

Safety Risks to Emergency Responders from Lithium-Ion Battery Fires in Electric Vehicles



Safety Report

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**National
Transportation
Safety Board**

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490 L'Enfant Plaza, S.W.
Washington, D.C. 20594

National Transportation Safety Board. 2020. *Safety Risks to Emergency Responders from Lithium-Ion Battery Fires in Electric Vehicles*. Safety Report NTSB/SR-20/01. Washington, DC.

Abstract: As part of an investigation into the safety risks emergency responders face when dealing with the high-voltage lithium-ion batteries that power electric vehicles, the National Transportation Safety Board (NTSB) studied three electric vehicle crashes resulting in fires (in Lake Forest and Mountain View, California, and Fort Lauderdale, Florida) and one noncrash fire involving an electric vehicle (in West Hollywood, California). The crashes caused extensive damage that extended into the protected area of the cars' high-voltage battery cases, rupturing the cases and damaging battery modules and individual cells. The noncrash fire was caused by an internal battery failure. In each case, emergency responders faced safety risks related to electric shock, thermal runaway, battery ignition and reignition, and stranded energy. The investigation also examined national and international standards established to maximize the safety of electric vehicles and the emergency response guides produced by vehicle manufacturers. The NTSB identified two main safety issues: (1) inadequacy of vehicle manufacturers' emergency response guides for minimizing the risks to first and second responders (firefighters and tow operators) posed by high-voltage lithium-ion battery fires in electric vehicles, and (2) gaps in safety standards and research related to high-voltage lithium-ion batteries involved in high-speed, high-severity crashes. On the basis of its findings, the NTSB makes safety recommendations to the National Highway Traffic Safety Administration, the manufacturers of electric vehicles equipped with high-voltage lithium-ion batteries, and six professional organizations that represent or operate training programs for first and second responders.

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Acronyms and Abbreviations

AC	alternating current
BEV	battery electric vehicle
CFR	<i>Code of Federal Regulations</i>
CTIF	International Association of Fire and Rescue Services (<i>Comité Technique International de prévention et d'extinction du Feu</i>)
DC	direct current
Euro NCAP	European New Car Assessment Programme
FMVSSs	<i>Federal Motor Vehicle Safety Standards</i>
GTR	global technical regulation
hazmat	hazardous materials
hp	horsepower
ISO	International Organization for Standardization
km/hr	kilometers per hour
kWh	kilowatt-hour
NCAP	New Car Assessment Program
NFPA	National Fire Protection Association
NFRD	Norwegian Fire and Rescue Department
NHTSA	National Highway Traffic Safety Administration
NiMH	nickel–metal hydride
NTSB	National Transportation Safety Board
PHEV	plug-in hybrid electric vehicle
PPE	personal protective equipment
SAE	SAE International (formerly Society of Automotive Engineers)
SCBA	self-contained breathing apparatus
SUV	sport utility vehicle
UNECE	United Nations Economic Commission for Europe
US-101	US Highway 101

Executive Summary

The National Transportation Safety Board (NTSB) investigated three electric vehicle crashes resulting in postcrash fires and one noncrash fire involving an electric vehicle, all of which illustrate the risks to emergency responders posed by the vehicles' high-voltage lithium-ion batteries. The NTSB also examined national and international standards established to maximize the safety of electric vehicles. Particular attention was given to the emergency guidance documents supplied by vehicle manufacturers to mitigate the safety risks to first and second responders who deal with electric vehicle crashes and high-voltage lithium-ion battery fires.¹

Fires in electric vehicles powered by high-voltage lithium-ion batteries pose the risk of electric shock to emergency responders from exposure to the high-voltage components of a damaged lithium-ion battery. A further risk is that damaged cells in the battery can experience uncontrolled increases in temperature and pressure (thermal runaway), which can lead to hazards such as battery reignition/fire. The risks of electric shock and battery reignition/fire arise from the “stranded” energy that remains in a damaged battery.

Safety Issues

The investigation identified the following safety issues:

- Inadequacy of vehicle manufacturers' emergency response guides for minimizing the risks to first and second responders posed by high-voltage lithium-ion battery fires in electric vehicles.
- Gaps in safety standards and research related to high-voltage lithium-ion batteries involved in high-speed, high-severity crashes.

Findings

- Manufacturers' emergency response guides provide sufficient vehicle-specific information for disconnecting an electric vehicle's high-voltage system when the high-voltage disconnects are accessible and undamaged by crash forces.
- Crash damage and resulting fires may prevent first responders from accessing the high-voltage disconnects in electric vehicles.
- The instructions in most manufacturers' emergency response guides for fighting high-voltage lithium-ion battery fires lack necessary, vehicle-specific details on suppressing the fires.
- Thermal runaway and multiple battery reignitions after initial fire suppression are safety risks in high-voltage lithium-ion battery fires.

¹ Additional information related to this safety report (NTSB case number HWY19SP002) can be found by accessing the [Docket Management System](https://www.nts.gov/docket-management-system) at www.nts.gov. For more information about NTSB safety recommendations, see the [Safety Recommendation Database](https://www.nts.gov/safety-recommendation-database) at www.nts.gov.

- The energy remaining in a damaged high-voltage lithium-ion battery, known as stranded energy, poses a risk of electric shock and creates the potential for thermal runaway that can result in battery reignition and fire.
- High-voltage lithium-ion batteries in electric vehicles, when damaged by crash forces or internal battery failure, present special challenges to first and second responders because of insufficient information from manufacturers on procedures for mitigating the risks of stranded energy.
- Storing an electric vehicle with a damaged high-voltage lithium-ion battery inside the recommended 50-foot-radius clear area may be infeasible at tow or storage yards.
- Electric vehicle manufacturers should use the International Organization for Standardization standard 17840 template to present emergency response information.
- Action by the National Highway Traffic Safety Administration, similar to that taken by the European New Car Assessment Programme, to incorporate scoring relative to the availability of a manufacturer's emergency response guide and its adherence to International Organization for Standardization standard 17840 and SAE International recommended practice J2990 into the US New Car Assessment Program, would be an incentive for manufacturers of vehicles sold in the United States with high-voltage lithium-ion battery systems to comply with those standards.
- Although existing standards address damage sustained by high-voltage lithium-ion battery systems in survivable crashes, as defined by federal crash standards, they do not address high-speed, high-severity crashes resulting in damage to high-voltage lithium-ion batteries and the associated stranded energy.

Recommendations

To the National Highway Traffic Safety Administration:

When determining a vehicle's US New Car Assessment Program score, factor in the availability of a manufacturer's emergency response guide and its adherence to International Organization for Standardization standard 17840 and SAE International recommended practice J2990. (H-20-30)

Convene a coalition of stakeholders to continue research initiated by your organization on ways to mitigate or deenergize the stranded energy in high-voltage lithium-ion batteries and to reduce the hazards associated with thermal runaway resulting from high-speed, high-severity crashes. Publish the research results. (H-20-31)

To the manufacturers of electric vehicles equipped with high-voltage lithium-ion batteries: (BMW Group; BYD Motors; FCA Group; General Motors Company; Ford Motor Company; Gillig; Honda Motor Company; Hyundai Motor Company; Karma Automotive; Kia Motors Corporation; Mercedes-Benz USA; Mitsubishi Motors; Nissan Motor Company; Nova Bus, Inc.; Porsche Cars North America; Proterra,

Inc.; North American Subaru; Tesla, Inc., Toyota Motor North America; Van Hool NV; Volkswagen Group of America; and Volvo Car Corporation):

Model your emergency response guides on International Organization for Standardization standard 17840, as included in SAE International recommended practice J2990, and incorporate vehicle-specific information on (1) fighting high-voltage lithium-ion battery fires; (2) mitigating thermal runaway and the risk of high-voltage lithium-ion battery reignition; (3) mitigating the risks associated with stranded energy in high-voltage lithium-ion batteries, both during the initial emergency response and before moving a damaged electric vehicle from the scene; and (4) safely storing an electric vehicle that has a damaged high-voltage lithium-ion battery. (H-20-32)

To the National Fire Protection Association, the International Association of Fire Chiefs, the International Association of Fire Fighters, the National Alternative Fuels Training Consortium, the National Volunteer Fire Council, and the Towing and Recovery Association of America:

Inform your members about the circumstances of the fire risks described in this report and the guidance available to emergency personnel who respond to high-voltage lithium-ion battery fires in electric vehicles. (H-20-33)

1 Introduction

1.1 Overview

For more than 100 years, highway vehicles have been powered by internal combustion engines that burn gasoline or diesel fuel. In the last 20 years, however, vehicles running on *alternative fuels* have become popular, viewed as a means of reducing the world's dependence on fossil fuels, lowering fuel costs, and lessening environmental pollution. The most widely used alternative vehicle fuel is electricity.¹

By 2000, vehicles combining an internal combustion engine with an electric motor, known as *hybrid-electric vehicles*, had been introduced to the US market (Honda Insight, 1999; Toyota Prius, 2000).² The vehicles used the electric motor as a secondary power source (to assist the internal combustion engine in acceleration, for example) and also to capture the kinetic energy from braking that would ordinarily be converted to heat and lost.³ A nickel–metal hydride (NiMH) battery, charged by the internal combustion engine, powered the motors in the early hybrid vehicles.⁴ The output of the motors was small, ranging from 13 to 40 horsepower (hp).

Plug-in hybrid electric vehicles (PHEVs) equipped with more powerful electric motors were introduced 10 years later.⁵ The first widely available PHEV was the 2011 Chevrolet Volt. The Volt had a 149-hp electric motor powered by a high-voltage lithium-ion battery, in addition to a small, 84-hp gasoline engine.⁶

Today, *battery electric vehicles* (BEVs) are becoming the dominant alternative energy vehicles.⁷ BEVs have a fully electric powertrain—that is, they do not have an internal combustion engine but are powered solely by an electric motor fueled by rechargeable batteries.⁸ Early BEVs included the Tesla Roadster, introduced in 2008; the Nissan Leaf, introduced in 2010; and the Tesla model S, introduced in 2012. High-voltage lithium-ion batteries are the standard power source for BEVs.

¹ Other common alternative vehicle fuels are natural gas, hydrogen, propane (liquefied petroleum gas), and biodiesel.

