Development of High-Performance Electric Vehicle "Eliica"

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A new electric vehicle named the "Eliica" was developed. As element technologies, a lithium-ion battery, permanent magnet type motor, and inverter with IGBT were applied. As new body component technologies, in-wheel motors, a component built-in frame, and tandem wheel suspension were invented. Although the Eliica is a five-passenger sedan, it recorded a maximum vehicle speed of 370 km/h and an acceleration time of 7.0 seconds from zero to 160 km/h.

***Key Words**: electric vehicle, environment, in-wheel motor, lithium-ion battery, Tokyo Motor Show, challenges for driveline, outer ring rotation hub-bearing*

1. Introduction

Global warming has become a serious issue that demands the attention of society.

Global warming is caused by carbon dioxide emissions, and vehicles account for approximately 20% of all such emissions. Moreover, vehicles are the major source of air polluting substances.

Because of this, numerous projects have been carried out around the world to develop hybrid vehicles, fuel cell vehicles, and battery-powered vehicles as replacements for conventional internal combustion engine vehicles.

Of these, the hybrid vehicle has already been commercialized and mass-produced. In the case of a hybrid vehicle, a motor-assist function is added to the conventional internal combustion engine as a means of reducing energy consumption.

It would be more precise to call a fuel cell vehicle than electric vehicle whose power source is a fuel cell. Around 2000, there was a boom in the development of fuel cell vehicles that was triggered by Daimler Chrysler's capital participation in the Canadian company Ballard beginning in 1996.

Cars using a secondary battery as the power source have been called "electric vehicles." Although these vehicles have a long history, commercialization thereof has not yet been achieved. However, in the New Sunshine Project instituted in 2000 by the Ministry of Economy and Industry, Japan, a large sized lithium-ion (Li-ion) battery was successfully developed, and because this new battery has promise for electric vehicles, the potential of electric vehicles once again has been magnified.

Of these electric vehicles, the author and his team have been convinced that Li-ion battery powered electric vehicles have an extremely high possibility of practical use in the future, not only because of the lightness of the burden they place on the environment but also because they enable the adding of new features to the vehicle. In an attempt to prove this, the first prototype Li-ion battery-powered automobile, the "KAZ," was developed in 2002. Subsequently, another prototype, the "Eliica" was developed based on the basic concept of the KAZ but with additional features to make it more practicable. This name, an acronym of "Electric Lithium-Ion Battery Car," is meant to convey a new image of electric vehicle having completely different functions than conventional electric vehicles.

The Eliica Project was a collaborative project participated in 38 companies including Koyo Seiko Co., Ltd.

This paper introduces the development target, basic technology, and development process of the Eliica.

2. Development Target of Eliica

The author and his team have so far been involved in the development of eight electric vehicles. Our goal has been to develop an electric vehicle that in the future will find widespread use in society.

In the initial stage of development, it was believed that an environmentally friendly car would be accepted by society as long as its performance was comparable to that of conventional internal combustion engine vehicles. Based on this belief, initial development efforts were focused on achieving such equivalent performance. In 1991 one of our team participated in the IZA project, organized around Tokyo Electric Power Company. At that time, the project's electric vehicle was improved to the extent that internal combustion engine vehicles would not outperform it. Nevertheless, the result of the IZA project was not sufficient enough to have an impact on society.

Discussion on the reasons resulted in the conclusion that society would not accept a new product that didn't have new features.

In order to create such new features, we recognized that the vehicle body structure should be different from that of conventional internal combustion engine vehicles. With this rationale, we started the development of other electric vehicles following the IZA. We arrived at the concept of an integrated platform and incorporated it in the KAZ, which was completed in 2002.

As shown in **Fig. 1**, this concept consists of the following components: (1) in-wheel motors, or motors housed in the wheels; (2) a component built-in frame, which has a hollow frame structure under the floor with the batteries and other major components housed therein; and (3) tandem wheel suspension, wherein each large wheel has been replaced with two smaller wheels so that the force from the ground acting on the wheel can be dispersed.

