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Development of New Hybrid System for Compact Class Vehicles

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Abstract

Toyota has been evolving the hybrid system since introducing the first mass-production hybrid vehicle in 1997 in response to the increasing automotive-related issues of CO_2 emissions, energy security, and urban air pollution. This paper describes a newly developed hybrid system design and its performance. This system was developed with the main purpose to improve fuel consumption, especially for better real world fuel consumption, and to enhance its compatibility with multiple vehicle adoption by downsizing and reducing the weight of its components. At the same time, the hybrid system achieved improved power performance while satisfying stringent emission regulations in the world.

Keywords: HEV(hybrid electric vehicle), powertrain, emissions, vehicle performance, environment

INTRODUCTION

After the industrial revolution in the 19th and 20th centuries, automobiles have greatly contributed to humankind's prosperity, and will continue to be an important factor in sustained development. On the other hand, in order to save energy resources and prevent global warming, there has been a pressing need in recent years to improve the fuel consumption of automobiles, thereby reducing CO_2 emissions. At the same time, urban areas are facing a serious problem of air quality, prompting the enforcement of stricter automobile exhaust emission regulations worldwide. Under these circumstances, the hybrid vehicle draws attention as a system compatible with the improvement of fuel economy and the reduction of exhaust emissions.

Toyota introduced the first mass production hybrid vehicle in 1997 with Toyota Hybrid System (THS). The vehicle achieved 100% fuel economy improvement, met stringent emission regulations around the world, and penetrated into the market as an environmentally friendly vehicle. The Toyota hybrid system was improved in 2003 not only in fuel economy and emissions, but also in power performance. It has had a good reputation in the market.

This paper describes a newly developed hybrid system, its low fuel consumption technologies, and downsizing technology of each powertrain component.

1. OBJECTIVE OF THE DEVELOPMENT

The current hybrid vehicles have achieved the fuel consumption of about half that of conventional vehicles at the drive cycle testing. The Federal Test Procedure mode of the United States, the Urban Driving Cycle (UDC), the Extra Urban Driving Cycle (EUDC) of Europe and 10-15 mode of Japan all simulate urban driving. Improving the urban fuel consumption becomes possible by idle stop, regenerative braking, and EV (Electric Vehicle) drive at low road load; all of which are basic functions of hybrid vehicle. However, it has been noted that hybrid systems do not maintain the same fuel consumption improvement during some real world situations such as high speed driving and during summer and winter. This is because the above-mentioned hybrid vehicle basic functions are not in effect during the high vehicle speeds. During the summer, practical fuel consumption includes the energy needed to run the air conditioner. Finally, idle stop is limited by the coolant heating requirement on the engine during the winter. Toyota's newly developed hybrid system improves not only the vehicle's basic functions; but also practical fuel consumption in high speed running and during winter, two of the hybrid vehicle's weak points.

If hybrid vehicles are to truly surpass the influence on the environment of conventional gasoline and diesel vehicles, their volumes must increase. Therefore, this newly developed hybrid system must be capable of being installed in different vehicle models. The number of components required and the vehicle mass both increase when the hybrid system is installed in a vehicle. This causes design and assembly considerations when installing the powertrain in the engine compartment, a reduction of luggage space, and the need to strengthen the vehicle structure to accommodate the increase in weight. Therefore, the aim of the newly developed hybrid system is to reduce the size and mass of each component. This enables the application of the system into other models, and further improves the fuel consumption by decreasing the mass of the vehicle. Since this system was developed with other vehicle models in mind, it is necessary to think about the adaptability of the system in a vehicle that may be heavier vehicle. Therefore in this new hybrid system, an additional goal was to improve the system output to give a higher level of driving force.

In addition, as the reduction of the tailpipe emissions is a requirement wherever a vehicle with this powertrain may be sold, the new hybrid system was developed to satisfy the stringent emission regulations all over the world. Moreover, it was assumed that the air-fuel ratio of the engine over almost all ranges should be stoichometric, which contributes to the reduction of emissions and CO_2 during real world driving.

