light loads with a high usage frequency (Fig. 7), reducing the switching loss of the motor inverter due to the smaller voltage difference between the FC and the motor system (Figs. 7 and 8, highlighted by the vertical arrows). Consequently, it may be possible to reduce the total incremental loss of the system with the FC boost converter to almost zero compared with the system without the FC boost converter.

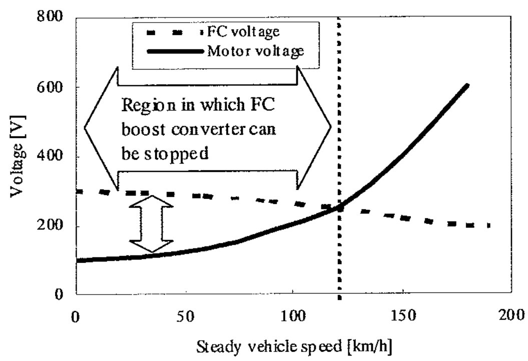

Figure 7: FC and motor voltages (with FC boost converter)

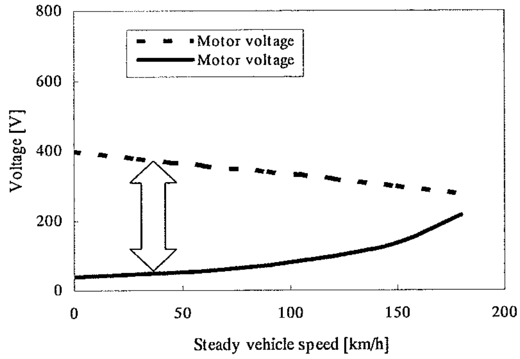

Figure 8: FC and motor voltages (without FC boost converter)

4 High-pressure Tank System Cost Reduction Activities

Cruising range is a critical issue for FCVs. For this reason, the fuel efficiency of the Toyota FCHV-adv was improved by 25% (Fig. 9) compared with the previous 2005 model to achieve a cruising range comparable to conventional gasoline vehicles. The Toyota FCHV-adv also took advantage of its SUV configuration to secure a large enough supply of hydrogen by installing four high-pressure tanks under the floor. However, this number has to be reduced, both to offset the major cost factor of four high-pressure tanks and to allow the FC system to be adopted in a sedan.

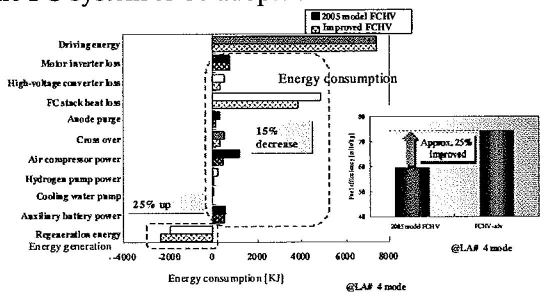

Figure 9: Fuel efficiency of the Toyota FCHV-adv

In addition to helping to improve the global environmental by reducing CO_2 emissions while driving to zero, Toyota is aiming to develop a feasible product without sacrificing the convenience of an EV (such as driveability and quietness) or a vehicle powered by a conventional internal combustion engine (such as practical cruising range and fast refueling). For this reason, a cruising range equal to a gasoline vehicle remains the target.

The key approaches to enable the number of tanks to be reduced are to improve fuel efficiency and to increase the volumetric density of the tanks to enable the vehicle to carry more hydrogen in the limited space.

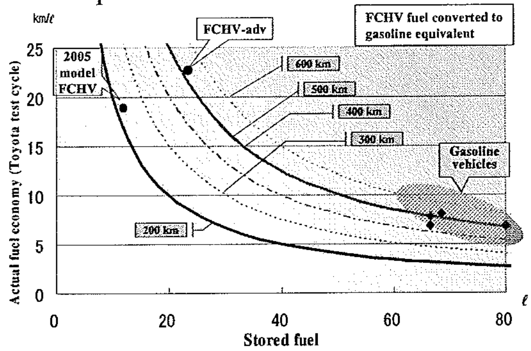

Figure 10: Actual Cruising Range

Fuel efficiency can be improved by making the system more efficient and reducing the load (running resistance). Although the Toyota FCHV-adv has a high energy efficiency of 60%, further improvements are required.

The volumetric density of the high-pressure tanks can be increased by reducing the wall thicknesses of the tanks. Further improvements are being targeted for 2015 (Fig. 11) by optimizing the layered structure (through the adoption of hoop winding and helical winding layering methods).

