Development of Ultralow-Floor All-Electric Light-Duty Truck

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ABSTRACT: The growth of e-commerce is making people's lives more and more convenient. However, the logistics industry is facing a deepening shortage of drivers to carry the continually increasing amount of goods that this growth is generating. One cause of this shortage is the physical stress placed on delivery drivers during transportation. At the same time, as all industries accelerate efforts to adopt more environmentally friendly business practices, expectations and demand are rising for domestically manufactured all-electric commercial vehicles. To respond to these environmental changes in the logistics industry, a carbon-free all-electric light-duty truck was developed for last-mile delivery services (i.e., the delivery of goods from the closet logistics depot to the customer) that also alleviates the physical stress placed on the driver. This truck adopts a front-wheel drive layout with a compact drive motor, battery, cooling components, and power distribution units. This layout enables an ultralow-floor walk-through structure in which the driver can move easily from the driver's seat to the cargo space inside the vehicle. The resulting layout makes it much easier to enter and leave the truck and greatly facilitates handling of the cargo. The adoption of an electrified powertrain also eliminates tailpipe emissions, including CO_2. It was confirmed that this truck alleviates driver fatigue during operation under actual conditions, which means it should help to relieve the physical stress placed on the driver during last-mile deliveries. This paper describes the technology adopted to realize an ultralow-floor in an all-electric light-duty truck, how the appropriate battery capacity was determined by analyzing the working conditions of last-mile delivery services, and the results of verification tests.

KEY WORDS: ultralow-floor, electric, light-duty, truck

1. INTRODUCTION

The growth of e-commerce is making people's lives more and more convenient. However, the logistics industry is currently facing a crisis, namely a deepening shortage of drivers to carry the continually increasing amount of goods that this growth is generating. One cause of this driver shortage is the physical stress placed on drivers engaged in last-mile delivery services by having to enter and leave the truck and handle the cargo. The height of the cargo bed in conventional light-duty trucks used for home delivery services is approximately 800 mm. Drivers are required to step in and out of the cargo space at this height many times every day. During a delivery, the driver is required to stop the vehicle, step down from the driver's seat, walk round to the rear of the truck, and remove the cargo from the cargo space. These actions all increase the stress placed on the driver. Further long-standing issues include air pollution and global warming caused by emissions such as NOx and CO_2. The United Nations Climate Change Conference held from November 30 to December 13, 2015 (COP 21) adopted the Paris Agreement as a new international framework to reduce greenhouse gas emissions and the like. Under this framework, the international community is working to realize a decarbonized "carbon-neutral" society.(1) In October 2017, Hino Motors, Ltd. announced the Hino Environmental Challenge 2050. As the first milestone under this challenge, Hino is aiming to reduce tailpipe CO_2 emissions in 2030 by 40% compared to 2013.(2) Therefore, to help resolve these social issues, a carbon-free all-electric light-duty truck was developed for last-mile logistics that also alleviates the physical stress placed on the driver. This paper describes the technology adopted to realize an ultralow-floor in an all-electric light-duty truck, how the appropriate battery capacity was determined by analyzing the working conditions of last-mile delivery services, and the verifications that were carried out.

2. DEVELOPMENT OF ALL-ELECTRIC LIGHT-DUTY TRUCK

2.1. Selection of battery for the drive motor

Figure 1 shows the daily operation time (horizontal axis) and average speed (vertical axis) of diesel light-duty home delivery trucks in central urban areas in Japan during the day. The curve in the center of the graph indicates the line at which a daily driving distance of 100 km would be reached based on calculations using the operation time and average speed. As shown in the figure, diesel light-duty trucks used for home delivery services in central urban areas in Japan are driven between approximately 50 and 80 km per day. The necessary energy for the battery was simulated by Hino using its central urban area driving pattern. A lithium-ion battery was selected that satisfies the conditions for this pattern, factoring in the daily driving distance, electricity consumed by the cooling and heating systems on the truck, and battery deterioration. Surveys were also conducted into the operation of these delivery trucks under actual conditions to confirm the daily driving distances. The battery capacity that satisfies these conditions was then calculated.

