TECHNICAL PAPERS

Development of i MiEV Next-Generation Electric Vehicle (Second Report)

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Abstract

Mitsubishi Motors Corporation (MMC) recently developed the i MiEV-an electric vehicle (EV) utilizing the ultimate eco-friendly zero-emission driving based on the "i" minicar. With the i MiEV, MMC addressed the shortcomings of earlier electric vehicles using revolutionary technologies such as high-performance lithium-ion batteries and compact, high-performance motors. MMC is verifying the i MiEV's real-world practicality by means of on-road running tests.

Key words: *Electric Vehicle (EV), Environment*

1. Introduction

As global warming has become a serious concern in recent years, there is a growing need to reduce the environmental burden caused by energy utilization. In response, in autumn 2006 MMC started to develop an advance test model of its next-generation electric vehicle (i MiEV) using revolutionary technologies such as high-performance lithium-ion batteries and compact high-performance motors, and has carried out various tests. In March 2007, MMC started a joint research project with Tokyo Electric Power Company and Kyushu Electric Power Co., Inc. on marketing the electric vehicle (EV). Together with Chugoku Electric Power Co., Ltd. which joined in June 2007, the project is now testing practical characteristics such as per-charge range and electricity consumption, mainly assuming the EV will be used for commercial applications. Compatibility with the quick chargers currently being developed by various electric power companies is also being tested. During the one year after completion of the advance test model, the project has verified the per-charge range, electricity consumption and charge time of the EV, which are the key issues of EVs. The project has clarified actual performance compared with development targets, and identified new issues with the EV. This paper reports on these results.

2. Issues concerning EVs to date

Ten years have passed since Toyota Motor Corporation started mass-producing the PRIUS, and hybrid .s (HEVs) have been spreading year by year as other manufacturers enter the hybrid market. However, EVs are limited to a very few business and governmental applications, and there are many challenges to be addressed before they can be sold to general consumers.

MMC started developing EVs as early as 1971, when Japan established its first agency governing environmental affairs, the then Environment Agency of Japan, to address air pollution and photochemical smog that were major problems at the time. At the height of Japan's rapid economic growth, EVs were considered the solution to air pollution and automakers competed to develop EVs. MMC started out by developing the MINICA VAN EV and the MINICAB EV under commission by an electric power company and 108 units were delivered.

MMC continued to develop EVs, producing the DELICA EV in 1979 and the MINICA ECONO EV in 1983 in response to the oil crisis and air pollution. In the 1990s, demand grew for protecting the ozone layer and addressing global warming. In this period, MMC developed the LANCER VAN EV and the LIBERO EV, which were delivered to an electric power company. This period also saw a surge in EV development by major automakers seeking to meet the requirements of the California Zero Emission Vehicle (ZEV) Program. Although MMC was not among the automakers designated by the Program and thus had a relatively long time for developing products conforming to the ZEV requirement, the company actively improved its EV technologies, developing in 1998 the FTO-EV which was powered by a large-capacity lithium-ion battery that could cover a much longer distance per charge, followed in 2001 by the ECLIPSE EV (**Fig. 1**).

However, using electricity as the energy source introduces various problems that have prevented automakers' electric vehicles from being marketed widely. The three major problems are: 1) vehicle performance, including too short per-charge range and too long charge time; 2) component technologies, such as the batteries and motors being too heavy, bulky and costly; and 3) battery charging infrastructure.

The per-charge range is no more than 100 km for currently marketed EVs, and even the new types currently being developed by various automakers have a range of only about 160 km. The battery, which determines the performance of the vehicle, is produced in

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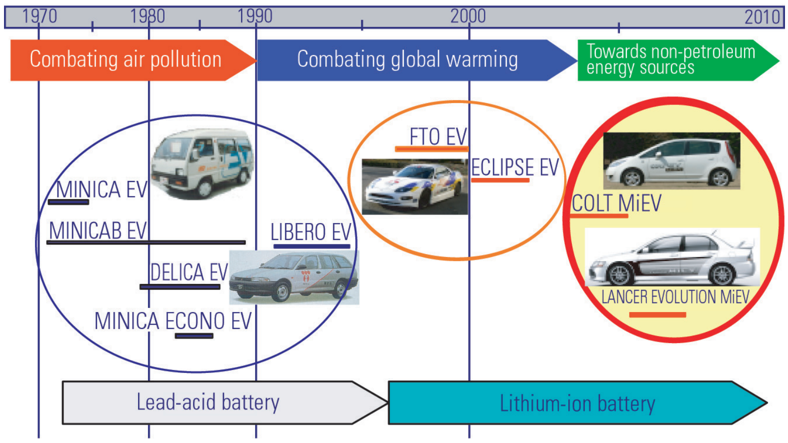


Fig. 1 History of electric vehicle development

Table 1 Overall energy efficiency

Vehicle type	Well to Wheel		
	Well to Tank	Tank to Wheel	Total energy efficiency
EV	Refining, power generation, electricity transmission 43 %*	On-the-vehicle efficiency 67 % (Including charging efficiency of 83 %)	29 %
Diesel engine vehicle	Refining, transportation 88 %	On-the-vehicle efficiency 18 %	16 %
Gasoline HEV	Refining, transportation 82 %	On-the-vehicle efficiency 30 %	25 %
Gasoline engine vehicle		On-the-vehicle efficiency 15 %	12 %

*: The above figures are based on Japan's average composition of energy sources for power generation.

