

Temperature Characteristics of a Hybrid Electric Vehicle Fire

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ABSTRACT

Recently, vehicles with high capacity traction batteries for driving such as Ni-MH, lithium-ion have come to be produced in the world. However, the damage has not been clarified in the case of these vehicles fire by a traffic accident or arson. In particular, lithium-ion cells in high temperature environment may cause a thermal runaway which emits smoke or flare. Therefore, it is necessary to examine what kinds of phenomena occur when a vehicle with a lithium-ion battery catches fire. In this paper, the authors studied the situation and temperature characteristics of a hybrid electric vehicle fire to investigate the temperature input to a lithium-ion battery on a vehicle. We assumed an accident that gasoline leaking from other vehicle would be spread under a vehicle and ignited. In a vehicle fire test, gasoline was spread under a hybrid electric vehicle without the traction battery instead of a vehicle with lithium-ion battery, and ignited. Thermocouple sensors were installed inside and under the vehicle. During the test, the situation of the vehicle fire was recorded by photos and videos. The authors got measurements of attainment times, continuation times and highest temperatures according to some criteria in this vehicle fire test.

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INTRODUCTION

As people become more aware of global environmental issues, vehicles with traction batteries such as hybrid vehicles ("HEVs") and electric vehicles ("EVs") are rapidly increasing. To downsize batteries and increase driving distance, these vehicles are beginning to use lithium-ion batteries with high-energy density.

However, as the temperature around lithium-ion batteries increases, thermal runaway may occur inside the batteries and trigger abnormal phenomena such as heating, ignition, bursting, and blowout of gas. If such an incident were to happen on an EV or HEV with a large amount of lithium-ion batteries, it could cause serious damage to the driver, passengers, and people and properly around the vehicle. Therefore, studying the safety of vehicles with lithium-ion batteries in a high-temperature environment is needed.

One situation in which lithium-ion or other traction batteries of a vehicle are exposed to high temperatures is a vehicle fire. Known causes of vehicle fires include traffic accidents, arson, and careless handling of matches, lighters, and cigarettes. It is also possible that a vehicle with traction batteries could be involved in a fire in a gasoline vehicle. However, studies on these vehicle fires have not clarified the temperature characteristics (change in temperature, maximum

temperature, etc.) of the areas where traction batteries are mounted.

The purpose of this study was to collect basic data for determining the conditions of safely evaluation tests of fires in vehicles with traction batteries. This paper discusses the results of a simulation in which a moving vehicle with traction batteries met an accident with a gasoline vehicle, causing the gasoline vehicle's gasoline to leak, flow and collect under the vehicle with traction batteries, catch fire, and thus expose the traction batteries to flames from below.

In the simulation, a hybrid electric vehicle with the structure of mounting a traction battery is burned, and flame behavior is identified, the temperature characteristics of gasoline flames is measured under the vehicle as well as the temperature characteristics of the areas where traction batteries are mounted (change in temperature, maximum temperature, etc). In this experiment, the influence from the battery burned in case of the vehicles fire is not taken into consideration. The temperature input into the traction battery is investigated. For example, if the temperature is figured out, one index at which temperature a vehicle should have the fire resistance, can be obtained when a vehicle is equipped with the battery that may cause thermal runaway like a lithium-ion battery. The influence of combustion of a battery is not considered in this study. The experiment was conducted using an electric hybrid car removed only the battery, but

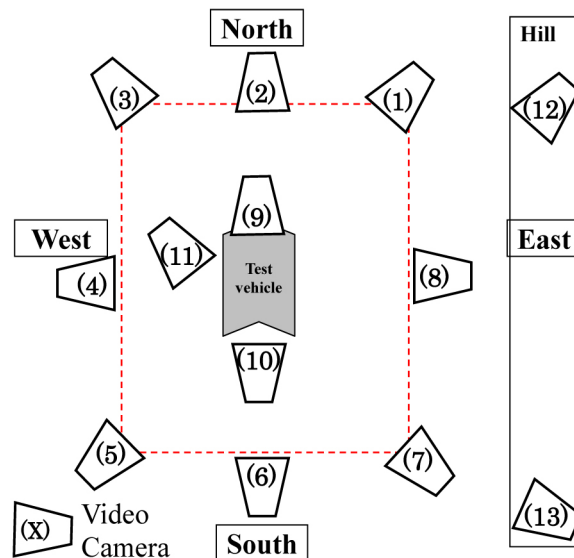


Fig. 1. Setup for the test vehicle

remaining the battery case as it was in the car. Note that these temperature characteristics may vary with the vehicle's properties (the vehicle's structure, material and thickness of the chassis, how accessory equipment and interior trims are installed, etc.). Therefore, this study identified quantitative temperature characteristics simply as an instance of vehicle fires.