² The Prius was introduced in Japan in 1997; the Insight was launched in Japan the same year as in the United States (see [Car and Driver website](#), accessed August 4, 2020).

³ The process is known as *regenerative braking*. The captured energy is stored in the battery.

⁴ Some manufacturers of electric vehicles, such as Toyota, continue to use NiMH batteries in their hybrid electric vehicles.

⁵ PHEVs are so named because their batteries are charged by plugging into an external electrical socket.

⁶ (a) In automotive engineering, *high voltage* is considered to be any amount above the maximum voltage safe for humans; see sections 1.3.1 and 1.3.2 for details. (b) The gasoline engine could generate power for the Volt's electric motor after the battery lost its charge, thereby extending the car's range.

⁷ According to year-end data, BEVs accounted for three-quarters of electric vehicle sales in the United States during 2019 (combined sales of PHEVs and BEVs totaled 326,000). See [Green Car Congress website](#) and [Argonne National Laboratory website](#), both accessed March 18, 2020.

⁸ Batteries that produce the power to move a vehicle are called *traction batteries*.

1.2 Scope of Report

By virtue of its mandate to study transportation safety issues, the National Transportation Safety Board (NTSB) has an interest in the safety of emerging technology, including alternative fuel sources. Safety issues with the high-voltage lithium-ion batteries used in electric vehicles first gained widespread attention when a Chevrolet Volt caught fire 3 weeks after a crash test in May 2011.⁹ The National Highway Traffic Safety Administration (NHTSA), which oversaw the crash test, investigated both the cause of the fire and the risk of fire in Volt cars that experienced serious crashes. After reviewing all reports of severe events involving Chevrolet Volts, NHTSA found no record of any crash-related fires involving batteries in a Volt, or in any other electric vehicle.¹⁰ Although NHTSA found no defect with the Volt, Chevrolet modified the design of the vehicle's battery case to offer improved resistance to crash damage.

At the time of the Volt fire, the transportation industry was beginning to evaluate the safety of lithium-ion batteries. In the weeks before the Chevrolet Volt fire, NHTSA sponsored a technical symposium on lithium-ion battery safety that summarized work by NHTSA, the US Department of Transportation, and the US Department of Energy in developing safer batteries for electric vehicles.¹¹ By then, NHTSA had developed a multitiered research plan to “understand failure risks, develop safety methods, and develop performance-based metrics” for lithium-ion batteries.¹² In the years that followed, NHTSA continued to sponsor conferences at which experts identified topics for further research.

In late 2011, NHTSA began working with the National Fire Protection Association (NFPA) to assist first responders (firefighters) and second responders (tow operators) in handling lithium-ion batteries after a crash, and was working with vehicle manufacturers to develop postcrash protocols for dealing with vehicles powered by lithium-ion batteries.¹³ The previous year, the NFPA had published the results of a study of the hazards to firefighters and emergency responders from electric vehicles, though focus was on the NiMH batteries then in common use (Grant 2010). A more recent study (Long and others 2013) laid out best practices for emergency responders to hazards involving the batteries in electric vehicles. In 2015, the NFPA began publishing emergency field guides for alternative fuel vehicles as part of its safety training program.

The first NTSB investigations of lithium-ion battery fires involved safety risks in aviation. In 2013, the NTSB investigated a lithium-ion battery fire in a Boeing 787 aircraft in Boston and

⁹ Section 3.1 describes the incident in detail.

¹⁰ This information is from NHTSA's report on the Volt fire (Smith 2012). Severe events were considered those in which an airbag deployed, an occupant was injured, or the vehicle's speed changed by more than 12 mph. See also NHTSA's [press release](#) of January 20, 2012, issued after its investigations were complete.

¹¹ The symposium (held May 18, 2011) was titled “Safety Considerations for EVs [electric vehicles] powered by Li-ion [lithium-ion] Batteries.” The Department of Energy's slide presentation can be viewed on the [NHTSA website](#) (accessed November 12, 2020).

¹² As stated in Smith (2012), p. 4.

¹³(a) *First responders* in this context refers to firefighters, but emergency medical technicians, paramedics, and police officers are also classified as first responders. *Second responders* in this context refers to tow truck drivers or tow yard operators, but they can also include those responsible for temporary traffic control or other support functions at a crash site. (b) The NFPA's efforts are reported in Smith (2012).

assisted in investigating lithium-ion battery fires in another Boeing 787 aircraft (in Japan) and in a Boeing 747 (in the United Arab Emirates). As a result of its investigation of the Boeing 787 fire in Boston, the NTSB issued safety recommendations for assessing and managing the risk of short circuit and fire in lithium-ion batteries (NTSB 2014). Also in 2013, the NTSB convened a public forum titled “Lithium Ion Batteries in Transportation,” and has continued to monitor safety issues related to lithium-ion batteries in aircraft. In 2018, the NTSB addressed hydrogen fuel cell electric vehicles when it investigated a fire on a vehicle transporting compressed hydrogen for use at a fueling station (NTSB 2019c). More recently, in May 2020, the NTSB issued a safety recommendation report titled *Standards for Lithium-Ion Battery Shipments by Air* (NTSB 2020b), following a fire involving large-format lithium-ion batteries that had been delivered by air. (See the appendix for further information on the above NTSB activities.)

The NTSB’s first investigation of electric vehicle battery fires on US roadways was in 2017, when a high-voltage lithium-ion battery caught fire after a BEV left the road and crashed into a residential garage at high speed (for details, see section 2.1). By 2017, the market leader in the electric vehicle industry was Tesla, Inc., which now accounts for about 80 percent of BEV sales in the United States.¹⁴ Between 2017 and 2018, the NTSB investigated two other high-speed, high-severity crashes that resulted in postcrash fires (see sections 2.2 and 2.3) and one noncrash fire involving a BEV (see section 2.4), all of which involved Tesla-manufactured vehicles. During the course of its investigations, the NTSB considered the safety risks to first and second responders posed by the vehicles’ high-voltage lithium-ion batteries—risks that differ from the issues presented by fires in vehicles powered by internal combustion engines. This safety report focuses on those risks.

As the NTSB concluded its investigations, international incidents concerning other vehicle manufacturers came to light, including the three high-voltage lithium-ion battery fires in Europe that are described in section 3. In addition, NTSB investigators evaluated six data sources for information on the prevalence of fires in electric vehicles. The research found that while each database contained some information related to vehicle fires, all had serious limitations—for example, in their ability to identify batteries as the source of vehicle fires.¹⁵

Section 4 describes regulatory and industry actions undertaken to maximize the safety of both the vehicles powered by high-voltage batteries and the emergency personnel who respond to crashes and other incidents involving those vehicles. The section concludes with a summary of the guidance available to emergency responders, including a detailed review of the emergency response guides published (voluntarily) by the manufacturers of electric vehicles.¹⁶ Section 5 presents the NTSB’s analysis and makes recommendations for addressing (1) inadequacies in the vehicle manufacturers’ guidance for minimizing the risks to emergency responders posed by high-voltage lithium-ion battery fires, and (2) gaps in the standards and research related to high-voltage lithium-ion batteries involved in high-speed, high-severity crashes. Below, we

¹⁴As reported for 2017 by Statista, “[Tesla Dominates the US Electric Vehicle Market](#),” and for 2019, also by Statista, “[Estimated Battery Electric Vehicle Sales in the US by Brand 2019](#)” (both accessed September 28, 2020).

¹⁵The data report (“Prevalence of Electric Vehicle Battery Fires”) is available in the [NTSB public docket](#) (case number HWY19SP002).

¹⁶There are no federal requirements for emergency response guides, although regulations cover the transportation and disposal of high-voltage lithium-ion batteries.

characterize the lithium-ion batteries that power BEVs and outline the unique risks they pose to first and second responders.

1.3 High-Voltage Lithium-Ion Batteries

BEVs require high-energy batteries—batteries that store significant quantities of energy (electricity), retain it efficiently, and discharge it at a high rate. Lithium-ion batteries have been chosen for BEVs because they have high energy density (allowing them to store large amounts of energy for a given volume), a low self-discharge rate (allowing them to retain a charge), and excellent electrochemical potential (allowing high-power discharge). Protection circuits are necessary to maintain charging and discharging within safe limits.

1.3.1 Properties

Like all batteries, lithium-ion batteries consist of cells that produce an electric current by converting chemical energy into electrical energy. Each battery cell consists of two electrodes (one negative, the *anode*, and one positive, the *cathode*) that conduct electricity. A permeable barrier between the electrodes prevents internal short-circuiting and allows another substance, the *electrolyte*, to transfer charged ions between the electrodes.¹⁷ The anode is typically made of carbon (graphite), and the cathode generally consists of layers of lithium and metal oxide.¹⁸ The electrolyte consists of a lithium salt dissolved in an organic solvent, mainly carbonates. (Electrolytes in lithium-ion batteries can be liquids or gels.) The organic solvents used in lithium-ion batteries are flammable.¹⁹

The more ions an electrode can absorb and release in relation to its size and weight—known as *capacity*—the more energy it can store. Capacity is measured in kilowatt-hours (kWh)—meaning the amount of electricity a battery can deliver or absorb over the course of 1 hour. The battery in the 2011 Chevrolet Volt (a PHEV equipped with both an internal combustion engine and an electric motor) has a capacity of 16 kWh. In the fully electric 2019 Tesla model S, which has both a basic and a high-performance version, the battery capacity ranges from 60 to 100 kWh.

The *voltage* of a battery (expressed in volts) is its potential to produce an electric current—that is, to push electrons around a closed circuit.²⁰ The lithium-ion batteries in electric vehicles are described as high-voltage because they have a potential of 300 to 400 volts or more, with 800-volt electric vehicles planned or already on the market.²¹ In comparison, the familiar lead-acid car

¹⁷ The *charged ions* in a lithium-ion battery are atoms of the element lithium that are missing one electron, giving them a positive electrical charge. Lithium is the lightest metal on the periodic table of elements.

¹⁸ Various metal oxides are employed in lithium-ion batteries, including lithium cobalt oxide (LiCoO₂), the most common. The batteries in the four fires investigated by the NTSB contained lithium nickel manganese cobalt oxide (LiNiMnCoO₂). See the online Battery University (“BU-205: Types of Lithium-ion”) for more information (accessed November 12, 2020).