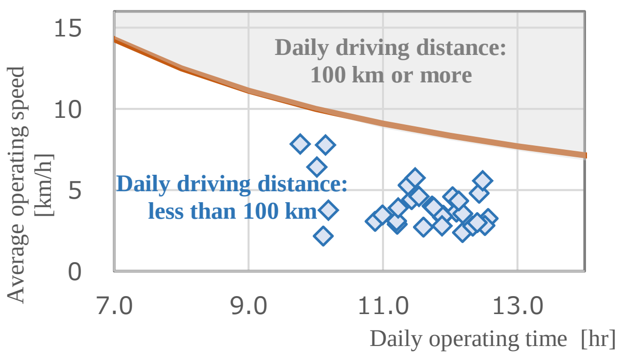

Fig. 1 Operating Conditions of Home Delivery Services in Central Urban Areas in Japan

* Source: Hino Motors Ltd.

2.2. Study of layout for ultralow-floor

Conventional diesel light-duty trucks tend to adopt a front-engine, rear-wheel drive configuration in which power is transmitted from an engine installed under the driver's seat to the rear wheels via a transmission and propeller shaft. This configuration makes it difficult to lower the floor of the truck since the transmission and propeller shaft must be installed below the cargo bed within the wheelbase. Therefore, to realize an ultralow-floor structure, this development decided to adopt a front-wheel-drive system that powers the front wheels using an integrated drive motor and transaxle. In addition, a thin lithium-ion battery with high energy density was selected to power the drive motor. Combining front-wheel drive with a battery installed in the center of the truck enabled more efficient use of the space required compared to conventional front-engine rear-wheel drive configuration.

In the overall layout, tall main components were installed at the front of the truck and slim auxiliary components were installed collectively at the rear to maximize the available space for the cargo area. Particular attention was given to efficient packaging at the front of the truck to eliminate excess space. Figures 2 and 3 show the overall component layout and layout around the front axle, respectively.

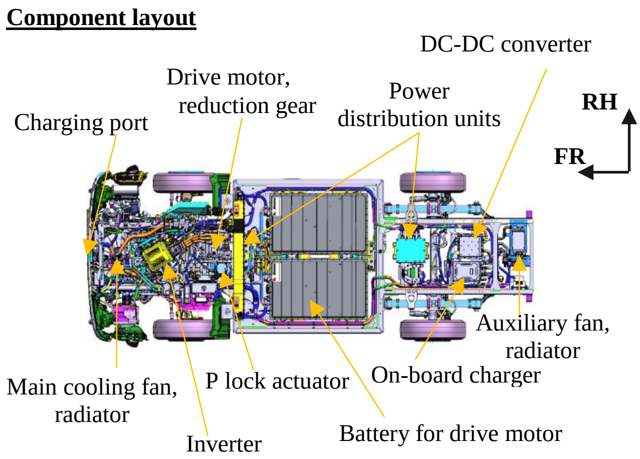

Fig. 2 Overall Layout (Top View)

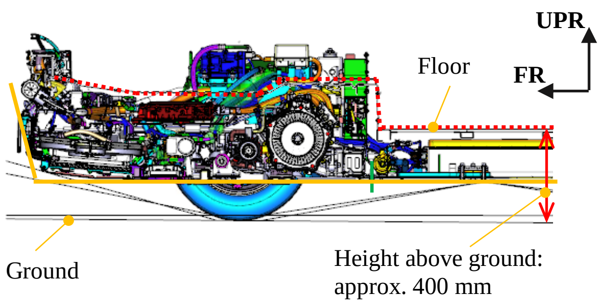

Fig. 3 Front Layout (Left Side View)

2.2.1. Drive motor

Figures 4 and 5 show the layout around the front axle and a side view of the drive motor, respectively. As shown in Fig. 4, a front-wheel drive layout was adopted to maximize the available space for the cargo area. The motor axis is offset from the axle to enable an ultralow-floor. Figure 5 illustrates the efficient drive motor layout in which the stator connection point was designed to avoid contact with the suspension cross member. In addition, a compact cooling system was realized by adopting direct oil cooling for the stator in the motor.