MAIN SECTION

1. EXPERIMENT METHOD

1.1. Experiment conditions

Figure 1 shows the outdoor setup for the vehicle fire experiment. During the experiment, winds blew from the southwest at 2.3 m per second. To film the behavior of the fire during the experiment, video cameras were installed at points (1) to (13).

The test vehicle, "Toyota Prius", was selected from among high-selling models with traction batteries. The test vehicle is 1,350 kilograms in weight, 4,460 meters in total length, and 1,490 meters in overall height. It has approximately a 1.8-liter engine and a 60-kilowatt motor. The vehicle was left with the gas tank empty and all the side windows fully open, in order to conduct the experiment under severe conditions with heat supplied from both flames from gasoline and a fire in the compartment.

The area in the vehicle where the lithium-ion batteries are mounted was assumed to be one of the spaces (a) to (c) in Fig. 2, judging from the battery layout in vehicles on the market and such constraints as center of gravity and space. In the test vehicle, a traction battery box was placed immediately behind the rear seat. For these reasons, the ignition source in a pan of gasoline ("pool of gasoline") was

placed under the vehicle with traction batteries. The size of the pool was 1 m × 1 m × 0.1 m.

In this experiment, the nickel hydrogen batteries in the battery box were removed, because the purpose of measuring the thermal input temperature to the battery box was simply to examine the vehicle structure. The gasoline used in this experiment was regular gasoline. The burning time of gasoline was assumed to be 8 min, so burning gasoline for 8 min on a liquid surface of 1 m² required 40 l of gasoline.

1.2. Measurement setup

As temperature sensors in this experiment, K thermocouples were used, and placed them at 44 points in total as shown in Fig. 3 and 4 ("points N1 to N46"). The size of this sensor is 3.2 mm in diameter. In this sensor, a chromel wire and an alumel wire of 1.6mm in diameter were used.

Figure 3 (a) and Fig. 4 show the locations of the sensors placed under the vehicle floor (N1 to N19), which measured the thermal input from flames of gasoline to the vehicle. These sensors (N1 to N19) are located in the air nearby between the vehicle floor and the ground. Therefore, the values measured by these sensors are superimposed on the heat of radiation from the underbody on flaming gas.

Figure 3 (b) and Fig. 4 show the locations of the sensors placed on the vehicle floor (N21 to N39).

These sensors are mounted on the vehicle floor and battery box. They were installed in areas where the traction batteries would be mounted. After the interior parts such as the battery box and seats were removed, the sensors were installed along the axes just above those of the sensors under the floor (N1 to N19), on the internal surface of the chassis. The removed interior parts were replaced again before the experiment.