¹⁹ Researchers have concluded that the flammable solvents in lithium-ion batteries are about as hazardous as the gasoline or diesel used in conventional vehicles (Stephens and others 2017, pp. 2-30–2-31).

²⁰ Technically, voltage is the difference in electric potential between two places, called the *electric potential difference*.

²¹ Porsche launched an 800-volt BEV sports car, called the Taycan, in 2019, as reported on the [Green Car Congress website](#) (accessed April 24, 2020).

battery, which supplies power to start an internal combustion engine and to run a vehicle's auxiliary electrical systems, has just 12 volts.

Lithium-ion battery cells come in various shapes and sizes (cylindrical, prismatic, elliptical, pouch). The battery for a BEV consists of individual cells packed tightly together to produce the required voltage, power, and energy. The cells are assembled into modules, and the modules assembled into battery packs and systems. The battery is packaged in a case designed to resist damage from external forces and located for protection from crashes.

Battery management systems maintain the safe operation of battery packs. In addition to monitoring voltage and temperature data from the cells and modules, they monitor the battery's state-of-charge (level of charge relative to capacity) to protect against overcharging or undercharging. The protection circuits mentioned earlier limit peak cell voltage and prevent the voltage from dropping too low. The cells are protected from temperature extremes by thermal management systems integrated into the modules and from overpressure by venting systems. Some battery designs incorporate liquid cooling systems.

Different vehicle manufacturers use different batteries and different battery packs. As shown in figure 1, the Tesla model S (like other of the manufacturer's vehicles) has a flat battery pack that lies under the floor. The battery pack is made up of thousands of small, cylindrical battery cells (slightly larger than an AA battery) packaged into 16 modules. The Chevrolet Volt, as an example from another manufacturer, uses pouch cells (about the size of a standard 8 1/2-inch by 11-inch envelope), and the battery pack is T-shaped, with the top of the T fitting under the car's back seat. The Volt's battery pack contains 192 cells packaged into four modules.

Lithium-ion batteries produce direct current (DC) power. Owners of electric vehicles can charge their cars by plugging them into a 120- or 240-volt alternating current (AC) residential outlet because the cars are equipped to convert AC power to DC. The batteries can also be charged at commercial DC fast-charging stations.²² The stations can charge a vehicle in less than an hour, compared with several hours using a residential outlet.

²² The [EVgo network](#) installs DC fast-charging stations at such locations as grocery stores (accessed November 12, 2020).

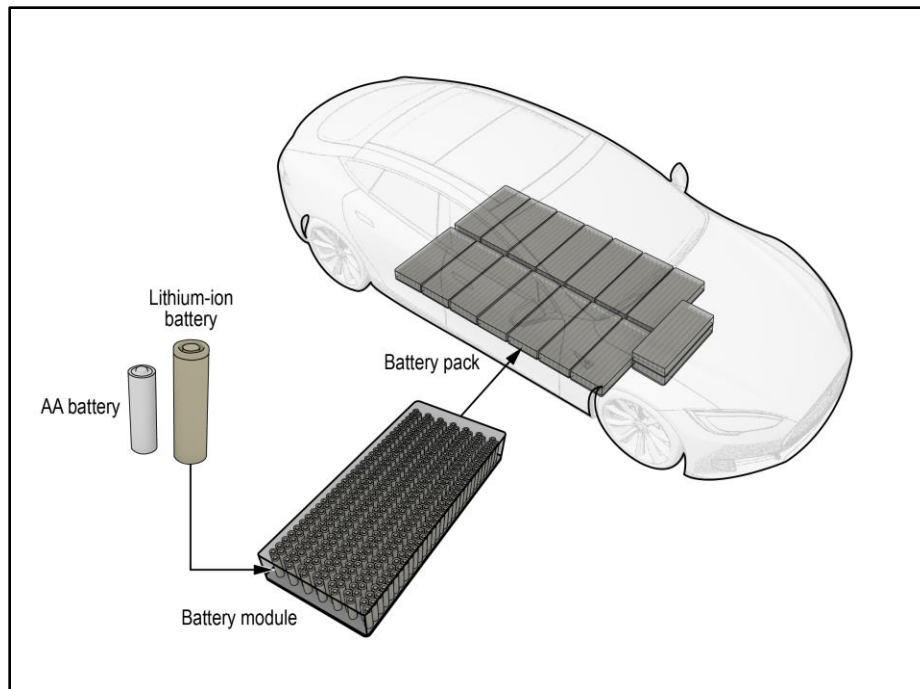


Figure 1. Illustration of Tesla model S showing location of battery pack and details of module and battery cell, with size comparison to standard AA battery. (NTSB drawing)

1.3.2 Safety Risks

Fires in electric vehicles powered by lithium-ion batteries pose two main dangers to emergency responders. First is the risk of electric shock from exposure to high-voltage connections in a damaged battery. Second is the risk that damaged cells in the battery will experience uncontrolled increases in temperature and pressure, known as *thermal runaway*, which can lead to venting and combustion of toxic gases, cell rupture and release of projectiles, and battery reignition/fire. The risks of electric shock and battery reignition/fire arise from the energy that remains in a damaged battery—known as *stranded energy*.

Electric shock. The human body is an electrical conductor; if it contacts an energized source of electricity, current will flow through it. The body's *resistance*—its ability to reduce an electric current—varies from person to person and according to whether the skin is wet or dry, among other things. The maximum voltages considered safe for humans are 50 or 60 volts DC and 30 volts AC.²³ The high-voltage system of a BEV operates well above those thresholds (at 300 to 400 volts or more), creating a safety risk when the high-voltage battery is damaged in a crash and safety features such as protective covers and circuit fuses are defeated. As described in section 4, to protect occupants, bystanders interacting with injured persons, and emergency responders from electric shock, safety standards require electrically isolating the high-voltage battery system from the vehicle's chassis. If a crash damages the electrical isolation system, a person who touches the

²³ The thresholds are based on International Electrotechnical Commission technical standard 60479-1; 2005-07, "Effects of Current on Human Beings and Livestock." The physiological effects of an electric current can be anything from a slight prickling sensation to burns and respiratory or cardiac arrest. DC current has a less-severe effect on the human body than AC current.

vehicle (or an exposed connector) can become part of the high-voltage circuit and suffer serious injury or death.

Thermal runaway. Thermal runaway is a chemical process that produces heat (an *exothermic reaction*); the heat increases the rate of the reaction, which further increases the temperature and escalates the process. Thermal runaway can spread from one battery cell to many cells, in a domino effect. The originating cause of thermal runaway is generally short-circuiting inside a battery cell and a resulting increase in the cell's internal temperature. A short circuit in a lithium-ion battery cell can result from defects introduced during manufacturing, such as contamination, or from damage to the cell caused by crushing or puncturing—precisely the kind of damage produced by high-impact, high-severity car crashes. An external fire might also heat a battery cell enough to initiate thermal runaway.

Fire and explosion can result when cells go into thermal runaway. The flammable solvent in the electrolyte can ignite if exposed to high temperatures or electrostatic sparks. Popping or other noises resulting from the venting of heat and gases often accompany a thermal runaway. A recent study (Stephens and others 2017) identified four primary hazards of thermal runaway: (1) venting of toxic and flammable vapors from the electrolytic solvent, through pressure-relief devices or holes in the battery casing; (2) combustion of vapors ejected from the flammable electrolyte solvent; (3) localized overpressure; and (4) rupture of the cell casing and release of projectiles if pressure-relief devices are absent or fail. Secondary hazards identified in the study were release of toxic and corrosive chemicals, ignition and burning of combustible parts of the vehicle, asphyxiation of vehicle occupants from toxic gases vented by the battery, and electric shock to occupants, first responders, or maintenance personnel from exposure to high-voltage conductors if electrical insulation and isolators melt or burn. Flammable gases (hydrogen, ethylene, ethane, and propane) released from a damaged battery constitute the most significant fire threat, according to the study.

As detailed in later sections of this report, extinguishing a burning lithium-ion battery can require applying thousands of gallons of water. Section 3 describes a method that firefighters in Europe have used to extinguish a lithium-ion battery fire—submerging the entire vehicle in a vat filled with water. That method, however, creates a potential for short-circuiting and might also be impractical.

Stranded energy. If a high-voltage battery is damaged, energy remains inside any undamaged battery modules and cells, with no path to discharge it. That stranded energy can cause a high-voltage battery to reignite multiple times after firefighters extinguish an electric vehicle fire. Emergency responders have no way of measuring how much energy remains in a damaged battery, and no way of draining that energy, other than such time-consuming methods as allowing a battery fire to burn itself out.²⁴ Engineers or other specialists can use the battery management system to check for remaining voltage if the system is operational, and some batteries have built-in discharge ports, also for use by specialists. However, the high-voltage battery system can be damaged in a crash, preventing access to the battery management system or to the discharge ports. Moreover, as described in section 4, one of the first steps in responding to an electric-vehicle fire

²⁴ The modules in Tesla batteries are separated in such a manner that allowing one of those batteries to burn itself out would be unlikely to remove all the energy.

is to cut the supply cable to the 12-volt battery—which will depower the battery management system.

Electric vehicles are often equipped with emergency *cut loops*, low-voltage wire loops that first responders can safely cut to disconnect the high-voltage system from the rest of the vehicle.²⁵ Severing the cut loops will isolate high-voltage power inside the battery, thereby protecting the rest of the vehicle. However, cutting the loops will not remove energy from the high-voltage battery.

Manufacturers have developed tools to drain the high-voltage batteries in their vehicles, but the tools, which require a specialist to operate, are usually specific to the vehicle and work only on an intact battery.²⁶ One method of deenergizing a damaged battery is to submerge it in a saltwater bath (saltwater conducts electricity). It might not be possible, however, to extract a damaged battery from a vehicle after a severe crash, and first responders generally lack the expertise to remove a damaged battery.

²⁵ The wires are tagged at the location where they should be cut.

²⁶ Tools and techniques for assessing stranded energy are investigated in Rask and others (2020). The authors developed a prototype discharge tool, suitable for use by nonexperts, that would connect to a dedicated high-voltage access port in a protected part of an electric vehicle. The tool would, however, require access to a functional battery management system or direct connection to internal battery modules. Such access would be problematic, or impossible, in the case of a battery that had been damaged in a crash or had suffered thermal runaway.