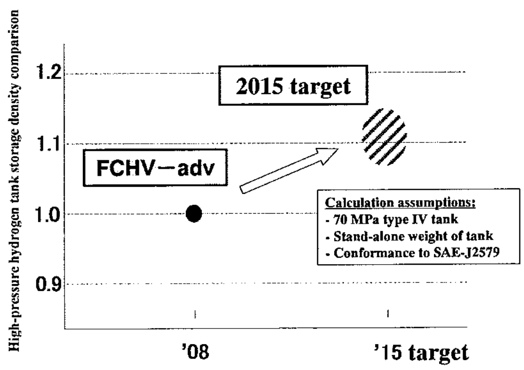

Figure 11: Increasing volumetric density of high-pressure hydrogen tanks

5 FC System Cost Reduction Activities

The polymer electrolyte fuel cell (PEFC) is the most common type of automotive FC. With a PEFC, the air supply must be humidified to prevent a loss of generation performance. For this reason, FC systems are generally provided with a dedicated humidifier that uses a steam exchange membrane. This humidifier is a cost factor (Fig. 3 and Table 2).

In addition, since the maximum operating temperature of a FCV is lower than a gasoline vehicle, a much larger radiator is required to secure the same cooling performance. This is another cost factor and restricts how the vehicle is packaged.

One countermeasure is to develop an FC system that can operate at higher temperatures. However, humidification using a steam exchange membrane becomes difficult if the operating temperature exceeds 100°C. For this reason, Toyota is developing a FC system that can operate without an external humidifier. Since the electrolyte membrane in this system uses a film that requires the same water content as a conventional membrane, it carries out humidification internally by making effective use of the back diffusion of water and water circulation by a hydrogen circulation. Figure 12 shows an example of high-temperature power generation performance. Although performance has been improved with each cell in a steady state, there are still many problems to be resolved from the standpoint of vehicle system operation, including in the FC stack and in transient states.

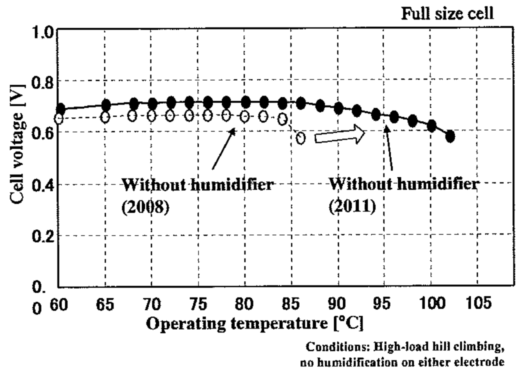

Figure 12: High-temperature power generation characteristics

6 FC Stack Cost Reduction Activities

Generally, the volume of an FCV stack is determined by the power generation portion, which consists of layers of several hundred cells, and the non-power generation portion, which consists of the seals between the cell layers, a surface pressure holding mechanism to maintain the contact resistance of the electrodes at a low level, and materials for insulation. The area of the individual cells and the thickness per cell must be made smaller to reduce the size of the power generation portion. The cell area consists of the electrodes, the manifold that provides the paths for the fluids necessary for power generation (i.e., the fuel, oxidant, and cooling medium), sealing portions, and joints. The cell thickness is determined by the electrodes, the flow field of the fuel and oxidant and the coolant paths either side of the electrodes, and the separator between them. Since the electrodes generally make up a large proportion of the power generation portion, an effective way of developing a smaller fuel cell stack is to reduce the size of this area.

Although the electrode area is set to meet the power required by the vehicle (current × voltage), it can be reduced by improving the voltage characteristics, providing that voltage can be maintained even at high currents. As shown in the example in Fig. 13, if twice the current can be obtained from the same voltage, then the electrode area can be reduced by half. If this can be accomplished, then the amount of catalysts, films, separators, and the like can also be reduced, which leads directly to lower cost and weight. Therefore, the improvement of voltage characteristics is regarded as a critical issue for improving the commercial appeal of fuel cells and research has made advances in this field.

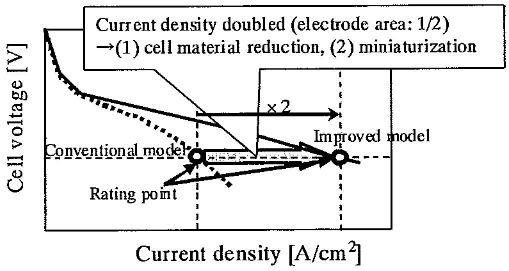

Figure 13: Comparison of IV curves

To improve the voltage characteristics of the FC (i.e., the power generation performance), it is important that the transfer of gases, water, ions, electrons, and heat in the reaction field be carried out with minimal losses. An ideal FC reaction field depends on the following five points: (1) hydrogen and oxygen supply, (2) electron conductivity, (3) generated water drainage, (4) hydrogen ion conductivity, and (5) heat conductivity. Focusing on points (1) to (3) as the most important, Goto et al. [7] [8] visualized and quantified a portion of the reaction field and identified the ideal form from the standpoint of the channel structure. Specifically, for point (1), pressure sensitive paint (PSP) was used to measure the oxygen concentration below the ribs of the flow field (Figs. 14 and 15). Additionally, for point (2), the contact resistance between the catalyst layer and gas diffusion layer (GDL) below the flow field ribs was measured at very fine intervals of approximately 0.1 mm to identify the relationship between contact resistance and the channel widths. Finally, for point (3), the water at the GDL interface was observed to clarify the relationship between the channel width-dependent water collection rate and the limiting current density.