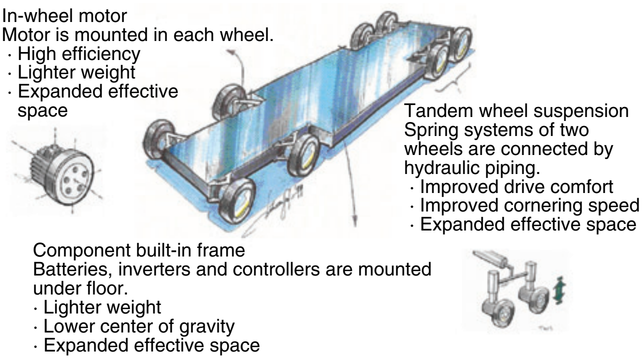

Fig. 1 Vehicle body with new integrated platform concept

The purpose of developing the Eliica was to create an electric vehicle with versatility, practicability and usefulness through applying the compactly engineered integrated platform concept to a normal passenger vehicle.

In line with this purpose, the Eliica was developed in two types: a "high-speed type," designed to make higher maximum speed available by adopting a smaller gear ratio in the built-in motor, and another with a larger gear ratio to place more emphasis on acceleration.

From the standpoint of vehicle practicability, the high-acceleration type is more useful. We thought, however, that development of the high-speed type was also important because it facilitates evaluation of safety and provides a clearer expression of the vehicle's capabilities.

Concerning vehicle applications, the Eliica was defined as a vehicle having features of both a sports car and a sedan. These days, the development of passenger cars is proceeding in three product-type directions. One is the sedan, which is widely used for ordinary applications. Another is the sports car, which has long existed for car enthusiasts, and the last is the sport utility vehicle (SUV), which has become particularly popular in recent years.

In the case of internal combustion engines, emphasis had to be placed on a certain feature to the sacrifice of other features. In the case of the integrated platform concept, however, the eight motors that can be installed because of the wide floor space and the batteries under the floor enable significant power to be generated. Also, the component built-in frame enables a lower center of gravity, which is effective for improving the ride and stabilizing the vehicle frame. In addition, the eight wheels of the tandem wheel suspension significantly improve the ride on rough roads as well as tire grip on tight curves.

Thus, use of the integrated platform enables both the interior space and ride comfort required of sedans and also the strong power and maneuverability required of sport cars.

Our aim in providing the Eliica with these characteristics was to create a vehicle that could be considered either a sedan with even better performance than a sports car or a sports car that offers space and ride comfort equivalent to or better than that of a sedan; in other words, we aimed to create a vehicle combining the features of both a sports car and a sedan, which is referred to herein as a "crossover vehicle."

3. Basic Technology of Eliica

The basic technologies of the Eliica are divided into element technology and frame technology. The element technology includes the battery, the inverter, the driving motors and other components that are common to electric vehicles. The frame technology is the method of packaging them into the in-wheel motors, component built-in frame and tandem wheel suspension.

3. 1 Element Technology

① Battery

The battery is a Li-ion battery employing Lithium Manganate for the plate. For each of the two Eliica prototypes, different battery specifications are used: a power-intensive battery for the high-speed type, and an energy-intensive type for the high-acceleration type. **Table 1** summarizes the basic properties of these batteries.

Table 1 Specifications of a Li-ion battery on Eliica

	Prototype No. 1	Prototype No. 2
Total length, mm	170	170
Total width, mm	47	47
Total height, mm	133	133
Weight, kg	2.1	2.1
Nominal energy density, Wh/kg	41	72
Nominal power density, W/kg	More than 1 500	More than 700

As shown in the table, both batteries have the same size and weight but different power density and energy density. The charging time for each battery is also different. These properties are based on a battery temperature of 25℃ and rated charging voltage of 4.15 V. By increasing the battery temperature, its power property can be improved, although a temperature over 60℃ can significantly affect battery life. The battery charging voltage can be set at approximately 0.1 V over the voltage shown in the table for improved power density and energy density without affecting life and other properties. However, taking into account the risk of detrimental effect on battery life, it is deemed important to use a charging voltage less than the rated voltage.

In this project, four batteries are packed into one module, and 20 modules are linked in series to form a battery stack.

Each Eliica carries four battery stacks, each providing power for two motors. With this power arrangement, the vehicle would not suddenly stall when one battery or motor fails, meaning there is improved fail-safe capability.

② Inverter

The inverter employed is a PWM controlled type with IGBT as the switching element. The basic specifications of the inverter are shown in **Table 2**. Since this inverter needs to be installed in the limited space of the component built-in frame, it was specially designed to have sufficient capability of supplying power while having size limitations regarding height, width and length as shown in **Table 2**.