2 NTSB Investigations of Electric Vehicle Battery Fires

The NTSB investigated all US domestic high-voltage battery fires in electric vehicles that we became aware of during a one-year period (August 2017 to August 2018).²⁷ In the four fires involving lithium-ion batteries that the NTSB identified during that period, three of the batteries had been damaged in high-speed, high-severity crashes that preceded the fires. All three crash-damaged batteries reignited after firefighters extinguished the vehicle fires. (For purposes of this report, a battery fire reignition is defined as a fire event—smoke, popping noises from the battery, or actual flames—that occurs in the battery after the vehicle fire has been extinguished and the vehicle has been stable for several minutes.)²⁸ The battery in the fourth case—a fire that occurred during normal vehicle operations—did not reignite.

All the batteries were examined after the incidents, as described below. For each incident, we indicate whether first and second responders consulted the emergency response guidance made available by the vehicle maker or contacted the manufacturer directly.²⁹ Note that full personal protective equipment (PPE) and self-contained breathing apparatus (SCBA) are standard firefighter equipment for all vehicle fires, not just those involving electric vehicles (Long and others 2013, p. 18).

2.1 Lake Forest, California, August 2017

On Friday, August 25, 2017, at 6:17 p.m. Pacific daylight time, a 2016 Tesla model X sport utility vehicle (SUV), occupied by a driver and one passenger, was traveling on a residential street in Orange County, California, that had a posted speed limit of 35 mph. The driver lost control of the vehicle, which left the road, crossed a sidewalk and an embankment, traveled down a drainage ditch, and collided with a culvert. Ultimately, the SUV hit a property wall, an open garage, and an unoccupied car parked in the garage. According to the SUV's onboard event data recorder, the driver had accelerated to 82 mph shortly before the crash.³⁰ The driver sustained serious injuries in the crash, and the passenger received minor injuries. A postcrash fire spread from the SUV to the car parked in the garage, the garage itself, and the house (figure 2).

²⁷ All the vehicles were BEVs.

²⁸ Reignition can occur with lithium-ion batteries because the battery itself contains the three elements necessary to sustain a fire (heat, fuel, and oxygen). Popping noises inside or between battery cells indicate an exchange of energy.

²⁹ See sections 4.3 and 4.4 for recommended practices and guidance for responding to electric vehicle fires. Emergency response guides are discussed in section 4.5.

³⁰ A report on the data retrieved from the vehicle's electronic control unit can be found in the [public docket](#) for this crash (NTSB case number HWY17FH013). The Factual Report of Investigation and other documents in the public docket give further details about the crash.



Figure 2. Postcrash view of garage showing firefighter directing water onto burning SUV and smoke coming from garage roof. (Source: Orange County Sheriff's Department)

2.1.1 Initial Response

The Orange County Fire Authority received the first alarm at 6:17 p.m., and firefighters arrived on scene at 6:25 p.m. Officers from the Orange County Sheriff's Department arrived at 6:28 p.m. and set up a unified command. The officers managed the scene, which included identifying those involved and taking witness statements.

When firefighters arrived, both the SUV and the house were on fire. The first crew on scene attacked the vehicle fire in the garage with water. By 6:44 p.m., the bulk of the fire was out, but there appeared to be a fuel source in the garage, and fire was burning in the attic above the garage. The garage structure was sagging, making it difficult for firefighters to access the attic fire, which threatened the house. Firefighters halted the progress of the structural fire by about 7:00 p.m. The fire under the SUV appeared to be extinguished but then reignited an unspecified number of times.

By 7:17 p.m., the crew from the heavy rescue truck on scene had stabilized the garage wall. Firefighters then removed the SUV from the garage to assess the fire and identified the fuel source as the SUV's high-voltage battery pack. At 8:04 p.m., after the SUV had been pulled onto the driveway, the battery reignited. The fire was quickly extinguished using water, after which the SUV remained stable for about 45 minutes. During that time, firefighters brought the house fire under control.

The SUV began to emit heavy white smoke 45 minutes after the flames had been extinguished. The SUV ignited again and began burning in what firefighters described as a "blowtorch" manner. Firefighters applied water at up to 200 gallons per minute, but that did not

extinguish the flames. The crew allowed the vehicle to burn freely to eliminate as many interior combustibles as possible. At 9:13 p.m., firefighters propped the SUV on cribbing blocks to expose the underside and applied more water, at a maximum rate of 600 gallons per minute, for about 45 minutes to cool the battery.³¹ Applying water to the underside of the SUV extinguished the fire.

One of the responding battalion chiefs told investigators that the fire was “very severe” and more difficult to extinguish than firefighters expected. Even though they applied a large amount of water, the underside of the vehicle kept reigniting and would not go out. According to the battalion chief, the fire crews reviewed emergency response guides and searched online for guidance on the appropriate action to take.³² The chief said that firefighters used breathing apparatus because of the large amounts of acrid smoke—he said it felt almost like a hazmat (hazardous materials) fire. He also said that those commanding the fire response would have liked to let the vehicle fire burn itself out, but they were concerned that it could take up to 24 hours and that the smoke would affect people in the neighborhood.³³

As a result of the initial emergency response efforts, two Orange County Sheriff’s Department officers sustained minor injuries from smoke inhalation. More than 20,000 gallons of water were applied to the vehicle fire, at varying rates, over at least 2 hours.

2.1.2 Secondary Response

A vehicle towing service was called at 10:40 p.m. and arrived at 11:09 p.m. While the SUV was being loaded onto the tow truck, it again began to emit smoke, and the battery fire reignited (figure 3). Firefighters applied water, but they had difficulty directing the water under the vehicle because it was resting on planks (its wheels had been displaced in the crash). The SUV was lowered off the flatbed, and firefighters again extinguished the fire. The tow truck driver suffered minor burns to his arms while lowering the SUV off the flatbed because the controls were near the sides of the burning vehicle, and he had to remove his wet, slippery gloves to operate them.

Firefighters continued applying water at about 300 gallons per minute to cool the battery. Once the battery had cooled, the SUV was towed from the scene. The time was 12:21 a.m., about 6 hours after the crash.

³¹ *Cribbing blocks* are temporary wooden structures used to support heavy objects during construction, vehicle extrication, and so forth.

³² The chief did not say explicitly that the crew consulted the vehicle manufacturer’s emergency response guide, but the guide for the SUV gives locations and descriptions of high-voltage components, airbags, inflation cylinders, seat belt pretensioners, and the high-strength materials in the vehicle body. The guide includes a high-voltage disabling procedure and safety considerations specific to this SUV. See section 4.5 for more information about the emergency response guides and how they can be accessed.

³³ The vehicle’s emergency response guide states: “Battery fires can take up to 24 hours to extinguish. Consider allowing the battery to burn while protecting exposures.”



Figure 3. Still image from video taken by sheriff's department officer showing SUV reloaded on flatbed of tow truck. (Source: Orange County Sheriff's Department)

The battery reignited for a few seconds while the SUV was being unloaded at the tow yard. Although the vehicle emitted smoke, it did not catch fire, and the tow driver did not call for an emergency response.³⁴ The SUV was positioned at the tow yard as far from other vehicles or buildings as possible—about 40 feet from other vehicles on two sides, about 20 feet from other vehicles on the third side, and about 10 feet from a concrete wall on the fourth side. According to the towing log, the job was completed at 1:15 a.m.

2.1.3 Postcrash Inspection

On September 6–7, 2017, NTSB investigators examined the SUV and the battery at the tow yard. They also visited the crash site. The SUV had extensive fire and impact damage. The high-voltage cut loop had been in the area of severe fire and impact damage to the interior, making it impossible to determine whether firefighters had been able to access and cut it. When the vehicle was raised so the underside could be viewed, investigators found that the right front corner of the battery case had ruptured, revealing individual battery cells, as shown in figure 4.

³⁴ As noted earlier, a fire event can consist of smoke or popping noises, not necessarily involving flames.

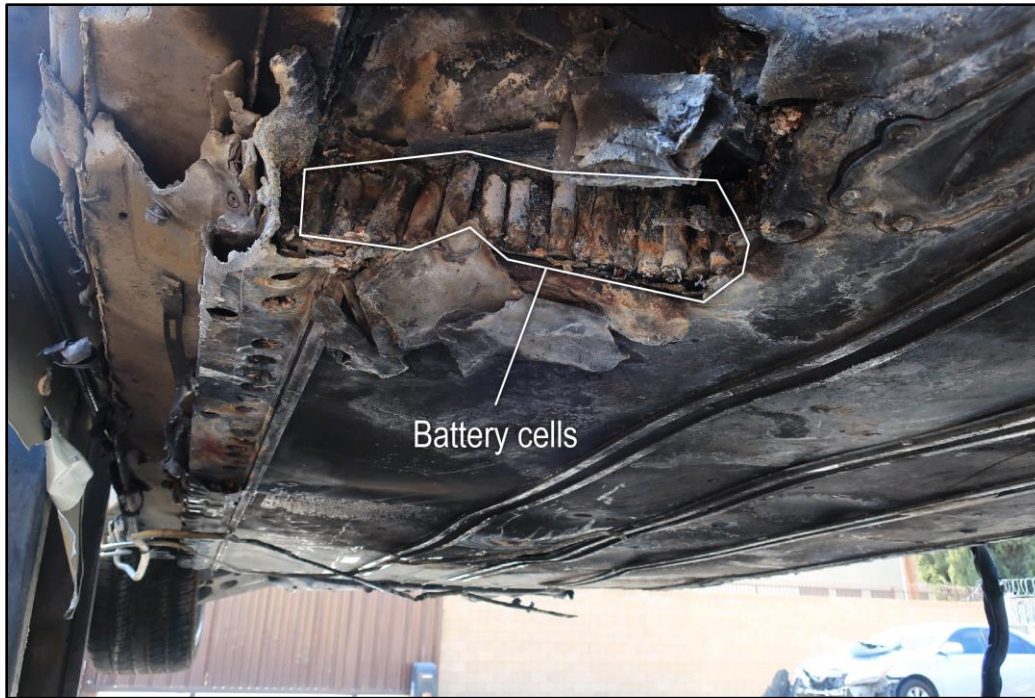


Figure 4. View from below and toward rear of SUV's underside showing ruptured right front corner of battery case and highlighting individual battery cells uncovered by rupture. Right rear wheel is visible in background.