Table1 Development targets for the new hybrid system

1. Improvement of fuel consumption (Especially real world driving, high-speed cruising, winter)
2. Applicability for different vehicle models (downsizing, lightweight, enhanced system output)
3. Satisfaction of the most stringent emission regulations

2. DESIGN OF HYBRID SYSTEM

The hybrid system of current model had been improved not only power performance but also fuel consumption by using a boost converter. Next model is based on the current system but almost all components of hybrid system are newly designed in order to improve fuel consumption, power performance and applicability for many vehicle models. Fig.1 shows the new hybrid system. The main difference of the hybrid system between current THSII and new THSII are engine displacement, system voltage and an addition of the motor reduction gear. The system voltage is raised from 500v to 650v in order to reduce the size of motor and improve motor and inverter efficiency because of decreased motor current. As a result a more compact, more efficient hybrid system is realized.

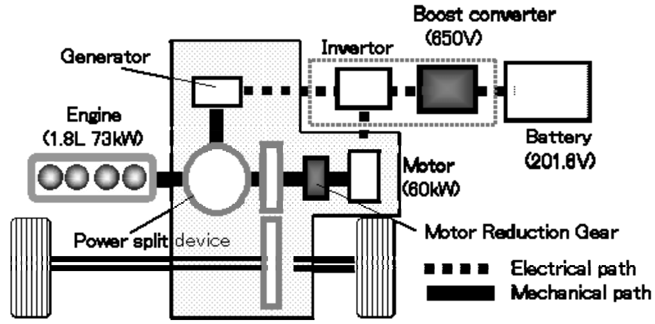


Fig.1 Hybrid System of THSII (new model)

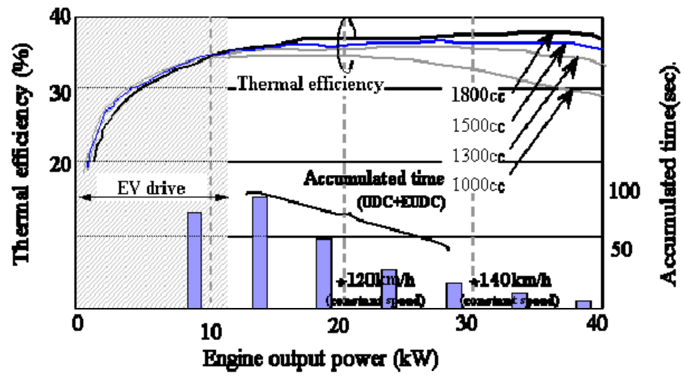


Fig.2 Brake Thermal Efficiency and Displacement

Fig.2 shows a engine thermal efficiency compared to various displacements. The current model has a good performance of fuel consumption especially in the city. To get a good performance not only in the city but also in the real world, engine efficiency in the higher power areas need to be improved. Therefore a 1.8L engine is selected. However, in the low power area, the 1.8L's thermal efficiency is lower than 1.5L's. But THSII has wide EV range. Therefore the disadvantage of large displacement is minimized.

Table2 Specification of the new THSII

		New model	Current model
Engine	Type	1.8L gasoline Atkinson cycle	1.5L gasoline Atkinson cycle
	Max. Output	73 kW	57 kW
	Max. Torque	142 Nm	115 Nm
System Voltage	Max. Voltage	650 V	500 V
Motor/ Transaxle	Type	Synchronous AC motor	←
	Max. Output	60 kW	50 kW
	Max. Torque	207 Nm	400 Nm
	Max. Current	170 Arms	230 Arms
	Max. Speed	13500 rpm	6400 rpm
	Motor Reduction Gear Ratio	2.636	–
	Differential Gear Ratio	3.267	4.113
Battery	Type	Nickel-metal hydride	←
	Max. Output	27 kW	25 kW
	Voltage	201.6 V	←

Table2 shows the specification of the new hybrid components. The output of the every component is higher than current model. As a result this system can be applied in a wide variation of vehicles. The system power is improved by about 14%-20% as fig.3. Therefore this system is applicable for the compact class, as shown in fig.4.