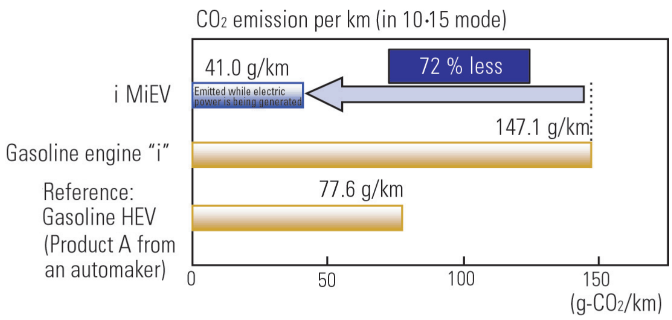
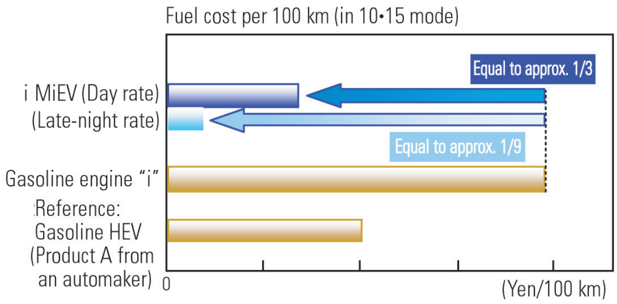


Fig. 2 CO_2 emissions

small quantities and so, like the vehicle, is expensive. The advantage of the battery is that it can be recharged using a household power outlet and no new infrastructure is required. On the other hand, the per-charge range is short, and it takes between four to eight hours to fully charge the battery. For EVs to spread among general users, recharging stations with quick chargers are needed. The EV itself does not emit exhaust gases while it is running and produces little noise and vibration. However, if it uses electricity produced by a thermal power plant, the plant has produced CO_2 in large quantities, causing doubt about the EV's environmental performance.

3. Benefits of EVs

EVs score highly on environmental performance as they emit no exhaust gases during running and provide a route for moving away from fossil fuels. In terms of total energy efficiency, CO_2 emission and energy economy, EVs rank above all other types of powered vehicles in all of these respects. The total energy efficiency data[1] shown in **Table 1** are based on a "well to wheel" analysis (covering the total energy path from fuel production and supply to consumption on the vehicle). Here, the efficiencies of a vehicle's energy sources are compared in terms of the "well to tank" (from fuel production and supply to tank filling) and "tank to wheel" (from tank filling to driving) analyses, which are the two analytic segments of the "well to wheel" analysis. In terms of the "well to tank" segment, the oil refining efficiency is generally estimated to be 82 % for gasoline and 88 % for diesel fuel. As for electricity, the refining efficiency is generally rated at 43 % when based on the average energy source composition in Japan (the refining efficiency varies with the composition of the energy sources used for power generation). Comparing the on-the-vehicle efficiency of the same energy sources in terms of the "tank to wheel" analysis assuming that vehicles are operated in 10·15 mode, the efficiency of gasoline engine vehicles is rated at approximately 15 % and that of gasoline HEVs at 30 %. Diesel engine vehicles show a better on-vehicle energy efficiency than gasoline engine vehicles but are still around only 18 %. In contrast, the on-the-vehicle energy efficiency of EVs is 67 % even when counting the loss during charging; this value is far higher than the other two energy sources. When compared in terms of the overall "well to wheel" analysis, the energy efficiency is rated at 25 % for gasoline HEVs, 16 % for diesel engine vehicles, and 29 % for electric vehicles. The results indicate that EVs are the most energy efficient in total. MMC is now striving to develop EVs that can achieve a total energy efficiency of 32 % by improving their on-the-vehicle energy efficiency. **Fig. 2** compares total CO_2 emission values of vehicles for three types of energy source in terms of "well to wheel" analysis[1]. The EV (i MiEV) produces 72 % less CO_2 than the base gasoline engine vehicle ("i"), and 47 % less than the gasoline HEV now available in the market. Furthermore, EVs emit CO_2 only during electricity generation in the power plant and not while driving. The EV (i MiEV) also outperforms gasoline or diesel fueled internal combustion engine vehi-