The SUV's lithium-ion battery contained 16 modules (figure 5).³⁵ The rupture exposed parts of modules 13 and 15 at the right front corner, in line with where the right front wheel, brake disk, and other components had been displaced, most likely in the SUV's collision with the drainage culvert. Modules 11 and 9, directly behind module 13, were damaged. Battery cells from modules 13 and 15 had been dislodged or displaced, and individual cells were found on the street, in the driveway, and in the drainage ditch.³⁶

The battery showed thermal damage, warping, and deformation to about 80 percent of the exterior of the battery case (refer to figure 4). Only the rear corners did not exhibit thermal damage. All the overpressure valves showed signs of hot gas venting, and the vents at the front were completely burned away.³⁷ Those on the left side and in the middle showed extensive thermal damage, while those in the rear had less.

Although the battery exhibited thermal damage, much of it remained intact. The duration of the postcrash fire and the multiple battery reignitions were evidence that the battery contained

³⁵ All the batteries discussed in this section of the report had the same basic configuration. Readers are invited to refer to figure 5 in the sections where battery damage in the other vehicles is described.

³⁶ Each module in the SUV's battery had 515 cells.

³⁷ The spaces between the modules of the battery case contained rows of small vents housing one-way valves that would discharge hot gas in the event of thermal runaway. The valves were positioned to direct the venting gas away from the passenger compartment.

stranded energy. The amount of stranded energy could not be directly measured, however, because the module connection terminals were inaccessible.

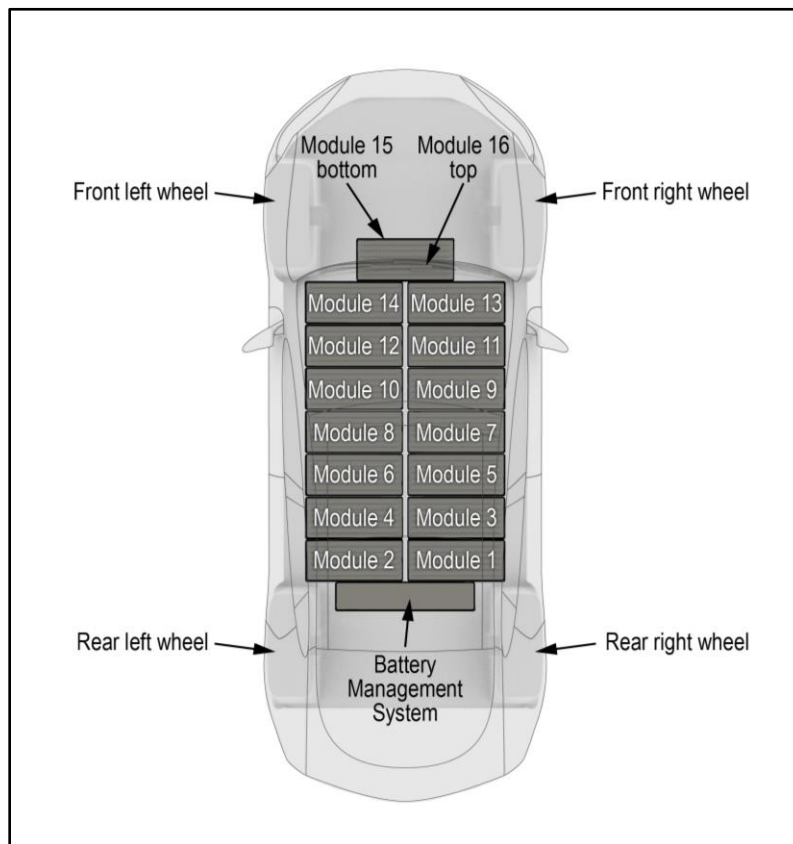


Figure 5. Arrangement of SUV's lithium-ion battery modules.

2.2 Mountain View, California, March 2018

On March 23, 2018, at 9:27 a.m. Pacific daylight time, a 2017 Tesla model X SUV was traveling on US Highway 101 (US-101) in Santa Clara County, California. The SUV entered a paved gore area dividing the main travel lanes of US-101 from State Route 85 and struck a damaged, nonoperational crash attenuator at the end of a concrete barrier at 71 mph.³⁸ The SUV collided with two other cars and caught fire after coming to rest (figure 6). The driver died of traumatic injuries sustained in the crash.³⁹

³⁸ A *crash attenuator* is a type of traffic safety hardware designed to protect motorists by reducing the collision forces on a vehicle. When the front of a vehicle hits an attenuator, the device telescopes to the rear and helps absorb the colliding vehicle's impact energy. Attenuators are usually placed in front of fixed structures on highways, such as barriers that separate traffic lanes. See the NTSB's safety recommendation report related to the collision with the attenuator in Mountain View (NTSB 2019a).

³⁹ For further details, see the NTSB's report on its investigation of the Mountain View crash (NTSB 2020a).



Figure 6. Burning SUV on northbound US-101 postcrash. (Source: witness S. Engleman)

2.2.1 Initial Response

The first emergency 911 call was received at 9:28 a.m. Three minutes later, the Mountain View Fire Department dispatched equipment and personnel to the crash scene (three engine units, one rescue unit, and a truck for patient care, fire suppression, and equipment or personnel recovery). The fire apparatus and rescue units arrived between 9:37 and 9:40 a.m. The California Highway Patrol joined the on-scene response at 9:46 a.m. and coordinated the work.⁴⁰

Firefighters told NTSB investigators that the vehicle fire was extinguished quickly, using a mixture of water and foam. They estimated that suppressing the vehicle fire took only about 30 seconds for the front and a similar time for the rear, using about 200 gallons of water and foam. Electrical arcing was visible at the front of the vehicle during fire suppression. After the flames had been extinguished, intermittent popping noises were heard, accompanied by smoke, which prompted firefighters to apply more water. Exposed electrical cables were visible in the wreckage. Firefighters tried to use a “hot stick” to measure voltage on the vehicle surfaces and exposed cables, but it did not yield a reading because it was designed to detect AC voltage.⁴¹

⁴⁰ Further documentation of the emergency response can be found in the Vehicle and Survival Factors factual report in the [public docket](#) for the Mountain View investigation (NTSB accident ID HWY18FH011).

⁴¹ A *hot stick* is safety device consisting of an insulated pole that responders can use to contact energized objects from a safe distance. New technology is being developed to measure DC voltage (Kane 2018).

Because of concerns about high voltage and stranded energy associated with the lithium-ion battery, the fire department's incident commander contacted the manufacturer about additional actions needed to make the vehicle safe. One of the manufacturer's battery engineers advised that the vehicle was not safe because of the extent of damage and that all personnel should stay away from the SUV until it could be evaluated by the manufacturer's representatives. (The crash occurred not far from the manufacturer's headquarters and its factory.)

The fire department's battalion chief coordinated with the California Highway Patrol, which agreed to keep the highway closed and wait for support from the manufacturer. While emergency responders waited, a loud popping sound came from the SUV, but no fire was apparent, so no further fire suppression was undertaken. The manufacturer sent two battery engineers, who arrived on scene about 12:30 p.m. They attempted to remove the damaged battery parts and placed loose battery cells and other battery components, including module 16 (which was in the wreckage but dislodged from the battery case) in a large bucket half-filled with water.

While the engineers attempted to remove the damaged battery components, popping sounds again came from the vehicle, and the floor of the SUV was observed to shift. The engineers moved away from the vehicle and determined that further attempts to remove damaged parts would be unsafe. A large part of the battery appeared to be intact, which made the battery a high-voltage safety risk.

The engineers determined that the SUV could not be stabilized on scene and that it should be removed. The engineers said that it would be best to maintain the vehicle on a flat surface to avoid flexing the vehicle structure (which could reignite the battery), but because the bed of the tow truck that came to the scene was metal, wooden blocks were used to maintain electrical isolation. The engineers advised having a fire truck escort the tow truck, despite anticipating an hour-long journey to the tow yard, so an escort was provided. The SUV was loaded onto the tow truck, and the scene was cleared at 3:05 p.m.

2.2.2 Secondary Response

The tow truck carrying the SUV was escorted by the California Highway Patrol and the Mountain View Fire Department to an impound yard in San Mateo, California. The engineers followed. The SUV arrived at the yard at 4:17 p.m. The engineers told NTSB investigators that they stressed the importance of leaving a 50-foot radius around the vehicle, as recommended by the manufacturer's emergency response guide, but that there was not enough room in the yard, so workers did the best they could to separate the SUV from objects that appeared to be flammable.

According to the engineers, about 20 minutes after the SUV arrived at the impound yard, a California Highway Patrol officer heard popping sounds coming from the wreckage and called the San Mateo Fire Department. A fire engine arrived at 4:46 p.m. Firefighters monitored the SUV with thermal cameras, but they took no fire suppression action. The fire engine was dispatched again to the impound yard less than an hour later (at 5:20 p.m.), after the battery reignited. Crews

monitored the vehicle, but the fire went out on its own and firefighters took no fire suppression action.⁴²

The battery reignited once again 5 days after the crash. At 7:01 p.m. on March 28, a security guard reported a fire at the impound yard. He had seen smoke coming from under a tarp that had been placed over the SUV wreckage. California Highway Patrol investigators had inspected the vehicle earlier that day, and in the course of removing electronic equipment, had stood on parts of the vehicle near the front of the battery case.

According to the San Mateo Fire Department's dispatch log, firefighters arrived at 7:09 p.m. and reported flames 8 to 12 inches high coming from the right front side of the SUV. Firefighters suppressed the fire using water and foam. A security camera recorded a firefighter applying water and foam onto the SUV, which was still partly covered by the tarp and a road sign that had been used to anchor the tarp (figure 7).