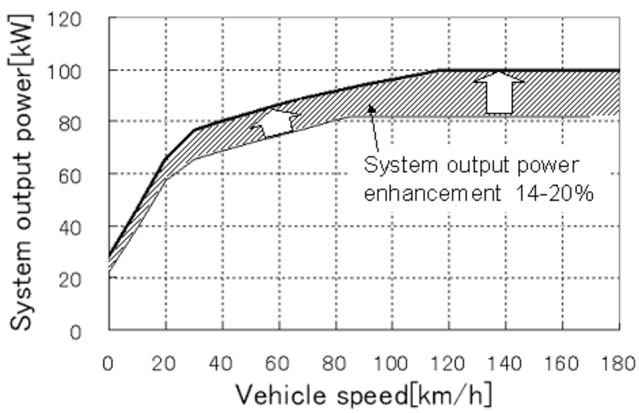


Fig.3 Comparison of system output power

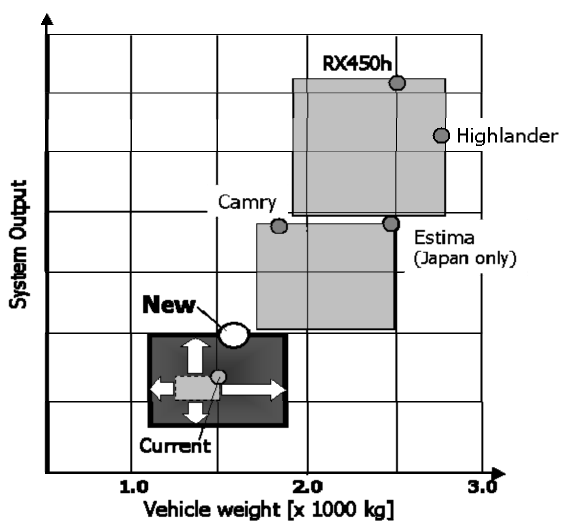


Fig.4 Comparison of system output power

3. FEATURE OF MAIN COMPONENTS

3-1. ENGINE

A 1.8 liter Atkinson cycle engine was developed, which includes a cooled Exhaust Gas Recirculation (EGR) system, an electric water pump, and an exhaust heat recirculation system.

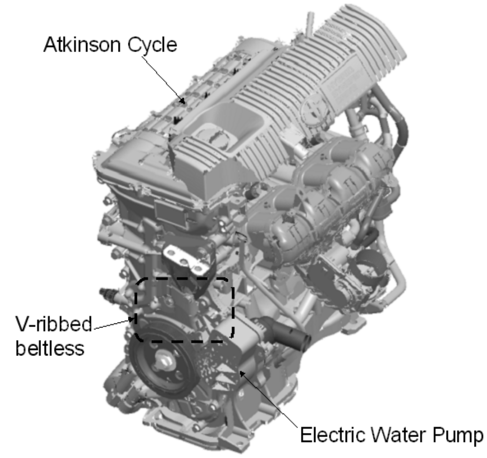


Fig.5 The engines adapted items

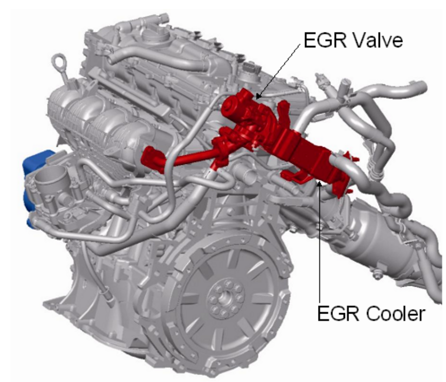


Fig.6 Cooled EGR system

The engine displacement selected was 1.8 liters, enlarged from 1.5 liters in the current system. As a result it became possible to reduce engine revolutions at high-speed cruising, and to reduce heat losses. Fuel consumption at high-speed cruising was reduced by about 10%.

The Atkinson cycle and cooled EGR system reduced the engine cooling heat and exhaust heat losses, thereby improving the engines efficiency. Reduced exhaust heat loss contributes to lower exhaust gas temperatures and all-range stoichometric air fuel ratio. Fig.7 shows the effect of EGR in light load conditions. Pumping losses have a great impact on fuel consumption in these conditions. A large amount of EGR introduction was more effective to reduce pumping loss than advancing the Variable Valve Timing (VVT) to increase the actual compression ratio.

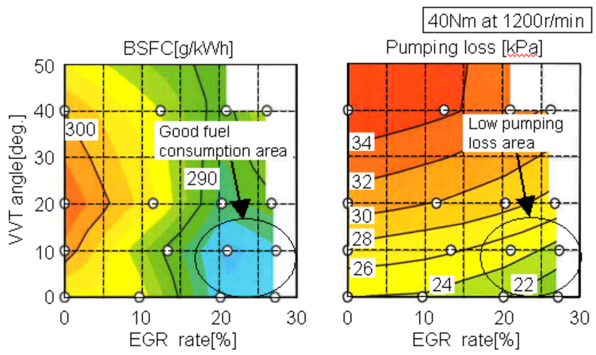


Fig.7 Effect of EGR in light load conditions

The electric water pump and exhaust heat recirculation system were sized to optimize the heat management system, all of which has made it possible to improve fuel consumption and cabin comfort in the winter. The addition of the electric water pump, in conjunction with the elimination of belt-driven air conditioning compressor and power steering pump in the current system, has made it possible to eliminate the V-ribbed belt, with the side effect of contributing to reduced maintenance.