• Electricity price (Kanto region):
Day: 22 per kWh (assuming no base rate change)
Late-night : 7 Yen per kWh (excluding base rate)
• Gasoline price: 140 Yen/liter

Fig. 3 Energy economy

Table 2 Major specifications

Overall dimensions (L x W x H) (mm)		3,395 x 1,475 x 1,600
Vehicle weight (kg)		1,080
Seating capacity (persons)		4
Maximum speed (km/h)		130
Per-charge range (10·15 mode) (km)		160*
Motor	Type	Permanent magnet synchronous motor
	Maximum output (kW)	47
	Maximum torque (N·m)	180
Drive system		Rear wheel drive
Batteries	Type	Lithium-ion
	Total voltage (V)	330
	Total wattage (kWh)	16

*: MY 2007 fleet test target value

Fig. 4 i MiEV

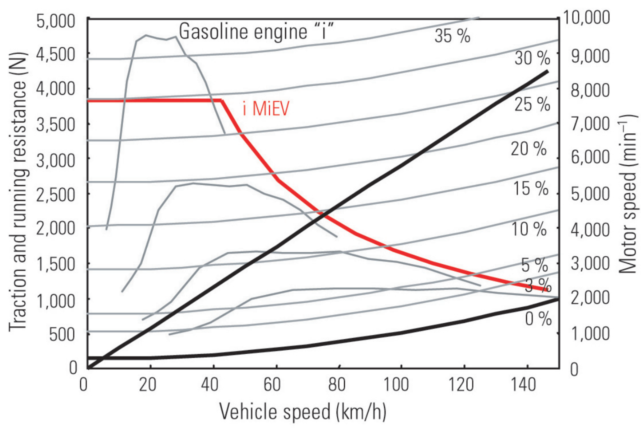


Fig. 5 Running performance curves

cles in both energy economy and fuel cost (**Fig. 3**). To cover a distance of 100 km, the EV costs just 270 Yen, which is approximately one third that of an "i" gasoline engine vehicle. Furthermore, using the late-night electricity billing rate in Japan, the cost falls to only 84 Yen, or 1/9th that of the gasoline engine vehicle.

The i MiEV newly developed by MMC incorporates innovative technologies including lithium-ion batteries and a compact high-performance motor. In the ongoing joint research with electric power companies, MMC is verifying the i MiEV's practicality by means of on-road experimental test (fleet monitoring).

4. Features of the newly developed i MiEV

4.1 Technical features of the i MiEV

The i MiEV (**Fig. 4**) directly inherits the advantages of its base model "i", which means that few modifications were required to turn the base model into an EV. The i MiEV is designed to offer an adequate per-charge range for daily use as well as sufficient power performance for sport-like driving. The major specifications of the i MiEV are listed in **Table 2**.

4.2 Higher power performance than the base model

The i MiEV uses a compact, high-performance, permanent magnet synchronous motor instead of an engine. This motor can deliver the maximum torque even from 0 min^{-1} speed and, unlike internal combustion engine vehicles, can cover the entire range of driving speed without any transmission system. A motor with a maximum output of 47 kW and maximum torque of 180 N·m combined with a reduction gear covers the entire traction performance available from the base model (**Fig. 5**).

4.3 Extended per-charge range

The i MiEV uses lithium-ion batteries as the driving power source. These compact, high-performance batteries have a per-weight energy density at least four times that of conventional lead-acid batteries. Lithium-ion batteries offer excellent output performance because of their internal resistance that stays low irrespective of the level of discharge, thus ensuring stable power performance right down to the discharge limit (**Fig. 6**).

The per-charge range of the i MiEV with the current battery system is 130 km in 10·15 mode. In preparation for the MY2008 fleet test, MMC is improving the running