Figure 7. Image from security video at impound yard showing firefighter pouring water onto SUV at right, partly covered by tarp and road sign; fire engine is visible on left. (Source: Atlas Towing)

A hose with a capacity of 90 gallons per minute was used until it depleted the engine's 500 gallons of water, after which firefighters laid a supply line to a fire hydrant. They applied an estimated 600 to 700 gallons of water over 30 to 40 minutes, but the fire continued to emit smoke and burn. The battalion chief on scene told NTSB investigators that firefighters were concerned about the risk of electricity traveling up the water stream and had been cautiously starting and stopping the application of water.⁴³ Firefighters telephoned the manufacturer's engineers, who

⁴² The small lithium-ion battery cells used in the battery were designed to create robust separation between cells. In this case, that design was a factor in the reignitions having stopped without further intervention and without consuming the rest of the battery.

⁴³ In 2013, the NFPA commissioned research (reported in Long and others 2013) on the potential for firefighters to suffer electric shock from the water stream used to suppress electric vehicle fires—a concern because water is an electrical conductor. The research showed that the electrical current between the vehicle chassis and the firehose nozzle used in the tests was negligible, as were voltage levels at the nozzle. No adverse electrical conditions were noted. As a result of the tests, the NFPA's emergency field guides (see NFPA 2018) include a statement that "The use of water or other standard agents does not present an electrical hazard to firefighting personnel."

advised them to apply foam and that electricity “should not be a big risk,” in the chief’s words. At 8:10 p.m., after about 5 minutes of foam application, no further smoke or fire was observed.

Firefighters monitored the vehicle with a thermal camera (they also checked the temperature in the bucket of water containing battery parts assembled on scene). An engineer from the manufacturer arrived and monitored the vehicle for additional smoke, but none appeared. A San Mateo Fire Department hazmat unit tested the fire runoff and determined that it was toxic. A public works crew was brought in to vacuum about 600 gallons of water, foam, and vehicle fluids from the nearest storm drain.⁴⁴ The scene was declared safe at 9:50 p.m.

Combining both initial and secondary responses, a total of about 1,400 gallons of water and foam was used to extinguish the battery fires.

2.2.3 Postcrash Inspection

Investigators from the NTSB and representatives of the California Highway Patrol inspected the SUV on March 27 and 28, 2018, and again on April 6, 2018. They were joined at the impound yard on April 6 by a fire engine and crew from the San Mateo Fire Department and by engineers from the manufacturer, who attempted to deenergize the vehicle’s high-voltage lithium-ion battery (remove its stranded energy).

According to discussions with the manufacturer, the SUV’s high-voltage battery had a discharge port under the battery case, covered by a panel, which could be used to discharge the battery. To access the port, the engineers had the vehicle elevated on wooden blocks, but only high enough to access the port so as to minimize vehicle movement. The underside of the SUV appeared undamaged by physical or thermal effects.

Engineers removed the panel, then pulled the plug from the discharge port. Water and debris drained from the port, and mud and debris could be seen on the inside of the cover. The water and debris had rendered the port’s electrical connector nonfunctional. Engineers tried to connect a discharge apparatus to the exposed battery terminals at module 14, at the front of the ruptured battery case (refer to the battery diagram in figure 5, section 2.1.3). The discharge apparatus’s computer showed that the terminal was not connected to a functioning battery, which meant that the terminal could not be used for discharging.

The voltage between the exposed positive bus bar of module 14 and the battery case measured 25.4 volts, and about 3 volts were measured in other areas of the damaged battery.⁴⁵ Although the measured voltage was not as high as the dangerous value for DC voltage (50 to 60 volts), the values indicated the presence of energized components, and high-voltage risk was assumed. Options for cutting back or otherwise reducing the exposed bus bar were considered but could not be tried with the available tools. Instead, efforts were made to isolate the exposed terminal. The exposed orange high-voltage cables (not the cut loops mentioned earlier) were measured and were found not to have electrical potential.

⁴⁴ A San Mateo environmental health and hazardous materials specialist consulted with the fire department in determining what actions to take.

⁴⁵ An electrical *bus*, or *bus bar*, collects and distributes current, providing power to a vehicle’s various subsystems.

The engineers tried to establish a computer connection to the battery management system under the SUV's rear seat. Access was accomplished by removing burnt material and cutting into the vehicle structure. The 12-volt battery powering the battery management system had been displaced in the crash. An alternate power source was established, and a computer was attached to the appropriate points. Attempts to communicate with the battery management system were unsuccessful. Because the battery could not be deenergized and information about the battery's status could not be obtained, the battery was inspected by hand, taking appropriate electrical and fire-safety measures.

The front of the SUV was extensively damaged. The high-voltage cut loop, normally located at the base of the windshield, was missing, as was the entire front electric motor and other components.⁴⁶ The orange cables that led to the motor and other high-voltage connection points were exposed (figure 8). Attempts to measure the voltage were inconclusive, and any exposed terminals, as well as damaged battery components, were assumed to pose a high-voltage risk.



Figure 8. Damaged SUV with exposed orange high-voltage cables forward of front seat.

Removing the burnt materials at the front of the battery case, just forward of the front seats, revealed that the steel battery cover over modules 15 and 16 had peeled back and was positioned over modules 13 and 14 (refer to the battery diagram in figure 5, section 2.1.3). The modules behind modules 15 and 16 appeared to be intact, although the case around modules 13 and 14 was damaged. The vents showed evidence of thermal activity at module 8 and at modules 10 through 14 (indicating that the battery's built-in thermal defenses worked as designed to discharge hot

⁴⁶ Some electric vehicles, including the model X, have dual electric motors, one for the front wheels and another for the rear wheels.

gases generated by thermal runaway).⁴⁷ Modules 15 and 16 were too damaged to establish the status of their vents. All other vents appeared to be undamaged.

The battery having reignited at least six times was evidence that it contained stranded energy, supported by the measurements of electric potential and the presence of intact cells. Removing the battery case for further inspection was deemed unsafe. Hence, the stranded energy remaining in the battery was not assessed.

2.3 Fort Lauderdale, Florida, May 2018

On Tuesday, May 8, 2018, at 6:46 p.m. eastern daylight time, a 2014 Tesla model S car, occupied by a driver and two passengers, was traveling on an urban road in Fort Lauderdale, Broward County, Florida. The car approached a curve while traveling at a recorded speed of 116 mph in a 30-mph zone.⁴⁸ The car left the road and erupted in flames after it hit the wall beside a residential driveway. The car reentered the road, hit a light pole, and came to rest in the driveway of an adjacent residence (figure 9). The driver and front passenger suffered fatal injuries. The rear passenger sustained serious injuries.⁴⁹



Figure 9. Car burning next to residential driveway postcrash. (Source: CBS4 Miami)

2.3.1 Initial Response

The Broward County call center received the first 911 call about the crash at 6:46 p.m. Police units arrived on scene at 6:49 p.m. Firefighters from Fort Lauderdale Fire Rescue were dispatched at 6:46 p.m. and arrived on scene 4 minutes later. When firefighters arrived, heavy

⁴⁷ As noted earlier, the valves in the vents were positioned to direct hot gases away from the passenger compartment.

⁴⁸ The curve had a posted advisory speed of 25 mph.

⁴⁹ For further details, see the NTSB's report on its investigation of the Fort Lauderdale crash (NTSB 2019b).

flames were coming from the front of the car, and the heat was intense, according to the battalion chief on scene. The engine crew applied a foam/wetting agent to the fire. After the engine had used up half the 500 gallons of water in its tank, a supply line was established to a hydrant about 150 feet north of the engine, and firefighters continued attacking the fire.

After suppressing the fire in the car's interior, which took less than a minute, firefighters focused on the fire at the car's right front corner. Firefighters reported that the heat was intense and that they could see electrical arcing. The battalion chief told investigators that the fire came from a lithium-ion battery module that was lodged under the car's A-pillar.⁵⁰ The module had ruptured, and the individual battery cells inside were visible. Firefighters estimated using 200 to 300 gallons of water and foam to stop the flames and electrical arcing. Two large pieces of the battery had been completely separated from the vehicle and were found in the street. Although the pieces did not appear to be on fire, firefighters applied water and foam to them. The main part of the high-voltage battery was still connected to the car but had dropped to the ground.

The battalion chief told investigators that when he arrived on scene, he used the "Tesla app" (the company's online emergency response guide) to "get a detailed explanation of the vehicle, and where our cuts and no-cuts and things of that nature were. And it had indicated where the batteries were located up underneath the vehicle."⁵¹

2.3.2 Secondary Response

As part of the police investigation and cleanup, the vehicle and associated debris were loaded onto tow trucks. The operator of one truck told NTSB investigators that he had attended a Tesla training class and was familiar with the company's vehicles. He said that while he was winching the car onto his truck (about 7:45 p.m.), the entire battery case separated from the vehicle. The battery reignited, but a brief application of water and foam extinguished the fire. The operator said that the battery briefly reignited again when a chain passed over the battery case while the battery and two piles of debris were being loaded onto a separate truck (about 8:00 p.m.). The battery self-extinguished (fire suppression was not performed).

While being unloaded at the tow yard about 3 hours after the crash, the battery case and modules briefly arced and smoked, but the battery self-extinguished once again, without any fire suppression being performed. At the tow yard, the vehicle and debris were stored outside. The employees at the tow yard had previously worked with electric vehicles and were aware that they should be isolated. The employees put the piles of debris about 20 feet from other objects or vehicles. One pile consisted of the battery pack on a wooden pallet with other loose car parts, wrapped in clear plastic. The second pile consisted of debris wrapped in a heavy tarp.

⁵⁰ A car's *A-pillar* is an upright structural piece that supports the windshield and the front of the roof.

⁵¹ A standard feature of the manufacturers' emergency response guides described in section 4.5 is a diagram showing where firefighters can safely cut the vehicle structure (to extricate the occupants) without hitting high-voltage elements or other hazards.

2.3.3 Postcrash Inspection

On June 7, 2018, the NTSB met at the tow yard with representatives of the Fort Lauderdale Police Department and Florida Highway Patrol to inspect the vehicle (figure 10) and the debris piles. The items wrapped in the tarp were removed and placed near the vehicle. Individual loose battery cells were found in the tarp, as well as the right front tire and small debris. Large items, including the left front door, front electric motor, right front wheel assembly, and damaged battery modules that had separated from the vehicle (determined to be modules 15 and 16), were found on top of the battery case in the second debris pile (figure 11).



Figure 10. Car parked at tow yard showing severe crash and fire damage.



Figure 11. Debris pile on pallet with remains of electric motor and battery modules highlighted.