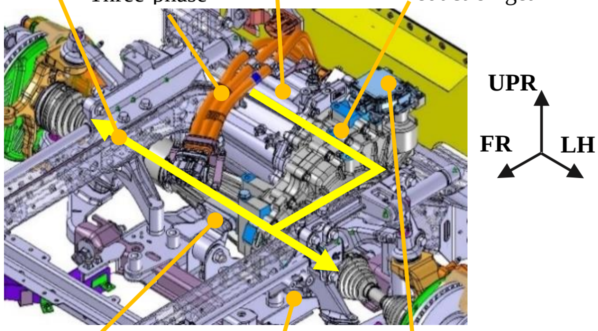

Fig. 4 Area around Drive Motor (Front View)

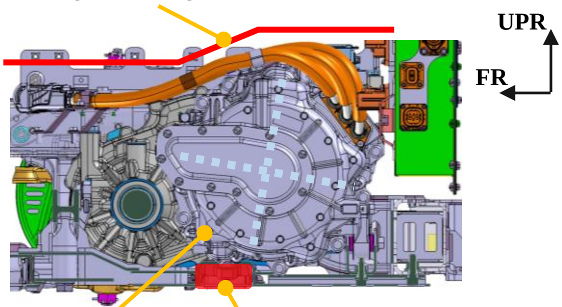

Fig. 5 Drive Motor (Left Side View)

2.2.2. Battery

To help realize an ultralow-floor, a thin drive motor battery was installed inside the truck frame.

In addition, factoring in the detachability of the battery, a structure was adopted that allows the battery, battery mounting bracket, cooling pipes, and cables to be attached and detached as an assembly from below the truck. Since, during the summer, the drive battery must be kept below the ambient temperature, a cooling system was adopted that circulates coolant chilled by refrigerant in a chiller. To save space and reduce the number of parts required, this chiller and refrigerant is shared by the air conditioning system for the driver's seat.

2.2.3. Cooling circuits

The design policy defined the following three separate cooling circuits depending on the temperature of use: (1) the drive motor, (2) the inverter, DC-DC converter, and normal on-board charger, and (3) the battery. Furthermore, the heat exchangers for the drive motor and inverter were integrated into the oil cooler (for the drive motor) and radiator (for the inverter), and located at the front of the truck to shorten the piping system. In addition, the cooling circuit for the DC-DC converter and the normal on-board charger was designed to be independent of the cooling circuit for the inverter. Locating this circuit at the rear of the truck eliminated the need to install cooling pipes in the battery area between the wheelbase, which helped to secure enough space to mount the battery. Figures 6 to 11 show outlines and simplified diagrams of each cooling circuit.