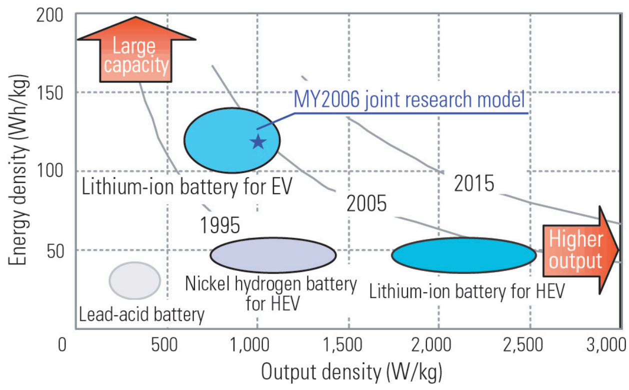


Fig. 6 Lithium-ion batteries

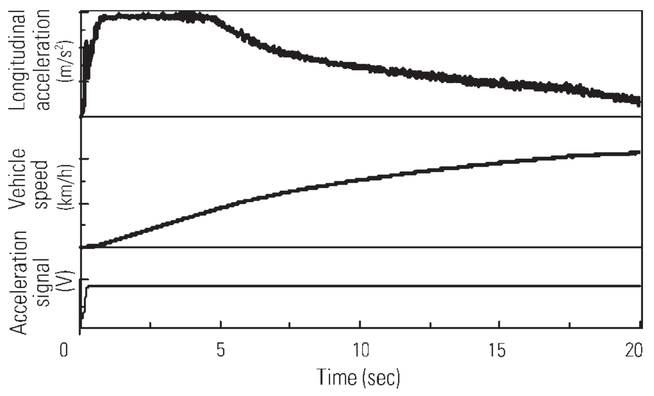


Fig. 7 Dynamic performance (acceleration and speed)

Table 3 Rapid charging and household charging

Type	Power source	Charge time
Quick charge (80 % charge)	3-phase 50 kW/200 V	Within 30 minutes
Household outlet charge (Full charge)	200 V (15 A)	Approx. 7 hours
	100 V (15 A)	Approx. 14 hours

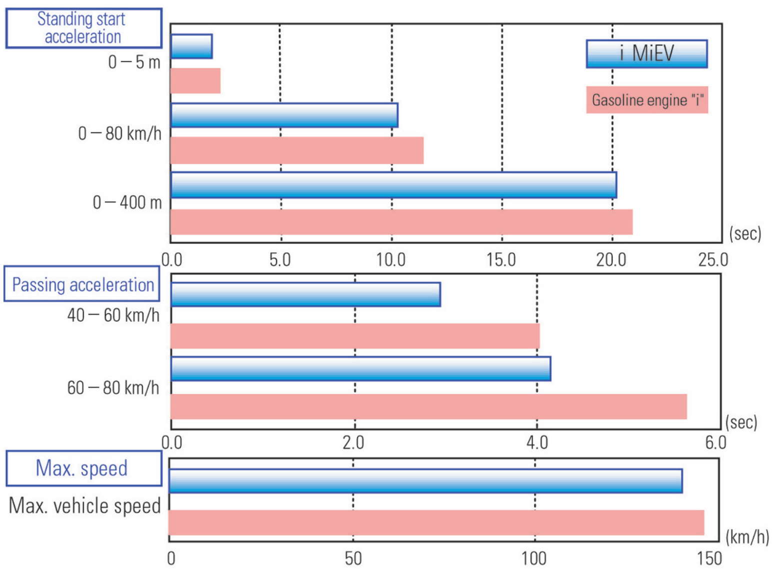


Fig. 8 Test results (dynamic performance)

efficiency as well as the battery performance of the EV aiming at a per-charge range of 160 km.

4.4 Quick charge and normal charge from 100 V/200 V household outlets

The battery system can be charged by either quick charge or normal charge from a 100 V/200 V household outlet for enhanced convenience (**Table 3**). The quick charger is a stand-alone type and can charge the battery to 80 % state of charge (SOC) in 30 minutes, which will be useful for quick charging when away from home. The home charger is an onboard equipment and compatible with both 100 V and 200 V household outlets. It charges the battery system to full SOC in 14 hours when using a 100 V/15 A power source, and in seven hours when using a 200 V/15 A power source. This assumes overnight charging at cheaper late-night electricity rates in a household garage.

5. Results of verification test of the i MiEV

5.1 Power performance

The i MiEV does not have any transmission system; the motor is directly connected to the drive wheels. Since the motor has a high torque response, the driver can accelerate the vehicle immediately after pressing the accelerator pedal even from a standing start and raise the speed continuously to the top speed.

In addition, unlike an internal combustion engine, the motor of the EV can generate the maximum output over a wide range; when the accelerator pedal is fully depressed, the motor's output quickly reaches the maximum power, so the vehicle accelerates quickly, smoothly and powerfully, because the motor is free of the torque interruptions that are common with a gasoline engine due to air intake delay or gear shifting (**Fig. 7**). This advantageous characteristic of the EV becomes more noticeable at higher vehicle speeds. The passing acceleration performance of the i MiEV both from 40 to 60 km/h and from 60 to 80 km/h is 30 % better than that of the gasoline engine model (**Fig. 8**).

These characteristics compensate for the surplus weight over the gasoline engine "i" of the i MiEV, resulting in an even higher performance than a normal gasoline engine vehicle. With high vehicle performance as well as the acceleration feel specific to EVs, the i MiEV offers true driving pleasure.

5.2 Drivability

EVs do not require a transmission, so the drive train from the motor is directly connected to the wheels.