The high-voltage cut loop was found attached to the front electric motor and had not been cut. Firefighters told investigators that the cut loop was inaccessible during the fire response. Review of the cut loop, emergency response guidance, and exemplar vehicles revealed a minor inconsistency in the cut loop instructions, such that in some vehicles, the cut loop label might be obscured from view under a trim panel. This vehicle model, manufactured after June 2013, also had a cut loop at the left rear door frame, in case the front cut loop was not accessible. Reaching the rear cut loop required penetrating the door frame with a circular saw at a depth indicated by a label at the location of the cut loop. The label was found to have been attached incorrectly to the vehicle's right rear door, where no cut loop was installed. Firefighters had not attempted to use the rear cut loop.

The battery case was severely damaged and ruptured along the entire length of the front surface and extending into the area of modules 13 and 14, which were mounted just behind modules 15 and 16 (figure 12).⁵² Two irregular holes had melted through the battery case, ranging from 3 to 5 inches in diameter. One was on the top of the battery case and would have been between the front seats in the intact vehicle. The other was on the bottom of the case and corresponded to a hole through the floor of the vehicle in roughly the same location. The photograph in figure 12 shows the steel cover on the top of the battery case. The location corresponds to the intersection of four battery modules (Nos. 11, 12, 13, and 14) and is the location of high-voltage connection points. The battery case was significantly warped and deformed in this area.



Figure 12. Top surface of forward part of battery case showing damage to front and hole melted through steel cover (circled), with modules numbered.

Investigators inspected the module vents and found either water and debris or the remnants of fire suppression foam in all venting channels. They found evidence of thermal damage and

⁵² As noted earlier, in all Tesla vehicles, the battery case is mounted under the floor.

venting at the vents for modules 9, 12, 13, and 14.⁵³ The condition of the vents for modules 15 and 16 was obscured by crash damage. Investigators removed the cover of the battery pack to access the high-voltage terminals and measured voltages across each module—at the forward terminal to ground, and at the aft terminal to ground. Module 14 had zero voltage. Modules 6 through 13 and modules 15 and 16 had voltages ranging from 3.3 to 46.9 volts. The voltages of modules 1 through 5 ranged from 69.9 to 167.3 volts. The measurements confirmed that stranded energy remained in the high-voltage lithium-ion battery.

2.4 West Hollywood, California, June 2018

On Friday, June 15, 2018, about 5:30 p.m. Pacific daylight time, a 2012 Tesla model S car was traveling on an urban road in West Hollywood, Los Angeles County, California. Other motorists saw smoke coming from the car and flagged down the driver. The driver stopped and left the vehicle, which then caught fire. The driver was uninjured. A Los Angeles Sheriff's Department patrol car stopped, and officers directed traffic around the burning car. After firefighters from a nearby Los Angeles County Fire Department station extinguished the fire, the vehicle was towed away without incident.⁵⁴

Two people captured videos of the event—a bystander and the driver. Video taken by the bystander captured the left side of the car. Figure 13 is a still image taken from the bystander's video showing fires behind the left front wheel and in the left rear wheel well (large circles), as well as pieces of material ejected from the vehicle (small circles). The image was taken 26 seconds from the start of the bystander's recording and occurred within 2 minutes of the start of the incident.



Figure 13. Image from bystander's video with fire visible behind left front wheel and in left rear wheel well. (Source: Los Angeles County Sheriff's Department)

⁵³ An intense fire had broken out near the car's front wheels, with loose battery cells shooting out of the case due to rapidly venting gas.

⁵⁴ Detailed information gathered in the NTSB's investigation of the West Hollywood battery fire can be found in the [public docket](#) (NTSB case number HWY18FH014).

2.4.1 Initial Response

According to the Los Angeles Fire Department's incident report, the alarm came in at 5:38 p.m., the fire engine arrived on scene at 5:40 p.m., and the last unit cleared the scene at 6:28 p.m. After firefighters extinguished the flames and cut the high-voltage disconnect loop, they applied water and foam to various locations, including the firewall and under the wheel wells.⁵⁵ Figure 14 is a still image from the video taken by the car's driver showing smoke coming from the front of the vehicle after firefighters had extinguished the flames. The image was taken 14 minutes 34 seconds into the recording.



Figure 14. Image from driver's video showing car after flames were extinguished but with smoke still rising (circled). (Source: car's driver)

The fire captain told NTSB investigators in a postincident interview that the flames were extinguished quickly, but that smoke continued to come from the vehicle. He was surprised that the vehicle continued to emit smoke and said that firefighters applied water for longer (about 30 minutes) than he would have expected for such an event. He estimated that firefighters used 300 gallons of water and foam and said that they did not connect to a hydrant.

In an effort to stop the smoke, firefighters removed parts of the vehicle's left front fender and hood trim, using a pry bar with a metal-cutting claw, and applied additional water and foam under the hood and behind the front wheels. The fire captain said that he was surprised that after the cut loop was severed, the vehicle's computer screen remained on. (The captain told investigators that he had been trained in electric vehicles and knew where to find the cut loop.) After they had extinguished the flames, but with smoke still present, the owner called the vehicle manufacturer's representative. The fire captain spoke to the representative, who told him that the 12-volt battery that powered the computer was separate from the main battery, and that after the loop was cut, it would take 10 to 15 minutes for the 12-volt system to power down. The fire captain

⁵⁵ Model S cars manufactured before 2013 have only one cut loop, at the front.

spoke to the representative about the continued smoke. He was told that firefighters needed to apply water to cool the high-voltage battery until it stopped smoking.

2.4.2 Secondary Response

The vehicle manufacturer's representative advised not to tow the car immediately, because of the risk that the battery could reignite. The fire captain decided, however, to move the vehicle from the scene in order to open the road to traffic. The car was taken to an impound lot. The manufacturer contacted the owner and received permission to inspect the vehicle; the company then bought the vehicle outright to do a complete investigation. The vehicle was taken from the impound lot to Burbank, California, for inspection at one of the manufacturer's service facilities (as described below). The car was deemed safe to transport. It was then taken to the manufacturer's research center in Sunnyvale, California, several hours north, for a complete inspection and battery teardown. The battery did not reignite at any time during the initial or secondary response.

2.4.3 Postincident Inspection

The NTSB was given access to photographs from the Burbank inspection. The battery pack was removed from the vehicle, and the cover of the pack was taken off so that the high-voltage terminals could be accessed. All modules were found to be intact except module 14, which was the only one to have experienced thermal runaway (refer to the battery diagram in figure 5, section 2.1.3). Module 14 was electrically isolated, and the other modules were discharged to about a 50 percent state-of-charge.⁵⁶ Reducing the battery's charge to 50 percent allowed for safe transport, and the vehicle manufacturer elected not to completely deenergize the battery so as to preserve evidence. The manufacturer informed the NTSB that its inspection had found no indication that an impact or other external factor was involved in the battery's failure.

NTSB investigators attended a second inspection in Sunnyvale to view the damage to the vehicle, the battery, and the battery case and to observe the effects of thermal runaway. The vehicle inspection was followed by a teardown of the battery pack. The battery case exhibited holes at the left and mid-front that appeared to be caused by venting gas. Figure 15 shows the whole pack, with damaged areas circled and insets highlighting details of the damage. The damage created paths for vented gas and flames to reach both the left- and right-side overpressure vents of the battery pack. The damaged areas were photographed after debris and parts of the battery pack were removed.

⁵⁶ The vehicle manufacturer informed the NTSB that it deenergized the battery modules by connecting them to a proprietary positive temperature coefficient heater. Such heaters use conductive inks printed on polymer-based substrates to generate heat, rather than wires and coils, and are self-regulating, so they do not overheat.



Figure 15. Battery pack with top cover removed to show location of holes in battery case and insets showing closeups of damaged areas.

3 Other High-Voltage Battery Fires

Although all four investigations conducted by the NTSB (section 2) involved Tesla cars or SUVs, the issue under investigation was vehicle fires caused by high-voltage lithium-ion batteries, not vehicle design. In three of the four investigations, the batteries had been damaged in high-speed, high-severity crashes. In one case, the fire resulted from an internal battery failure. In all cases, the battery fires presented unique problems to first and second responders. As illustrated below, the high-voltage lithium-ion batteries in electric vehicles from other manufacturers have posed similar problems to emergency responders when the battery case or battery cells were damaged or failed internally.

3.1 Chevrolet Volt Fire After NCAP Test

In June 2011, a Chevrolet Volt caught fire at a test facility 3 weeks after a crash test performed on May 12. The crash test was carried out as part of NHTSA's New Car Assessment Program (NCAP) for 2011 model year vehicles and to verify compliance with the *Federal Motor Vehicle Safety Standards* (FMVSSs). NCAP is a federal consumer information program that evaluates the performance of new automobile designs against safety threats such as crashes.⁵⁷ (Other countries operate similar programs.)

The crash test performed on the Chevrolet Volt in May 2011 was a side-impact pole test (the car was crashed sideways into a rigid pole at a speed of up to 20 mph, with a dummy placed in the driver's seat). The car was rotated along its longitudinal axis (rolled) 90 degrees at the end of the test to check for fluid leaks. As a result of the test, NHTSA gave the Volt a five-star crash safety rating—the highest.

Three weeks after the test, the Volt caught fire while parked outside the test facility. The fire damaged four nearby vehicles. Forensic examination found that the transverse stiffener under the driver's seat had penetrated the Volt's battery compartment, damaged the lithium-ion battery, and ruptured the battery's liquid cooling system.⁵⁸ The damage was “not easily detected by visual inspection [and] went unnoticed at the time of the test,” according to NHTSA's report on the incident (Smith 2012). Examiners determined that the fire was precipitated by damage to the battery cells and electric shorting. Coolant had leaked into the battery cells through the damaged battery case and dried out over time, creating short circuits from residual coolant salts.

In September 2011, NHTSA repeated the side-pole test on another Volt. The test did not replicate the results of the original—there was no intrusion into the battery compartment, no cell damage or shorting, no leaks, and no postimpact fire. The car was monitored for 3 weeks afterward, with no thermal or electrical activity observed in the vehicle or the battery. NHTSA then conducted impact tests on six Chevrolet lithium-ion batteries that had been removed from vehicles and attached to fixed supports. Three batteries caught fire, one as a result of another battery catching

⁵⁷ NHTSA announced in a [press release](#) on October 16, 2019, that it planned to upgrade NCAP in 2020, the 40-year anniversary of the program.