The carrier frequency of the inverter is set at 12 kHz, which is high enough to cope with the maximum rotational speed of the motor.

Also, the inverter is equipped with a water cooling system with maximum water temperature of 50℃.

The motor controlled by this inverter has maximum torque of 100 N·m, maximum rotational speed of 12 500 min^{-1}, and maximum output of 80 kW. The basic motor rotational speed at these conditions is 6 500 min^{-1}.

Table 2 Specifications of an inverter

	Prototype No. 1	Prototype No. 2
Total length, mm	380	380
Total width, mm	300	300
Total height, mm	150	150
Weight, kg	17	17
Maximum output capacity, kW	80	80
Maximum input voltage, V	360	360
Maximum current, Arms	459	459
Carrier frequency, Hz	12	12

③ Motor

The electric motor selected is a synchronous motor using a Nd-Fe type permanent magnet. The numbers of poles and slots are 8 and 12, respectively.

The rotor is an inner rotor type with its surface lined with firmly fixed magnets. The rotor dimensions are diameter 114mm and length 86mm, and the permissible mechanical rotational speed is 14 400 min^{-1}, for which maximum speed in service is set at 12 500 min^{-1}.

A concentrated winding method has been used for the stator coil. The coil has a diameter of 0.9mm with H class insulation. In particular, this stator uses a well-engineered coil winding method to achieve a space factor of 80 percent.

The heat radiation of this motor is achieved by natural air-cooling by means of fans on the outer case.

The rated specifications of this motor include 80 kW in 40 second short-time rating as well as 4 kW in 2 400 min^{-1} continuous rating.

The specifications of this motor are shown in **Table 3**.

Table 3 Specifications of a motor

	Prototype No. 1	Prototype No. 2
Total length, mm	195	195
Diameter, mm	214	214
Weight, kg	20	20
Maximum torque, N·m	100	100
Maximum rotational speed, min^{-1}	12 500	12 500

3. 2 Vehicle Body Construction Technology

① In-wheel motor

The in-wheel motor itself is as described in section **3.1**-③ above. Each motor, mounted in a wheel, comprises a planetary gear for speed reduction, an outer ring rotating wheel hub bearing, and a disc brake. The gear ratio for the planetary gear is 3.257 for the No. 1 vehicle and 6.923 for the No. 2.

Each in-wheel motor is attached to the upper frame and lower arm of the suspension through the attachments fixed to upper and lower sides of the motor.

A floating type disc brake is used, and a parking brake is attached to the rear side of this brake.

Figure 2 shows overall view of the in-wheel motor.

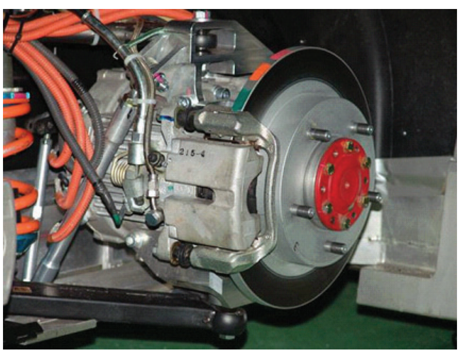

Fig. 2 Appearance of in-wheel motor

Numerous bearings and oil seals containing advanced technology are used in the in-wheel motors.

Bearings for the in-wheel motor are those for the motor and the planetary gear, and the hub bearing. Among these, particularly advanced technology is required for the planetary gear bearings as they need to operate at extraordinarily high speeds while taking up very limited space. Therefore, specially designed needle roller bearings are used for this application.

Oil seals are used to prevent the leakage of oil from the various bearings. Concerning the hub bearing oil seals, the space for these seals was restricted by the brake disc inner diameter and the outer diameter of the spindle, which transmits the output from the hub bearing to the wheel. A very thin but high-strength oil seal was specially developed for this application.

Design work and prototyping of these bearings and seals were undertaken by Koyo Seiko Co., Ltd. This success has demonstrated Koyo's high technological capability.

② Component built-in frame

The component built-in frame comprises the central block, where the batteries are stored, and the side blocks, where the inverters are housed. In addition, a rectangular stick-out is provided on both sides of the central block to accommodate the suspensions and various components.

The battery storing block and the rectangular stick-out portion are formed with thin, hollow structural members of extruded aluminum, with four such members being welded together. **Figure 3** shows a section of the frame. As shown in **Fig. 3**, each member has a thickness of 2.5mm on the top, bottom and side faces, making the structure lightweight but sufficiently rigid.