Table3 Advantages for adopting electric water pump

1. Reduction of friction (Elimination of V-ribbed belt and mechanical seals)
2. Power saving of water pump (Reduction of cooling system water flow resistance and optimization of flow rate)
3. Improvement of heater performance (Optimization of flow rate to heater core)
4. Improvement of fuel efficiency (Control of water flow for appropriate temperature and load)
5. Early engine warm-up (Reduction water circulation during engine warm-up)
6. Reduction of maintenance (Elimination of V-ribbed belt)

Fig.8 shows the improvement of fuel consumption by the electric water pump, which is 1–4% on the engine's operating line.

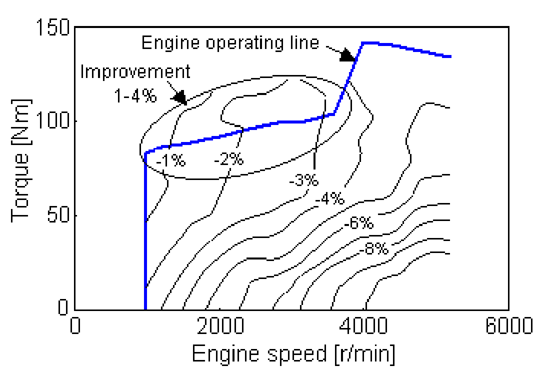


Fig.9 Improvement of fuel consumption by the electric water pump

3-2. TRANSMISSION AND MOTOR

The transmission and motor were newly designed to reduce both size and weight. The transmission adopted a motor speed reduction device and a compound gear. Also the method of coil winding for the generator was changed. As a result, a transmission length and weight reduction of –4% and –20% respectively were achieved.

As shown in Fig.10, the motor speed reduction device was installed between motor and planetary gear to reduce the maximum torque needed from the motor. Additionally, the motor maximum speed was increased to 13,500rpm by adding the reduction gear.

As shown in Fig.11, the compound gear is composed of two ring gears, a counter drive gear and a parking gear. Integrating these four parts produces an extremely compact gear train.

In an effort to reduce the size of the generator, the coil winding method was changed from conventional distributed windings to concentrated windings.

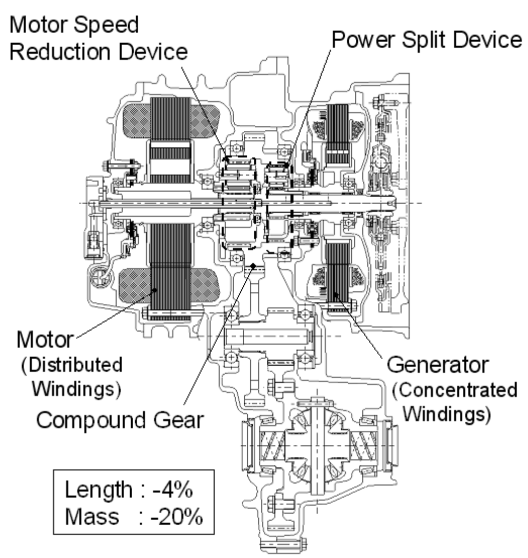


Fig.10 Cross section of transmission and motor

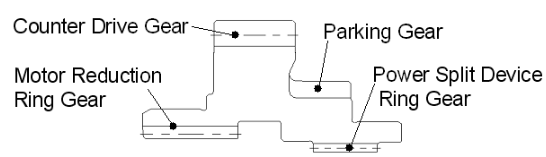
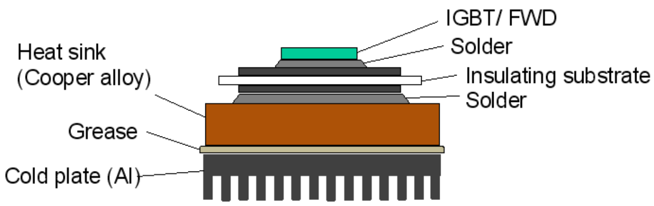


Fig.11 Structure of compound gear

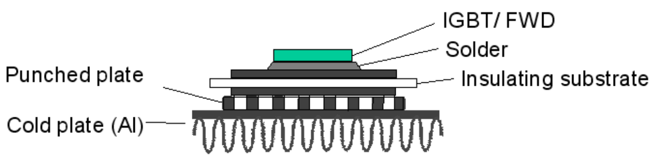
3-3. POWER CONTROL UNIT (INVERTER)

The power control unit was also redesigned to reduce size and weight. As a result, it is 36% lighter and 37% smaller compared to the current unit.