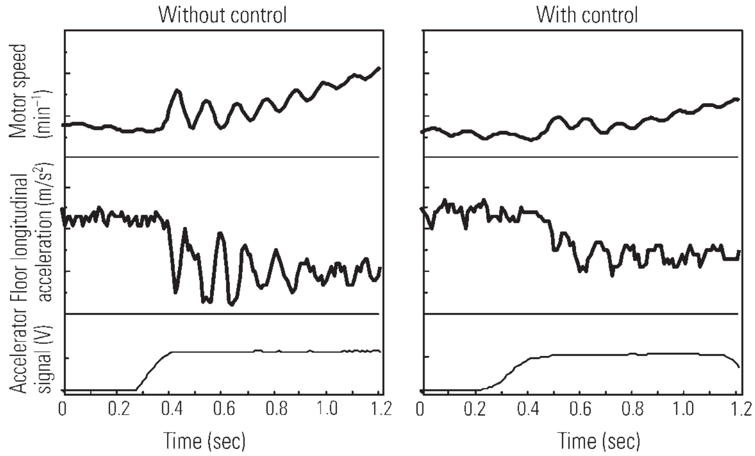


Fig. 9 Driveability improvement

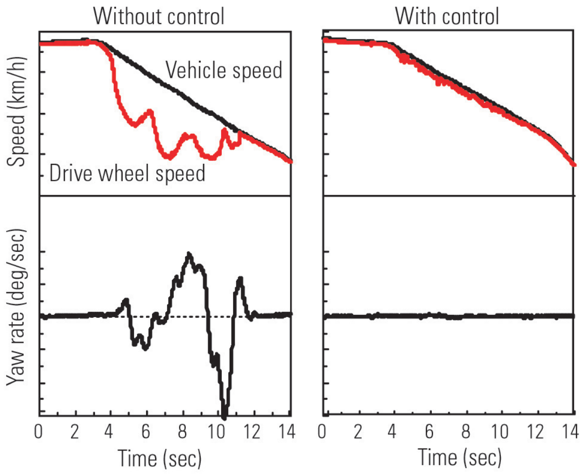


Fig. 10 Vehicle stability

This, together with the output characteristics of the motor, ensures a rapid response to the driver's control. However, this also means that EVs do not have a cushioning medium to absorb torque fluctuations; when the transmission of torque to the body is stopped, the body may resonate, resulting in large shock and vibration. This is also true with the i MiEV. When the motor operation switches from the regeneration to drive phase, the direction of the torque is reversed. This releases the twist energy that has been absorbed in the motor mounting and drive shaft and then these components reabsorb the twist energy now acting in the reverse direction. The resulting momentary interruption of torque transmission at this point constitutes a vibration source. Without any protection, the generated shock would cause the body to resonate and vibrate. In the i MiEV, the torque from the motor is controlled during the changeover from the regeneration to drive phase in order to mitigate shock, and also phase control is used to rapidly dampen vibration. This produces a smooth acceleration feel without spoiling the rapid response that is characteristic of the motor (**Fig. 9**).

5.3 Vehicle stability

The i MiEV is a rear-wheel-drive vehicle, so if the drive wheels spin during acceleration, the body posture may become unstable. To prevent this, traction control using the rapid response of the motor is applied to the drive wheels to ensure stability and standing start performance. The traction control is also used to prevent unstable vehicle body posture during regeneration. Regenerating energy during deceleration is a feature specific to EVs, not available with gasoline engine vehicles. However, the vehicle body could become unstable on a surface with a low coefficient of friction (μ) if the braking effect resulting from regeneration is great. The traction control ensures that the vehicle remains stable from acceleration to deceleration (**Fig. 10**).

5.4 Power consumption and per-charge range

The electricity consumption and effect of the running environment on consumption were investigated by driving the i MiEV on specified general roads in addition to performing a 10·15 mode driving test. Two courses were selected for electricity consumption evaluation: an urban course and a mountainous road