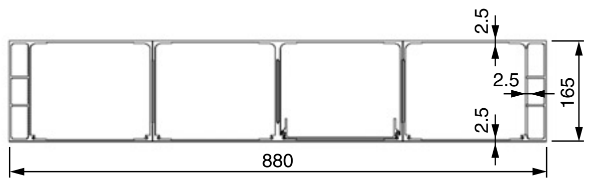

Fig. 3 Cross section of component built-in frame

The batteries are installed into the component built-in frame as fixed on a tray having locating ribs on its bottom. The locating ribs are snugly fit between ribs provided on the inside surface of the hollow frame.

This design facilitates loading and unloading of the batteries while preventing them from oscillating in the frame when the vehicle is moving.

③ Tandem wheel suspension

Regarding the tandem wheel suspension, the distance of each wheel in front of or behind its adjacent wheel is a crucial design factor. In the KAZ, the two adjacent front wheels were widely separated, and a front sheet was placed between them, but in the Eliica, very little space has been provided in front of the front sheet.

With this type of suspension, the steering system is also an important design factor. The Eliica No. 1 has a steering structure whereby only the two front axles are steered, whereas the No. 2 is provided with a steering system whereby the fourth axle also can be steering, which reduces the turning radius and restrains tire sliding during turning.

The two front axles are steered by a system wherein the steering column rotational force is distributed to the first and second axles through different gear ratios. This steering effort distribution mechanism is called a steering distributor herein. An electric power steering mechanism has been attached to each axle. Steering of the fourth axle is controlled by signals from a steering rotational shaft sensor attached to the steering distributor.

4. Vehicle Body Design

Regarding body design of the Eliica, working with the foundation of the body construction technology described above, we attached the suspension structure, upper frame, upper body, and finally the interior.

4. 1 Suspension

For the basic suspension structure of the Eliica, the double wishbone type was selected. The reasons for selecting this type are that it enables maximum utilization of suspension performance and easy connection of the floor surface to the very high-strength component built-in frame because of this suspension's low arm mounting position.

In addition, in the front suspension the spring and damper are placed side by side in the front-back direction, and these parts are connected to the suspension arm by a pull rod. This minimizes stick-out of the suspension parts from the component built-in frame upper surface.

Figure 4 shows a photograph of the integrated platform with the suspension mounted viewed from the rear side of the vehicle.

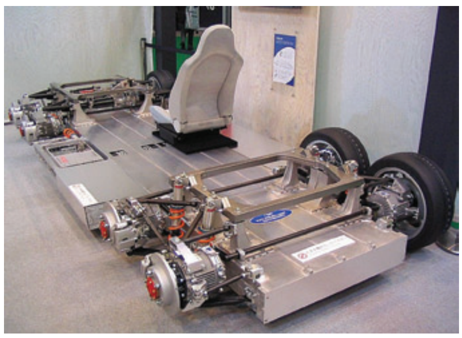

Fig. 4 Integrated platform

4. 2 Upper Frame

The upper frame is designed for the dual purposes of ensuring strength and rigidity of the overall chassis in coordination with the component built-in frame and supporting the body.

The Eliica's upper frame basically is made of steel tubing (SPKM) having a diameter of 38.1mm.

Figure 5 shows a photograph of the upper frame as mounted on the integrated platform.

Fig. 5 Integrated platform with upper frame

4. 3 Body

The body design is one of the most important deign factors for the Eliica. First, because like any other electric vehicle the Eliica can carry only a limited power supply, it is necessary to keep power consumption to a bare minimum. Secondly, as the Eliica is designed as a crossover between a sports car and sedan, the air resistance is liable to be greater as a consequence of securing the large interior space required of a sedan. Still another point is that in order for this type of vehicle to be accepted by society in the future, the visual characteristic of there being eight wheels must be perceived as an expression of functional beauty.

Design work was carried out in a manner such that the results of free discussions, group discussions and brainstorming were reflected in the design. The design process was not significantly different from those for ordinary vehicles; it included making multiple image sketches, digitalization thereof, fabrication of a one-fifth-size prototype, conducting wind tunnel experiments, making full-size mock-ups, and making molds.

The appearance of the completed car body is shown in **Fig. 6**. As can be seen through the windows, the car has enough space for five passengers.