Direct cooling was adopted for cooling the switching device, which is the main component in the inverter. It was possible to eliminate the heat sink and to reduce its size and weight by downsizing the switching device. At the same time, cooling efficiency was improved and electrical losses were reduced. Operating voltage of the motor was enhanced from 500 to 650 volts. The higher voltage enabled the use of a high-speed, high-power of motor with motor speed reduction device. The higher boost voltage leads to improvement of power performance and reduction of electrical losses by decreasing the current.



(a) indirect cooling



(b) direct cooling

Fig.12 Comparison of cooling structure

3-4. BATTERY

The battery pack and its components were redesigned, except for the battery cells themselves. Fig.11 shows the overall newly developed battery pack. The cooling system for the battery cells was optimized while components such as the system main relay, located in the battery pack, were designed to reduce size and weight. The battery cooling duct was downsized as shown in Fig.13. As a result, luggage space was expanded by 6% compared with current model.

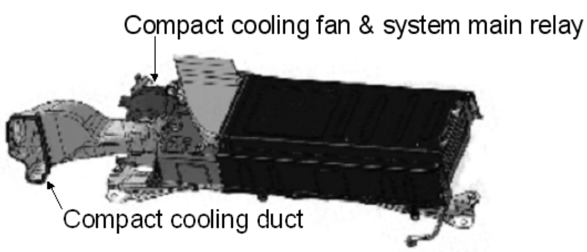


Fig.13 Battery pack (Newly developed)

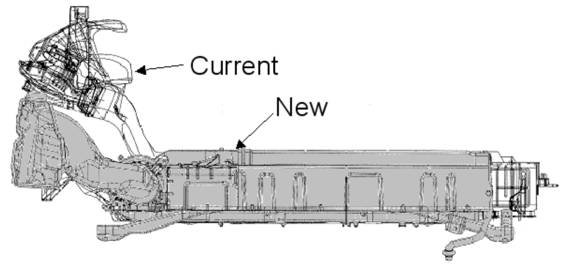


Fig.14 Comparison of battery system from vehicle frontside view

3-5 DOWNSIZING AND WEIGHT REDUCTION OF THE HYBRID SYSTEM

Fig.15 and 16 show the comparison of mass and volume of the total hybrid system. Total system mass (–17%) and volume (–13%) reductions were achieved.