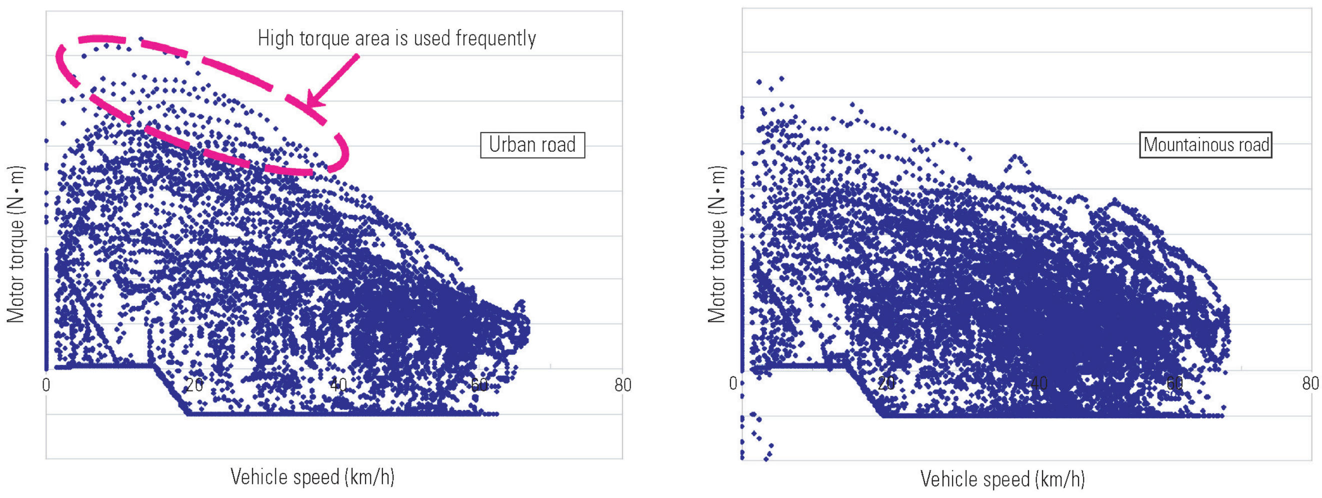


Fig. 11 Torque range differences due to running conditions

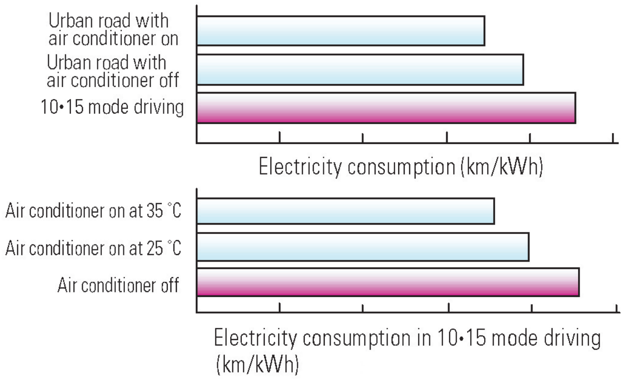


Fig. 12 Power consumption in typical conditions

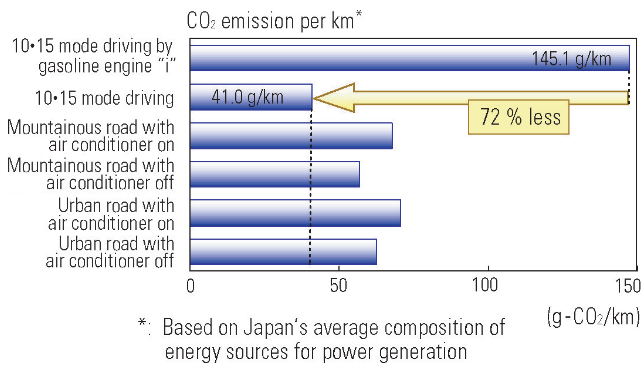


Fig. 13 CO_2 emissions in typical running conditions

course. The result of the running test on the urban course showed that the electricity consumption was increased by about 14 % on average compared with the 10·15 mode driving because of the traffic situation specific to the course such as frequent stopping and starting caused by congestion and traffic lights, but that a distance of at least 80 km could be covered per charge. On the running test on the mountainous road, the driving conditions were severer than those in the urban area with acceleration and deceleration due to slopes and curves, but the overall electricity consumption was less than that on the urban road because there was less stopping and starting at traffic lights (**Fig. 11**).

Next, the vehicle was driven in midsummer on an urban course with the air conditioner turned on and with it turned off, and the difference in electricity consumption between the two cases was studied. The increase in electricity consumption due to the use of the air conditioner was between 15 and 25 %. From this result, the typical per-charge range in urban areas should be between about 70 and 90 km (**Fig. 12**).

The average distance traveled per day by an average passenger car driver is approximately 30 km, so it has been confirmed that the i MiEV can satisfy typical usage patterns for daily life.

5.5 Effectiveness in reducing CO_2 emissions

The per-kilometer CO_2 emission involved in battery charging was calculated from the average values of electricity consumption obtained from the urban road and mountainous road tests (**Fig. 13**). In calculating the amount of CO_2 emitted, the proportions of the power generation methods (atomic power, thermal power, wind power, etc.) were estimated from Japan's average composition of energy sources for power generation announced at the JHFC* seminar. Including the cases where the air conditioner is not used, driving the i MiEV on urban and mountainous roads emits more CO_2 than 10·15 mode driving, but the CO_2 emission of the i MiEV is far smaller than that of the gasoline engine "i", showing that the EV has high environmental performance.