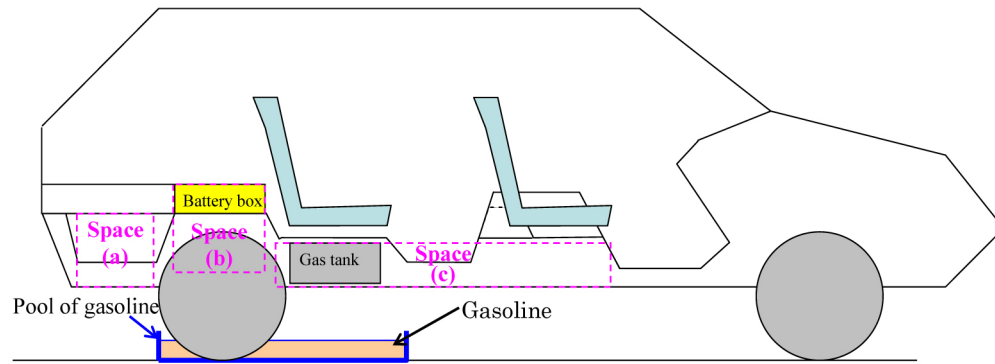
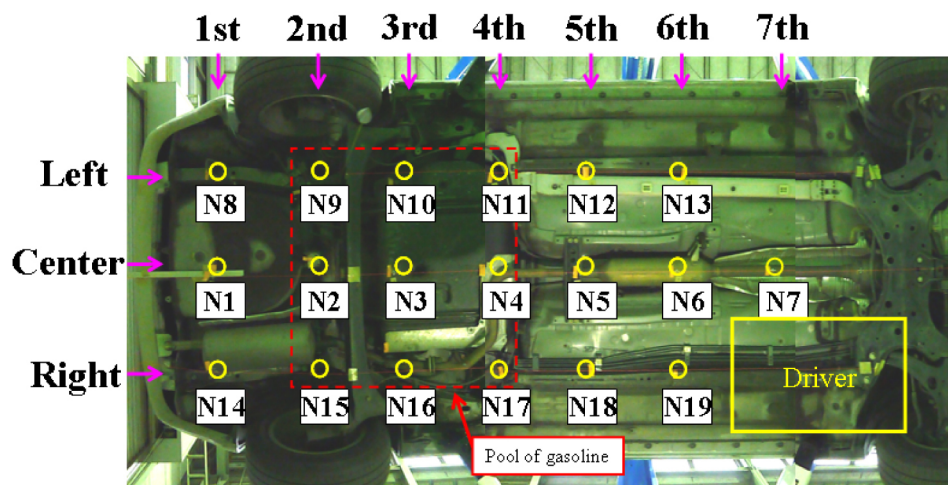
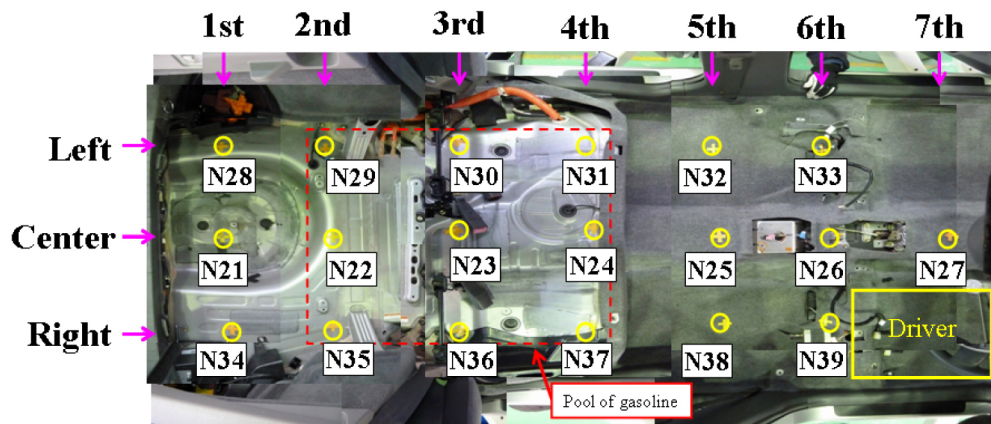