Fig. 6 Eliica

In addition, in order to reduce the influence of the bonnet area on air resistance, the bonnet is designed to have a round shape, taking advantage of there being no big engine under it. Also, for the same purpose, the inclination of the windshield is made greater. The passenger compartment has been moved toward the front end, while, in the rear area, the overhang portion has been made longer to minimize air resistance.

The above-mentioned specifications of the Eliica are summarized in **Table 4**.

The size of the vehicle is equivalent to that of a full-size sedan. The output of the No. 1 and No. 2 prototypes are 640 kW and 480 kW, respectively, as the rating for short time.

Table 4 Specifications of Eliica

Model name		Prototype No. 1	Prototype No. 2
Type		For challenging maximum vehicle speed	For high acceleration
Dimension	Total length, mm	5 100	
	Total width, mm	1 900	
	Total height, mm	1 365	
Capacity, persons		5	
Motor output, kW		640	480
Performance	Maximum speed (Target), km/h	400	190
	Maximum acceleration, G	0.38	0.78
	Mileage per one charge, km	180	320
	Charging time (70% recovery), min	4	30

5. Driving Performance Test

The Eliica was subjected to maximum speed testing at Bridgestone's test course in Japan for a total of five days in January and February 2004 and then again in March on the proving ground of Prototipo Corp. in Nardo, Italy.

The results of the maximum speed test conducted in Italy are shown in **Fig. 7**. As shown in this figure, the Eliica achieved a maximum speed of 370 km/h, which is performance surpassing that of general sports cars.

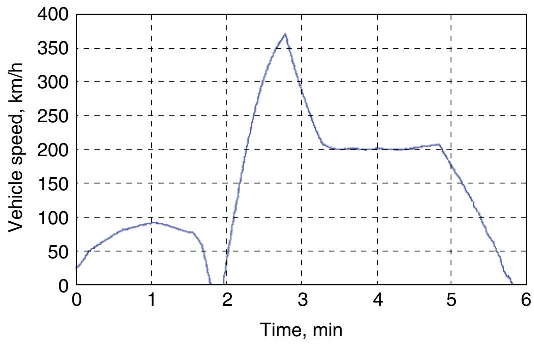

Fig. 7 Results of maximum speed test on Eliica

Figure 8 shows the results of acceleration testing. In this test, in-wheel motors having a gear ratio of 6.923 were used. In this figure, the horizontal axis represents time from the start, and the vertical axis represents speed. According to this figure, the time required for the Eliica to reach speeds of 100 km/h and 160 km/h were 4.1 and 7.0 seconds, respectively. This figure also shows the results of the same test for a Porche 911 Turbo. According to those results, the Porche reached speeds of 100 km/h and 160 km/h in 4.2 and 9.2 seconds, respectively. This test has shown that the Eliica has acceleration performance surpassing that of a sports car, which is supposed to have the highest level of acceleration performance. Furthermore, if you look at the acceleration curve of the Eliica closely, you can see that the Eliica's acceleration is fast and steady as demonstrated by the straight line. Such uninterrupted acceleration would give the driver and passengers an extremely high level of comfort. This feeling of steady acceleration has been sought after in the case of internal combustion engine cars for a hundred years without success.

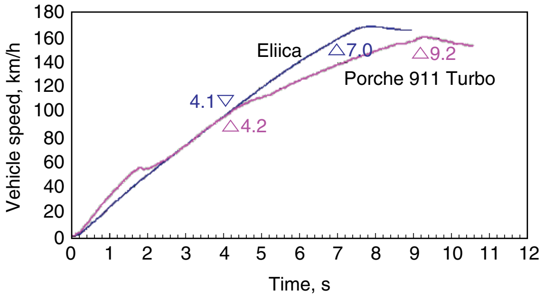

Fig. 8 Results of acceleration test on Eliica

6. Conclusion

Herein the development of a Li-ion battery vehicle with a new concept has been described. The Eliica has achieved a maximum instantaneous speed of 370 km/h and a 0-to-160 km/h acceleration time of 7 seconds, representing performance that exceeds that of all types of existing sports cars.

At the same time, the Eliica has sufficient interior space as a sedan. Ukyo Katayama, who undertook the test drive, commented that the Eliica's ride is more than sufficient as a sedan even at high speeds.

It is concluded that the Eliica has succeeded in achieving features as a crossover between a sedan and a sports car.