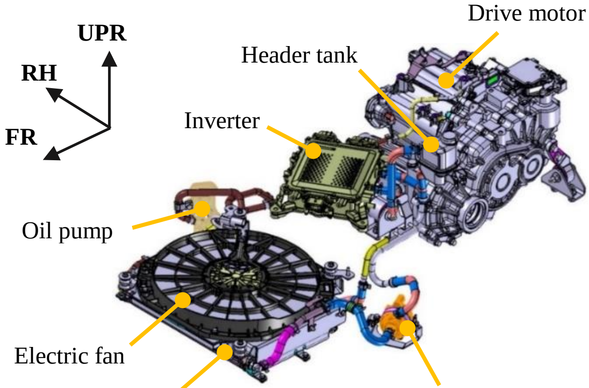

Fig. 6 Outline of Drive Motor and Inverter Cooling Circuit

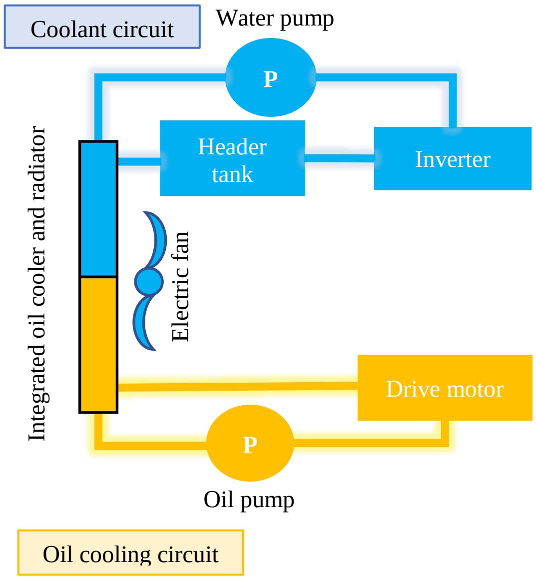

Fig. 7 Simplified Diagram of Drive Motor and Inverter Cooling Circuit

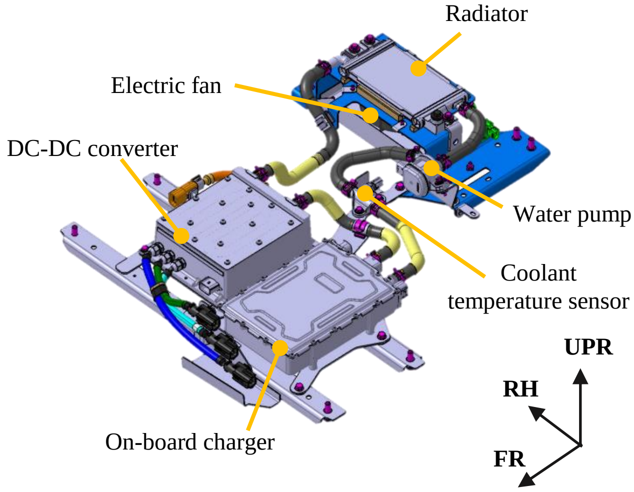

Fig. 10 Outline of DC-DC Converter and On-Board Charger Cooling Circuit

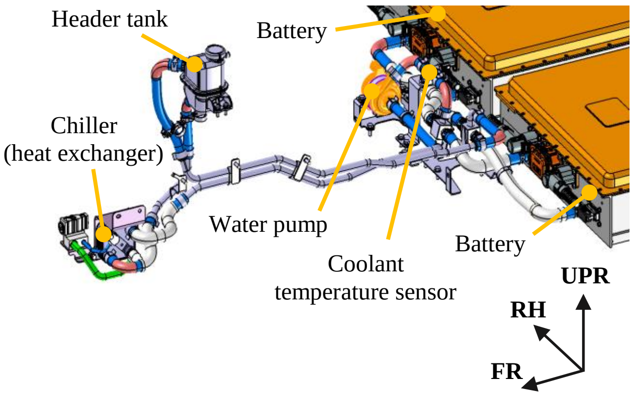

Fig. 8 Outline of Battery Cooling Circuit

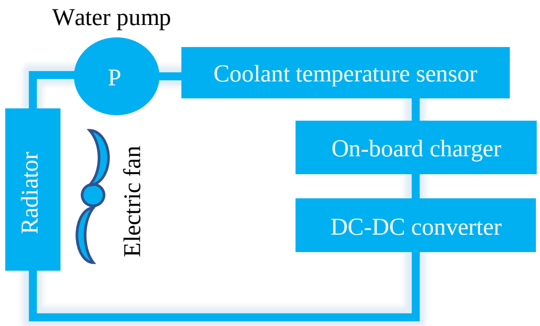

Fig. 11 Simplified Diagram of DC-DC Converter and On-Board Charger Cooling Circuit