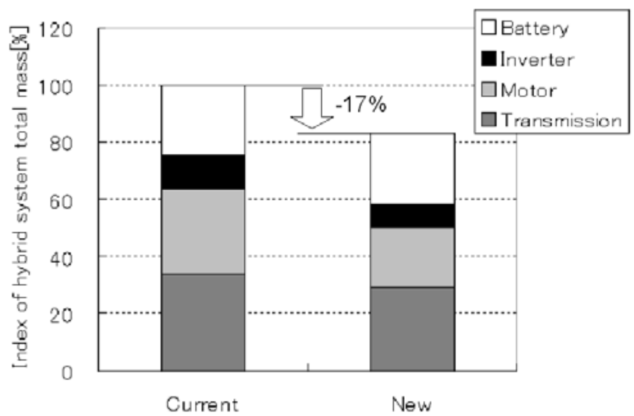


Fig.15 Comparison of the hybrid system total mass

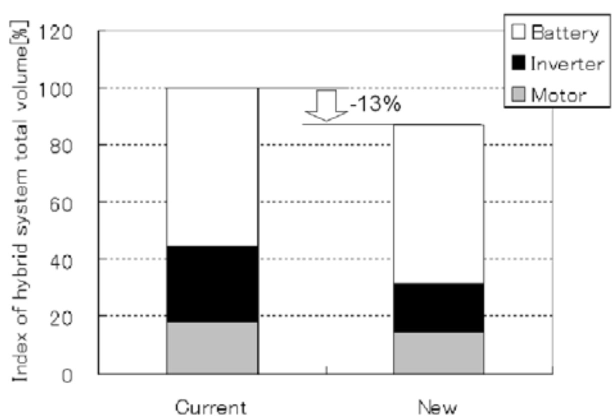


Fig.16 Comparison of the hybrid system total volume

4. VEHICLE PERFORMANCE

4-1. FUEL CONSUMPTION & POWER PERFORMANCE

Table 4 shows the test driving cycle fuel consumption performance of the vehicle with the above mentioned system installed. In spite of total vehicle weight increase, fuel consumption improvements of between 7-14% were accomplished on the test driving cycles of the United States, Europe and Japan. Fig.17 shows each contribution to energy efficiency improvement from current model to new model for the Japanese 10.15 mode.

Table 4 Fuel consumption performance of the vehicle

Test driving cycle	Current model	New model
U.S. Comb. (lavel value)	46mpg	50mpg
UDC+EUDC (Europe)	104g/km	89g/km
10.15 (Japan)	35.5km/L	38.0km/L

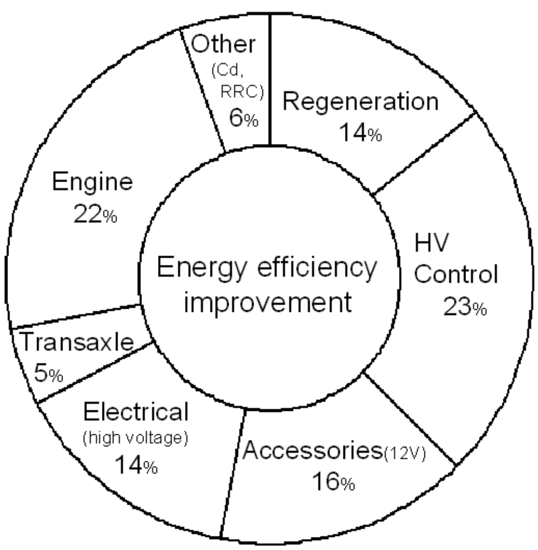


Fig.17 Contribution to energy efficiency at 10.15 mode

In addition, the comparison of high-speed fuel consumption is shown in Fig.18. It shows an improvement of 11-14% compared to the current model. This is because of reduction of engine rpm and heat loss by engine upsizing, and improvement of the vehicle's road load. Moreover, not only the amount of CO_2[g/km] but also the fuel consumption[km/L] in high-speed is better than an equivalent diesel manual transmission car.

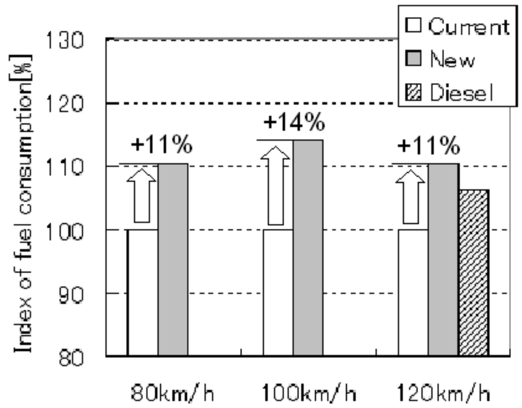


Fig.18 Comparison of high-speed fuel consumption

Fig.19 shows that the improvement of vehicle fuel efficiency in winter with the newly developed hybrid system is about 19% over the current model. This was partially achieved due to the addition of the electric water pump and its control strategy. The electric water pump enabled the pump speed to be reduced relative to the engine speed after cold start-up. The remainder was achieved by the adoption of the exhaust heat recirculation system, as shown in Fig.20. The warm-up performance of engine and engine coolant is improved by usaging the exhaust heat, which is wasted in current models. Fig.21 shows that the engine warm-up time was shortened by about 57% by the exhaust heat recirculation system and the electric water pump.