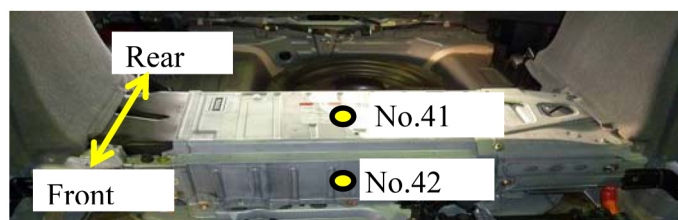
Fig. 2. Experiment setup



(a) Under the vehicle floor



(b) On the vehicle floor



(c) Battery box

Fig. 3. Locations of the temperature sensors

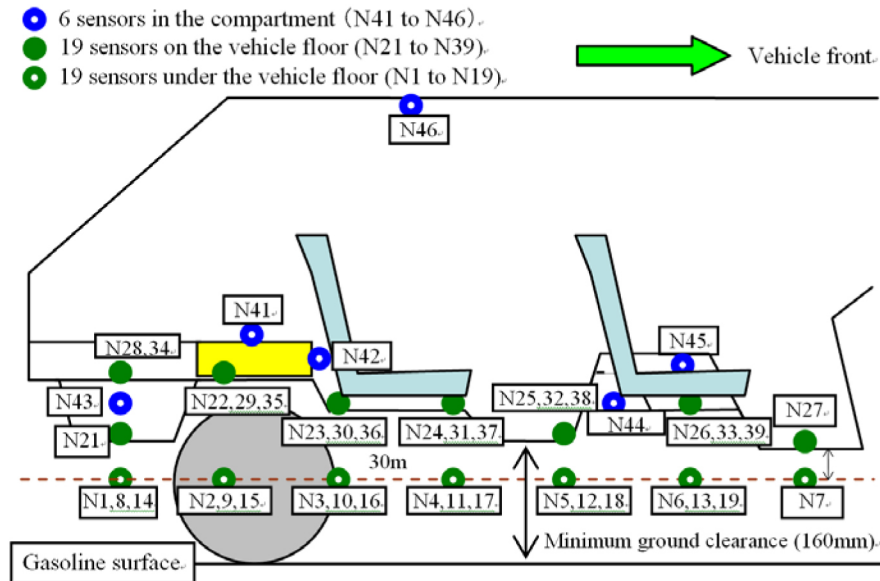


Fig. 4. Sectional view: Locations of the temperature sensors

The temperature sensors around the battery box shown in Fig. 3 (c) and Fig. 4 (N22, N41, and N42) were installed to measure the thermal input temperature to the battery box.

2. ASPECTS OF FLAMES IN THE FIRE EXPERIMENT

Figure 5 shows the aspects of the vehicle fire in this experiment. Winds blew from the left behind the vehicle to the right ahead of the vehicle. For this reason, the gasoline flames heated the vehicle floor from the rear toward the front of the vehicle, leaving the rearmost underfloor part of the vehicle (under the floor, 1st row) not directly exposed to the flames.

In this experiment, gasoline flames first heated the vehicle floor from below, reached the sides, and then entered the compartment through the side windows, ignited the ceiling, and burned the entire compartment.

3. RESULTS OF EXPERIMENT

3.1. Fire phenomena in the vehicle fire and temperature change

Figure 6 shows an example of measurements by the temperature sensors installed under and on the vehicle floor. During the first few minutes following the ignition of the pool of gasoline, the temperatures under the floor rapidly changed. This was presumably because the sensors were directly exposed to the gasoline flames, so the movements of the spreading flames directly influenced the measured temperatures. After this rapid change, the temperatures shifted to a gradual, steady change. The chassis of the vehicle becomes a reflector of the heat by gasoline bursting into flames. Therefore, in this case, the heat of the flame of gasoline reflects in the lower part of the chassis of a vehicle, and the reflected heat is applied to gasoline. It is considered that burning velocities of gasoline result in increase. Moreover, the situation of supplying oxygen in the circumstance changes. However, the total quantity of heat is controlled by setting up the quantity of gasoline in this study.

As the total quantity of heat, 40 liters gasoline was burned for about 8 minutes.

After the ignition of the pool, the temperatures of the sensors on the floor started to rise due to heat from under the floor. The reason why there was not a rapid temperature change in this period was presumably that the heat of gasoline flames was conducted upward through the chassis, causing the temperatures to even out. Afterward, the fire reached inside the compartment, and the temperatures on the floor rose. For this reason, in the range of the more gradual temperature change that started about five minutes after ignition, the decrease in the heat power of gasoline flames and the increase in the heat power of the compartment fire caused the temperature sensors under the floor to be significantly influenced by the heat from the compartment fire, which led the temperatures on both sides of the floor to reach similar levels.

The above results suggest that in this fire experiment, the fire passed from a fire in which heat was generated by gasoline to one in which heat was generated by fire in the compartment. In the discussion below, the former is called **Gasoline heat source mode** and the latter **Internal fire heat source mode**. The timing of the shift from the former to the latter is called **Mode shifting time**.

3.2. Input temperature from gasoline flames

The input temperature from gasoline flames was examined in the range of the gasoline heat source mode that was not influenced by the fire in the compartment. Figure 7 shows the measurements by the temperature sensors installed under the floor, those of the third row. The temperatures in the direction of the vehicle width showed drastic, diverse changes for some time following the ignition. These three points showed roughly the same fluctuation ranges. Figure 8 shows the average temperatures in these ranges of fluctuation and distribution of temperatures in this mode, revealing that the highest average temperature was 841°C.