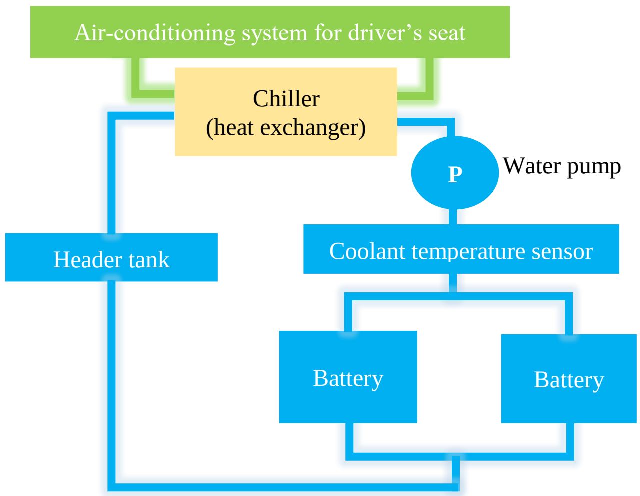

Fig. 9 Simplified Diagram of Battery Cooling Circuit

After simulations using computational fluid dynamics (CFD), the integrated oil cooler and radiator was laid out horizontally in consideration of the necessary airflow velocity and the balance of the vehicle layout. Actual measurements confirmed that this layout satisfies the cooling performance requirements. Figure 12 shows the airflow distribution simulated by CFD.

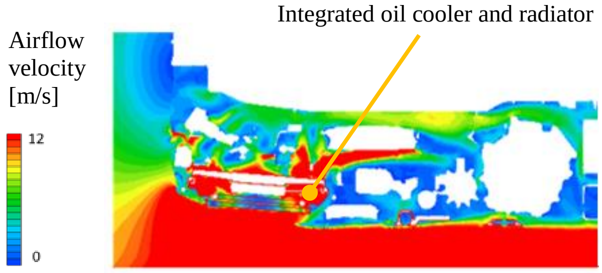

Fig. 12 Airflow Velocity Distribution (Section W0)

2.2.4. Power distribution units

The power distribution units function to distribute electricity to the components.

These units are connected electrically to each of the components and cut off these connections using relays.

Each power distribution unit consists of a pre-charge relay, main relay, pre-charge resistor, current sensor, electrical leak sensor, fuse, connector, bus bar, and wiring harness.

Figure 13 shows a rear view of the vehicle layout. As shown in the figure, two units are adopted to ensure the optimum distribution of electricity. The power distribution unit mounted at the front of the truck supplies electricity to the main components and the power distribution unit mounted at the rear supplies electricity to the auxiliary components. The front-mounted power distribution unit makes effective use of the dead space between the cab and cargo area and was designed to fit the walk-through structure of the truck.

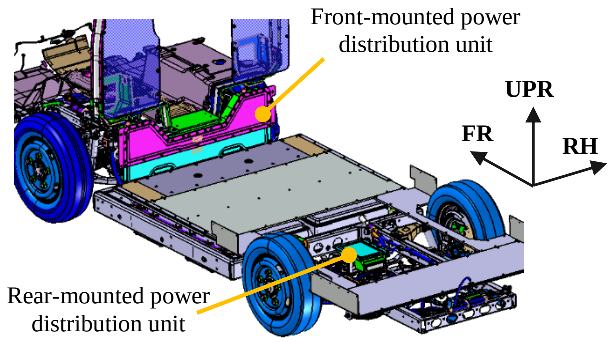

Fig. 13 Mounting Locations of Power Distribution Unit (Rear View)

2.3. Main specifications

Table 1 lists the specifications of the developed all-electric light-duty truck. As shown in the vehicle lineup in Fig. 14, three variants of this truck were prepared: a walk-through van, an aluminum van with a side door, and an aluminum van without a side door.[3] This is the first all-electric truck mass produced by Hino. Figure 15 illustrates the internal structure of the walk-through van. The van is structured to give the driver direct access to the cargo space from the driver's seat. A low floor was also realized to make the truck easier to enter and leave while working. Since this truck was developed for use in Japan, the quick charging inlet adopts the CHAdeMO specifications.[4] The basic design concepts assume that the truck will be charged normally at night while it is not being driven, and charged quickly in the morning between deliveries if there is insufficient charge. Although the exact figure will differ depending on how the customer uses the truck, the range between charges of the 40 kWh lithium-ion battery is approximately 150 km.