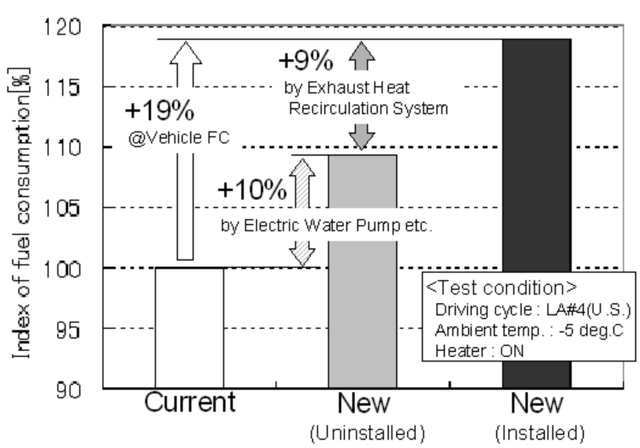


Fig.19 The improvement of vehicle fuel consumption in winter by exhaust heat recirculation system

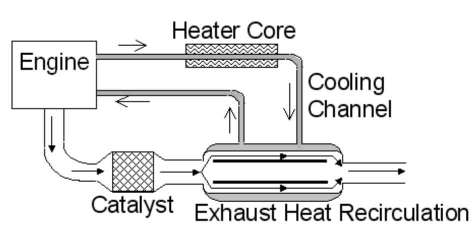


Fig. 20 Exhaust Heat Recirculation system

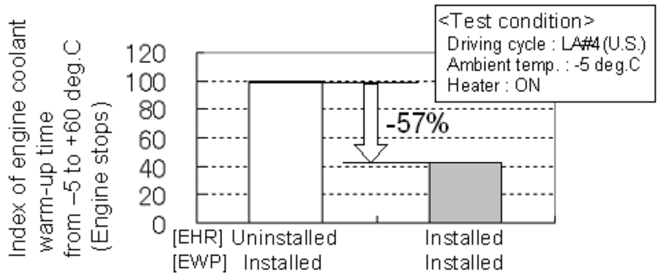


Fig.21 The improvement of the engine warm-up time by exhaust heat recirculation system in newly developed system

Furthermore, the power performance enhancement of 5% is accomplished in this vehicle since the system output power has been increased by 14-20%, so that the hybrid system can be applied to other model vehicles. The power performance is similar to a conventional car, equipped with a 2.4-liter engine, which enhances the customer acceptance of hybrid vehicles.

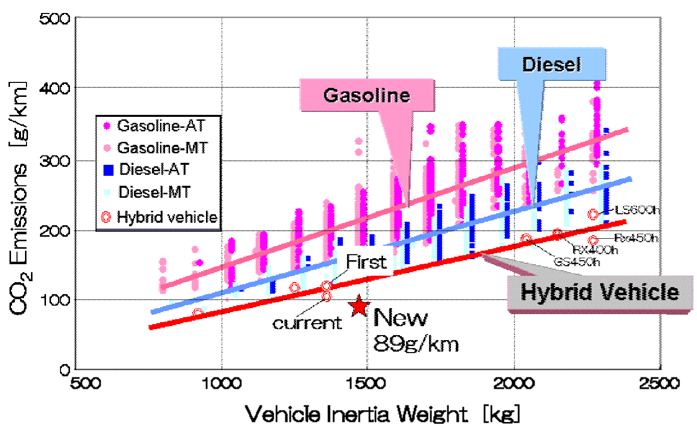


Fig.22 Fuel consumption

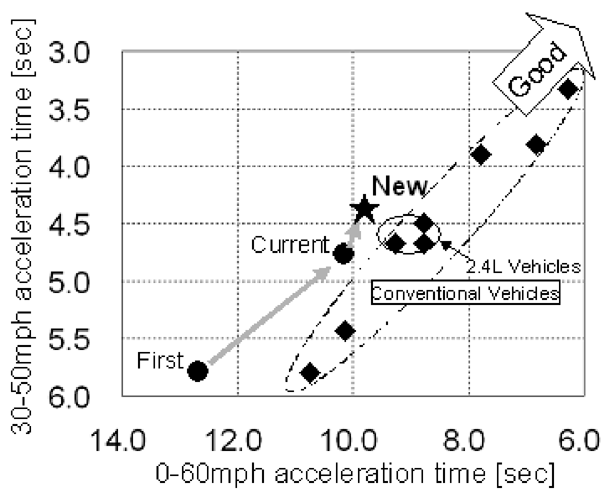


Fig.23 Power performance

4-2. EXHAUST EMISSION

Fig.24 shows the target of emission regulations. Toyota's fundamental policy is to meet whichever emission regulation is most stringent, as was the case the current system. The AT-PZEV regulation of the United States is thought to be the most stringent emission regulation. Fig.25 shows comparison of the current and new developed emission systems corresponding to this regulation.