*: Japan Hydrogen & Fuel Cell Demonstration Project

5.6 Energy efficiency

The energy efficiency of the i MiEV in terms of battery charging cost was calculated from the per-100 km average electricity consumption obtained from the urban and mountainous road tests (**Fig. 14**). The elec-

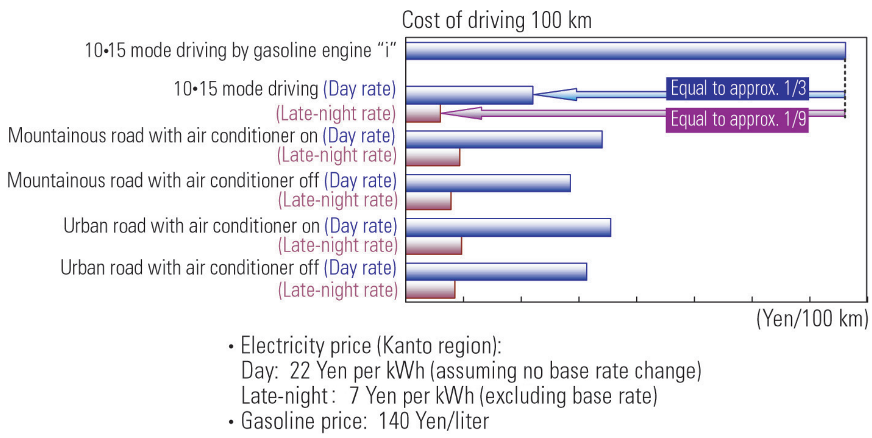


Fig. 14 Energy economy in typical running conditions

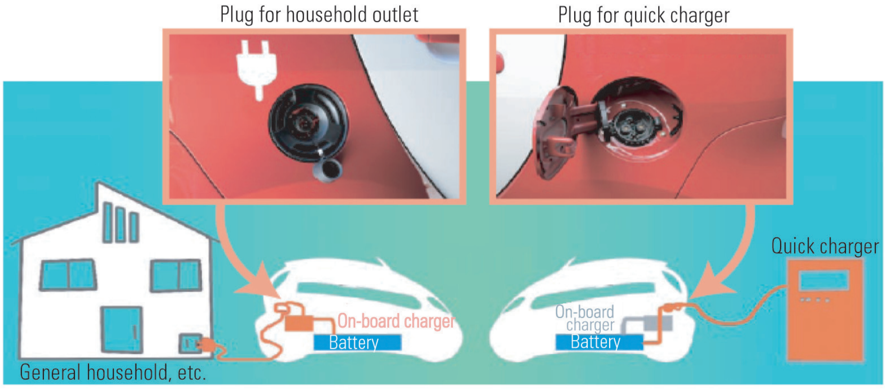


Fig. 15 Charging systems

tricity prices used in the calculation are shown below the figure but in reality, each power company has its own electricity price plans and may levy a special basic charge as part of the late-night use charge. Although the energy efficiency in both the urban road and mountainous road driving is inferior to the 10·15 mode driving regardless of whether the air conditioner is used, the i MiEV offers significantly better economy than the gasoline engine "i".

5.7 Quick charge and normal charge from household outlets

The quick charger is a stand-alone type. It is connected to the dedicated quick charger plug on the i MiEV, and exchanges data with the i MiEV via a dedicated communication line in order to control charging according to commands from the i MiEV. The 100 V/200 V charger for normal charging from a household outlet is an on-board device. When the on-board charger plug is connected to a household power outlet, the charger automatically distinguishes between 100 V and 200 V before it starts charging (**Fig. 15**).

A charging test with the quick charger was performed on the i MiEV. Quick charging is con-

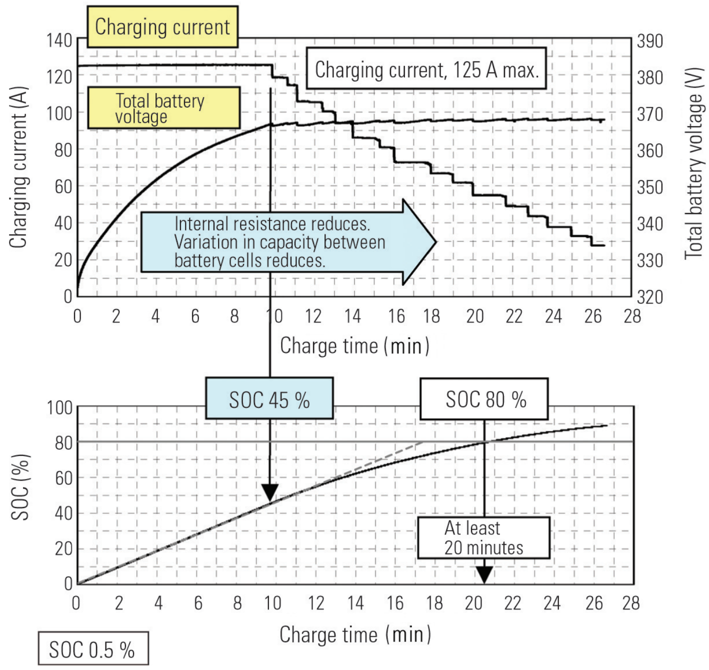


Fig. 16 Results of rapid charging test

trolled such that constant-current charging at a maximum of 125 A takes place as soon as charging starts, and when the voltage of the driving battery system reaches the specified value, the charging mode switches over to constant-voltage charging. When this is expressed using the state of charge (SOC), the constant-current charging initially takes place until approximately 45 % SOC is reached, and then constant voltage charging follows. It takes just 20 minutes to quick-charge the battery system to 80 % SOC (**Fig. 16**).