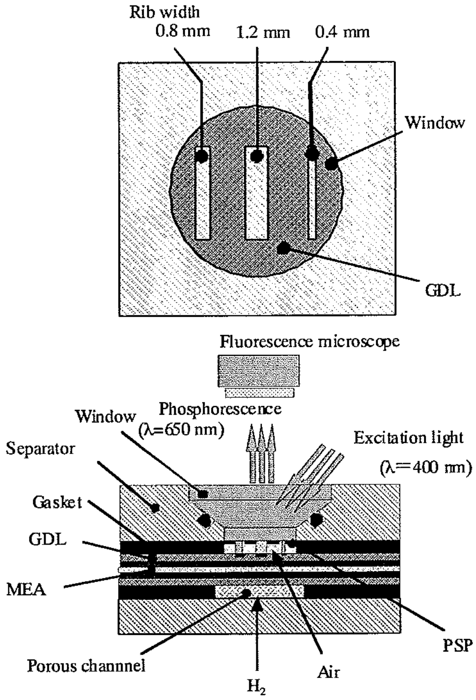

Figure 14: Configuration of PSP measurement

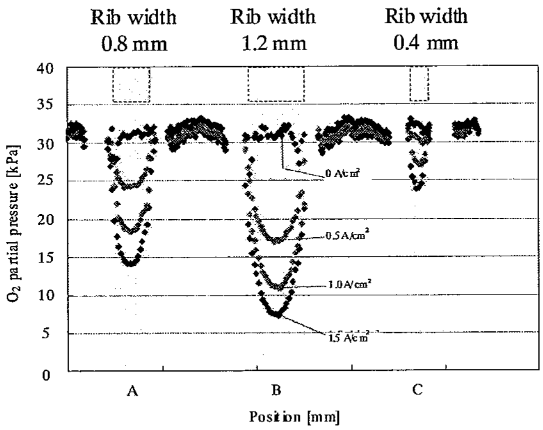

Figure 15: Result of PSP measurement

Based on these results, it was concluded that the ideal reaction field has a porous structure that can be formed by setting the rib intervals to between several 10s and several 100s of μm, approximately one decimal place smaller than conventional flow fields (Fig. 16).

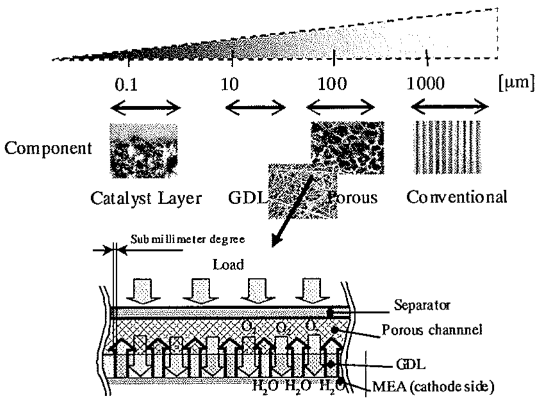

Figure 16: Component pitch of PEFC and schematic of cross-section of cell with porous channel type flow field

Figure 17 shows the power generation performance using several hundred layers of cells with the structure described above. Approximately twice the current can be obtained with the same voltage compared to the conventional flow field type. From an assumption based on the measurement results for cell resistance, roughly 50% of the improvement in current is due to a reduction in resistance. The remaining 50% is due to an improvement in oxygen transportability resulting from improved water drainage.

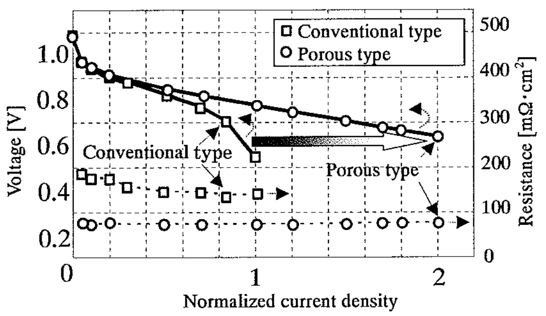

Figure 17: Comparison of polarization curves

7 Conclusion

This paper has introduced various activities to reduce costs, which is one of the most important issues in the development of a mass-produced FC system. Toyota is continuing the development of FCVs as one of the most promising technologies for achieving sustainable mobility and energy diversification. At the same time, it will carry on actively working with governments and related fields toward the establishment of a hydrogen-based society.

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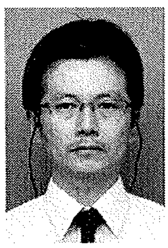

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