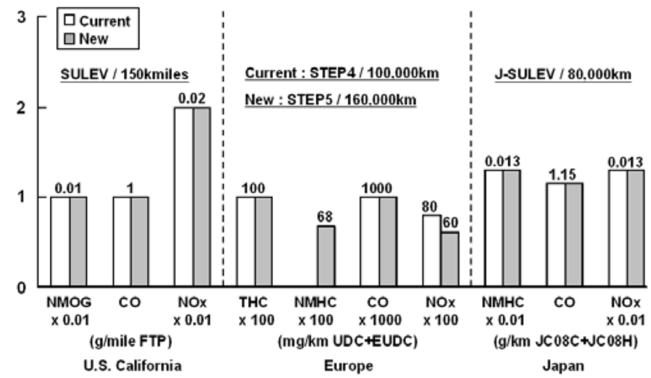
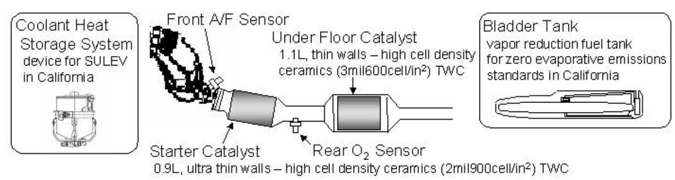
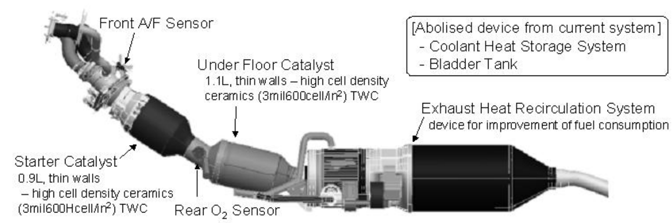


Fig.24 The target of emission standards



(a)Current emission system



(b)New emission system

Fig.25 Comparison of emission system for U.S. model

The current system utilizes an engine/catalyst warm-up strategy, coolant heat storage system, and bladder fuel tank to meet the emission regulations. In the new system, the warm-up control strategy is maintained and exhaust heat recirculation system has been added, but the coolant heat storage system and bladder tank have been abolished. By further optimizing the utilization of electric motor torque to propel the vehicle, while controlling the engine to maximize exhaust temperatures so as to activate the catalytic converter as quickly as possible; the emission control system has been simplified. This leads to higher applicability for other model vehicles.

5. FUTURE PROSPECT

The number of production hybrid vehicles produced by Toyota has exceeded 1,000,000 units since introducing the first mass production hybrid vehicle in 1997. Now the market share of hybrid vehicles is expanding further, synchronized with the worldwide rise of oil price.

From the viewpoint of future energy security, Toyota began a demonstration experiment of plug-in hybrid based on the Toyota hybrid system in 2007. The purpose is to search for the possibility adding enhanced electric-only energy operation to the Toyota hybrid system, which has the ability to correspond to various fuels easily, while maintaining the advantages of a strong hybrid system.

It is thought that the Toyota hybrid system contributes to the solutions of environmental problems that vehicles pose to CO_2 reduction, energy security and emission reduction. Toyota keeps improving the hybrid system to achieve a sustainable automotive society.

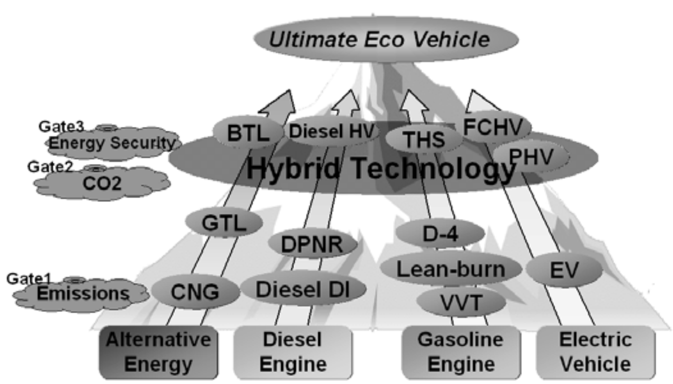


Fig.26 Toyota's approach toward the ultimate Eco-vehicle

CONCLUSION

・The hybrid system was newly designed to improve fuel consumption and applicability to other vehicle models.

・An improvement of about 10% in vehicle fuel consumption, through hybrid component mass reduction, slightly increased engine displacement, and improvements and additions to the overall engine system.

・The Toyota hybrid system is a real solution to the problems that vehicles currently have, and contributes to improving their future prospects.

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