A test of normal charging from a 100 V/200 V household outlet was also performed on the i MiEV. Normal charging is controlled such that it begins with constant-power charging to ensure that the power capacity of the household outlet is not exceeded and when the voltage of the driving battery system reaches the preset value, constant voltage charging follows. The initial constant-power charging takes place at approximately 6 A and 2 kW for a household outlet of 200 V, and at approximately 3 A and 1 kW for a household outlet of 100 V. The charging mode then shifts to constant voltage charging late in the charging process. The normal charging takes about 6 hours with 200 V, and about 16 hours with 100 V (**Figs. 17** and **18**).

In the case of normal charging from household outlets, the charge time may be longer because of the larger proportion of power consumed by a vehicle's accessory loads.

Although the battery charge time is one inherent disadvantage of EVs, the i MiEV uses compact, high-performance lithium-ion batteries for the driving battery system to shorten the charging time. For the future development of EVs, it is important to improve the convenience, including building battery charging infrastructure, to enable the battery to be charged easily at any time, anywhere and by anyone.

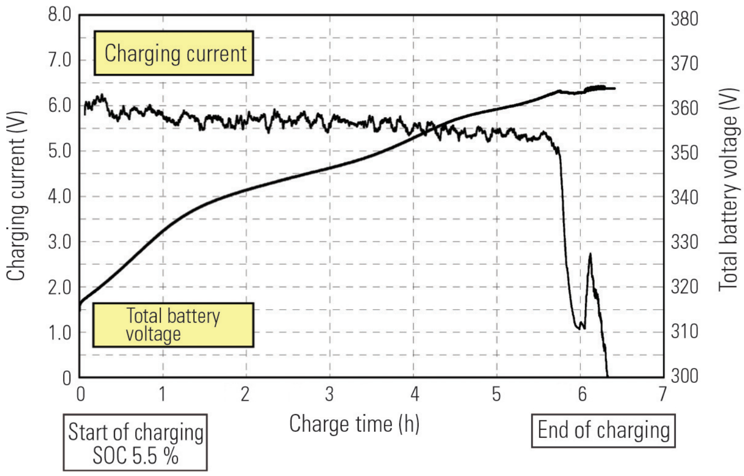


Fig. 17 Results of household 200 V charging test

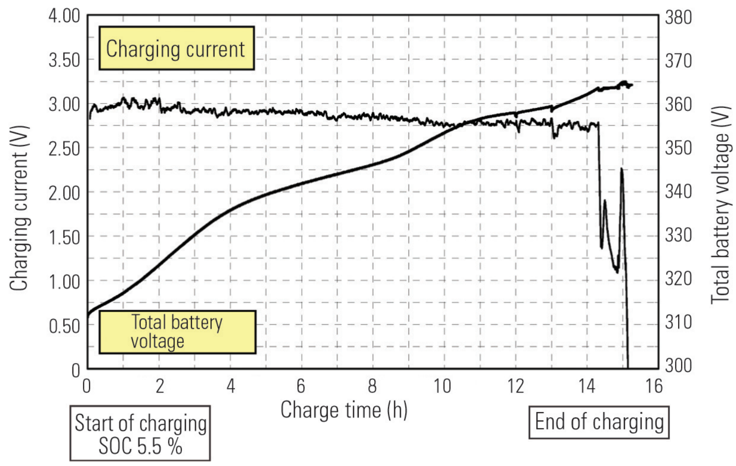


Fig. 18 Results of household 100 V charging test

6. Conclusion

EVs have seen two booms in the past. The current boom is the third one and started 10 years after the second boom. As a result of technical innovations during the last decade, EVs now offer almost practical running performance and per-charge range. Also, general users are becoming increasingly interested in the environment rather than focusing on vehicle performance, due to rising public awareness of the environment and the recent rise in oil prices. Although various challenges remain for the practical use of EVs, MMC will address these and improve the i MiEV to the level where EVs can be widely used as the ultimate eco-car by general users.

Reference

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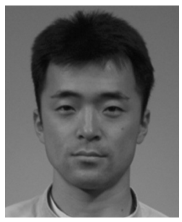
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