Table 1 Specifications of Developed All-Electric Light-Duty Truck[3]

	Walk-through van	Aluminum van (with side door)	Aluminum van (without side door)
Length	4,695	4,690	4,690
Width	1,695	1,925	1,755
Height	2,290	2,480	2,490
Gross vehicle weight	Under 3.5 tons		
Battery capacity	40 kWh (lithium-ion battery)		
Maximum drive motor power	50 kW (67 PS) / 1,550 rpm		
Range per charge	150 km (WLTC)		
Charging systems	CHAdeMO (quick charging inlet), SAE J1772 (normal charging inlet)		

Fig. 14 All-Electric Light-Duty Truck Lineup[3]

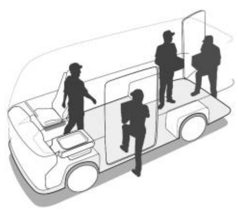

Fig. 15 Internal Structure of Walk-Through Van

3. CONFIRMATION OF OPERATION UNDER ACTUAL CONDITIONS

Before the launch of the truck, operating tests were carried out under actual conditions. The following items were verified using six trucks to perform home delivery services in central urban areas in Japan.

(1) Driving distance and electricity consumption [kWh] under actual conditions
(2) Battery cooling performance
(3) Energy consumption (ΔSOC)

The following sections describe the verification results and discussion points.

3.1. Driving distance and electricity consumption [kWh] under actual conditions

The graph in Fig. 16 shows the average operating speed and daily driving distance of the all-electric light-duty trucks under actual conditions. The line in the graph indicates a daily driving distance of 100 km. Area A shows the data for individual deliveries and area B shows the data when delivery bases are used. Unlike the system that delivers items in sequence to individual houses, the delivery base system locates several bases along a delivery route. Compared to the individual delivery system, this reduces the number of stops and starts made by the truck. Figure 16 indicates, that for either delivery pattern, the daily driving distance under actual conditions is approximately less than 100 km.

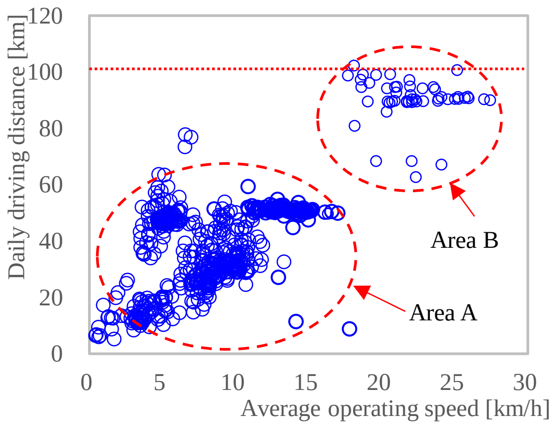

Fig. 16 Daily Driving Distance and Average Operating Speed

Next, the graph in Fig. 17 shows the average operating speed and daily energy consumption of the all-electric light-duty trucks under actual conditions. The line in the graph indicates a daily energy consumption of 40 kWh. Area A shows the data for individual deliveries and area B shows the data when delivery bases are used. Figure 17 indicates, that for either delivery pattern, the daily energy consumption is less than 40 kWh.

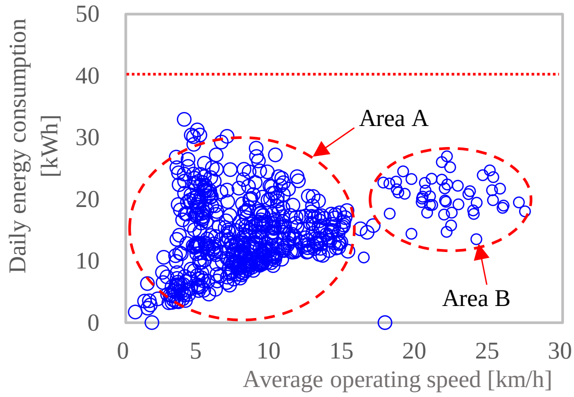

Fig. 17 Daily Energy Consumption and Average Operating Speed

These results prove that, from the perspectives of the daily driving distance and energy consumption, the trucks were operated under actual conditions as expected and that the trucks clearly satisfy the requirements for single-day operation.

3.2. Battery cooling performance

Figure 18 shows the confirmed results for the daily maximum battery temperature. The vertical axis shows the maximum temperature of the battery and the horizontal axis shows the month. The line in the graph indicates a battery temperature of 30°C. A temperature range between 25 and 30°C is recommended to preserve the lifetime and performance of the battery. This is because battery lifetime generally decreases when the battery is kept at high temperatures and because charging and discharging output decreases at low temperatures.

Figure 18 shows that, since the battery is cooled using refrigerant, the battery temperature is kept at or below 30°C virtually all the time throughout the year. These results confirm that the battery can be used throughout the year within a temperature range that does not adversely affect battery lifetime, while satisfying the energy requirements of the driving pattern.

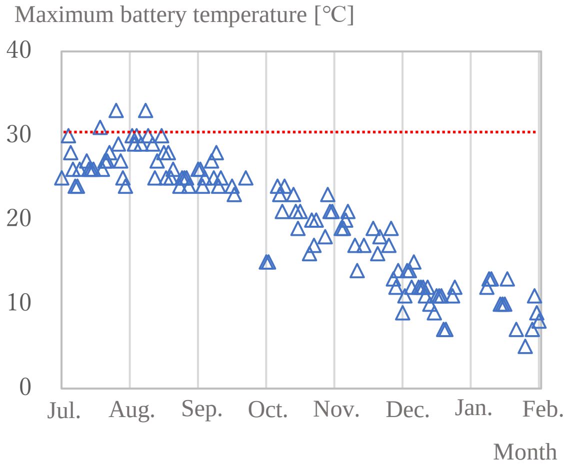

Fig. 18 Daily Maximum Battery Temperature

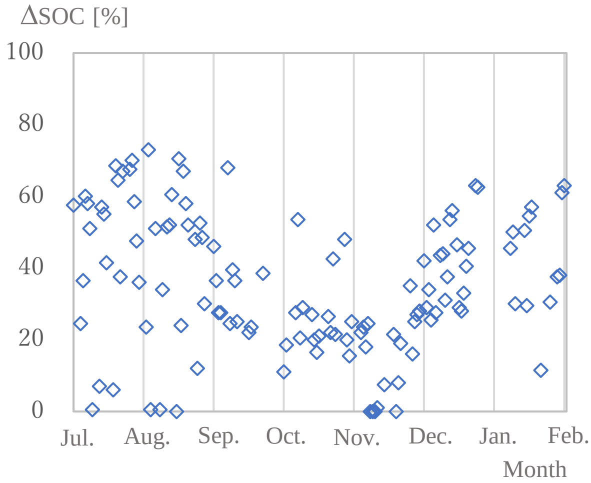

Fig. 19 Daily ΔSOC

3.3. Energy consumption (ΔSOC)

Figures 19 and 20 show the daily ΔSOC (i.e., maximum SOC - minimum SOC) and the electricity consumption ratio of each component each month, respectively.

The vertical axis in Fig. 19 shows the daily ΔSOC (%). The vertical axis in Fig. 20 shows the monthly electricity consumption as a ratio compared to the average electricity consumption in February, which recorded the highest electricity consumption during the year of the test. The horizontal axis of both figures shows the month.

Figure 19 indicates that the ΔSOC is 80% or less, which demonstrates that the battery capacity is adequate.

The graph also shows that the remaining SOC is low throughout the year in both summer and winter.

This is because, according to Fig. 20, although the energy required for driving (i.e., the energy consumed by the drive motor and inverter) remains virtually unchanged throughout the year, the air conditioning or heating is used frequently during these seasons.

These results demonstrate that the electricity consumption is greatly affected by the usage rate of the air conditioner and heater.

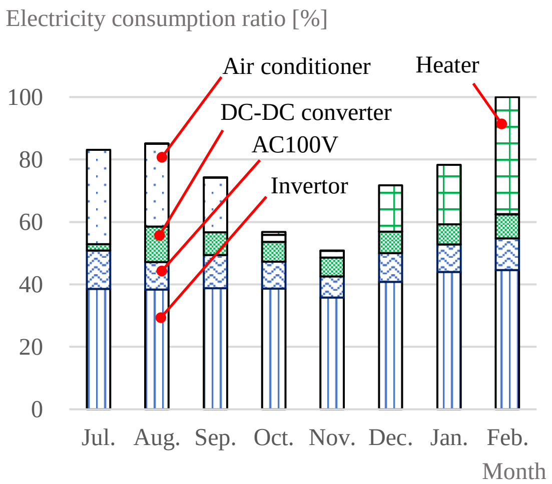

Fig. 20 Average Monthly Electricity Consumption Ratio

4. CONCLUSIONS

(1) A concept for an all-electric light-duty truck for last-mile delivery services was proposed with an ultralow-floor and a walk-through structure from the driver's seat to the cargo area. A design to realize this concept was then implemented.

(2) This concept was primarily targeted at home delivery services in central urban areas in Japan. The following verification results were obtained in response to the development targets in operation under actual conditions.

- ΔSOC was 80% or less, indicating that sufficient margin is achieved for the battery capacity.

- The battery temperature remained 30°C or less at almost all times, indicating that the cooling performance conditions are satisfied.

- The ease of entering and leaving the truck and handling the cargo greatly relieves the physical stress on the driver.

In addition, adoption of this all-electric light-duty truck has the potential to reduce annual CO_2 emissions by 2.9 tons per vehicle on a well-to-wheel basis.

Table 2 and Fig. 21 show the detailed conditions used to calculate this estimated reduction in CO_2 emissions. The driving distance value is the average value for diesel light-duty trucks shown in Fig. 1.

Table 2 Detailed Conditions for Calculating CO_2 Emissions per Truck

Item	Details	Level	Diesel light-duty truck	All-electric light-duty truck
Operating conditions	Driving distance (average value for diesel light-duty truck)	km/day	45.7	
	Number of days in operation	day/year	240.0	
Daily driving energy	Fuel efficiency	km/L	6.8	-
	Electricity consumption efficiency	km/kWh	-	2.8
	Fuel	L/day	6.7	-
	Electric energy	kWh/day	-	16.3
Generated by fuel	CO_2 emissions factor related to fuel (diesel) manufacture	kg-CO_2/L	0.32[5]	-
	CO_2 emissions factor related to electricity	kg-CO_2/kWh	-	0.45[6]
	Annual CO_2 emissions	kg-CO_2/year	522.9	1771
Tailpipe emissions	Emissions factor related to use of fuel (diesel)	kg-CO_2/L	2.58[7]	-
	Annual CO_2 emissions	kg-CO_2/year	4161	-
Annual CO_2 emissions (well to wheel)		kg-CO_2/year	4684	1771

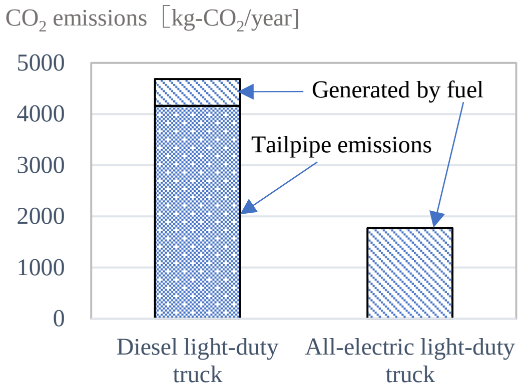

Fig.21 Annual CO_2 Emissions per Truck (Well to Wheel)

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