⁵⁸ A *stiffener* is a structural support that strengthens and stabilizes the vehicle body. In this case, the stiffener was a metal beam that ran from side to side under the driver's seat.

fire. NHTSA concluded that the fires were caused by shorting of the battery electronics, caused in turn by battery coolant that leaked into the battery compartment when the batteries were rolled over as part of the test.

In November 2011, NHTSA announced that it was opening a safety defect investigation to assess the risk of fire in Chevrolet Volts that had been involved in serious crashes.⁵⁹ At the conclusion of its investigation, NHTSA issued a press release stating, “NHTSA does not believe that Chevy Volts or other electric vehicles pose a greater risk of fire than gasoline-powered vehicles” and that the agency remained “unaware of any real-world crashes that have resulted in a battery-related fire involving the Chevy Volt or any other electric vehicle.”⁶⁰ After the test incident, General Motors made design modifications to improve the battery case’s resistance to crash forces.

3.2 International Examples

International cases of high-voltage lithium-ion battery fires have been documented. The NTSB was not involved in the investigations of any of those fires, and limited information is publicly available. Three cases that illustrate the issues such fires pose for emergency responders, and how emergency personnel responded, are described below.

3.2.1 Norway, March 2017

On March 30, 2017, the Norwegian Fire and Rescue Department (NFRD) in the region of Nedre Romerike used a donated, lightly damaged 2017 BMW i3 in a test and training exercise.⁶¹ Participants in the exercise were the NFRD, the Norwegian Defense Research Establishment, the local police, a local ambulance service, an insurance company, and a battery disposal company.

The exercise consisted of cutting the vehicle’s body and frame (without touching the battery), attempting to trigger a short circuit and fire by crushing the vehicle in different places with a bulldozer, and driving a large metal rod through the center of the vehicle to pierce the battery. Piercing the battery resulted in a fire, but firefighters could not stop the thermal runaway, and the fire was left to burn itself out.

Figure 16 illustrates the sequence of events using images from a video recording of the training exercise. About 2,000 gallons of water and foam were applied during the exercise.

⁵⁹ See [press release](#) dated November 25, 2011.

⁶⁰ See [press release](#) dated January 20, 2012.

⁶¹ See letter from the NFRD dated September 18, 2018, in the NTSB [public docket](#) for this report.



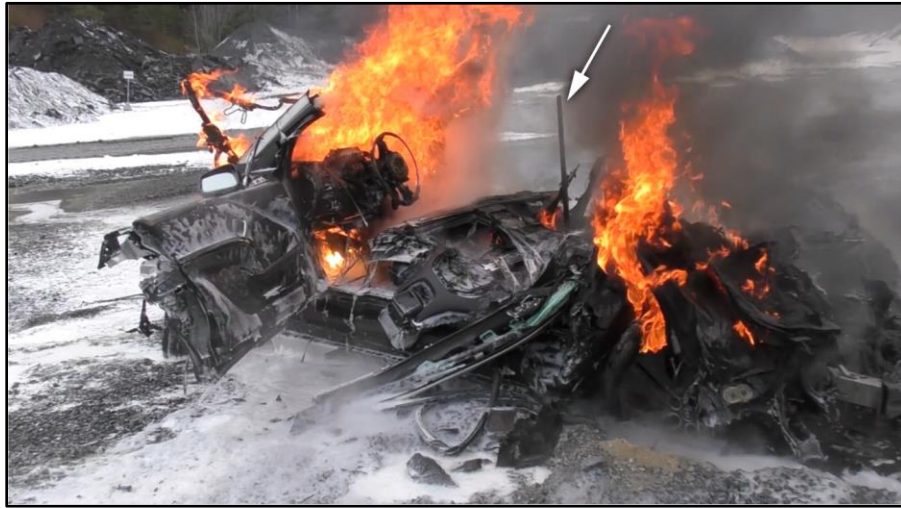
(a)



(b)



(c)



(d)

Figure 16. Series of images showing (a) attempt to trigger short circuit by crushing car with bulldozer; (b) flames erupting 8 minutes after piercing car with metal rod; (c) flames no longer visible, but battery continuing in thermal runaway; and (d) fire burning itself out, with arrow pointing to metal rod. (Source: NFRD video)

3.2.2 Belgium, May 2017

On May 13, 2017, a Mitsubishi Outlander PHEV, equipped with a high-voltage lithium-ion battery, struck a tree in Dilsen-Stokkem, Belgium, and caught fire. According to an account published by the International Association of Fire and Rescue Services (CTIF), an emergency rescue team received a call that a car was against a tree with a person trapped inside.⁶² While a fire engine and intervention team were traveling to the scene, another call informed the team that the vehicle might be on fire. The commander directed two firefighters to don breathing apparatus.

When firefighters arrived, smoke was coming from the car's motor compartment, and flames were visible. Firefighters brought the fire under control and extricated the driver by removing the car's B-pillar.⁶³ The driver was taken to a local hospital, where he died of his injuries.

Firefighters disconnected the car's 12-volt battery and applied water to cool the motor compartment. Before leaving the site, they checked the vehicle using a thermal imaging camera. While the car was being winched onto a truck, the fire reignited, preceded by a loud bang and a blue jet of flame, according to the tow truck driver. Responders put the car on its side, hoping to reach the high-voltage battery. After a "long time," they found the service plug, removed it while wearing the recommended PPE (electrically insulated gloves and face shields), and extinguished the fire. Firefighters accompanied the car to a safe place.

⁶² See the [account published by CTIF](#) on March 7, 2018 (accessed November 12, 2020).

⁶³ The *B-pillar* is the structural vertical support behind a car's front door.

3.2.3 The Netherlands, March 2019

On March 25, 2019, in Tilburg, the Netherlands, firefighters dropped a BMW model i8 coupe into a water bath after the car began smoking while on display at a dealership (see figures 17 and 18).⁶⁴ The car was kept in the water for 24 hours. As the Central and West Brabant Fire Brigade explained in a message on its Facebook page, “Extinguishing an electric car requires a lot of water for a longer period of time, partly because the battery packs are difficult to reach and the fire flares up again cell after cell.”⁶⁵



Figure 17. BMW after firefighters attempted to extinguish fire, with crane positioned above and faint plume of smoke visible above car's windshield. (Source: Central and West Brabant Fire Brigade)

⁶⁴ See various online news reports ([autorevolution](#), March 26, 2019; [Motor Illustrated](#), March 26, 2019; [Motor 1 News](#), March 26, 2019; [Energy Live News](#), April 4, 2019) and the [BMW blog](#), March 26, 2019 (all accessed November 12, 2020). The incident is also described in Roman (2020) and is cited in a Swedish study on the safety of lithium-ion vehicle batteries (Bisschop and others 2019).

⁶⁵ (a) See original [Facebook post](#), March 26, 2019 (Google translation) (accessed November 12, 2020). (b) The NTSB could not confirm that the car's high-voltage battery was the source of the fire.



Figure 18. BMW being loaded into tank filled with water. (Source: Central and West Brabant Fire Brigade)

4 Regulatory and Industry Actions

Since the early 1990s, both national and international organizations have issued regulations and standards for electric vehicles and the high-voltage lithium-ion batteries that power them. Among the US organizations whose work relates to the safety issues faced by emergency responders are NHTSA, SAE International (SAE), and the NFPA. International entities include the United Nations Economic Commission for Europe (UNECE) and the International Organization for Standardization (ISO).

4.1 US Federal Motor Vehicle Safety Standard 305

To sell a vehicle in the United States, manufacturers must self-certify that it meets the FMVSS performance requirements. FMVSS 305 applies specifically to electric vehicles.⁶⁶ The standard was adopted in September 2000, in parallel with NHTSA's participation in the United Nations effort (described in the next section) to harmonize global standards for vehicle safety. The original purpose of FMVSS 305 was to reduce crash-related deaths and injuries that could occur because of electrolyte spilled from batteries, intrusion of batteries or electrical converters into the passenger compartment, or electric shock:

- Electrolyte is not permitted to spill into the passenger compartment, and no more than 5.0 liters of electrolyte are allowed to spill outside the vehicle within 30 minutes of a crash test and after a static rollover test (conducted after barrier crash tests; see below).
- Electric energy storage or conversion devices must be anchored to the vehicle and remain attached by at least one anchorage after crash tests. Devices positioned outside the occupant compartment must not intrude into the compartment.
- Each high-voltage source must meet one of three requirements: (1) it must be electrically isolated from the vehicle's chassis; (2) its voltage must be below levels considered safe from electric shock hazards (30 volts AC or 60 volts DC); or (3) it must be enclosed in a physical barrier to prevent direct human contact.⁶⁷

⁶⁶ FMVSS 305, codified at Title 49 *Code of Federal Regulations* (CFR) 571.305, was adopted in September 2000 and was effective on October 1, 2001 (65 *Federal Register* 57980). Its full title is "Electric-Powered Vehicles: Electrolyte Spillage and Electrical Shock Protection." The standard applies to passenger cars and to multipurpose passenger vehicles, trucks, and buses with a gross vehicle weight rating of $\leq 4,536$ kilograms (10,000 pounds) that use electrical propulsion components whose working voltages are more than 60 volts DC (or 30 volts AC) and that can attain a speed greater than 40 kilometers per hour (km/hr; 25 mph) over a distance of 1.6 km (1 mile) on a paved level surface.

⁶⁷ The standard defines *electrical isolation* as "the electrical resistance between the high voltage source and any of the vehicle's electrical chassis divided by the working voltage of the high voltage source." Electrical resistance is measured in ohms. Minimum electrical isolation requirements for DC components and AC systems that have physical barrier protection (100 ohms/volt) are lower than for AC components that do not have a physical barrier (500 ohms/volt).

The above requirements of FMVSS 305 are evaluated after an electric vehicle is crash-tested and then rolled on its longitudinal axis (rollover). The crash-test conditions are specified by FMVSS 208 (CFR 571.208, “Occupant Crash Protection”). The following tests are administered: (1) hitting a frontal barrier at up to 48 km/hr (30 mph); (2) being impacted from the side by a barrier moving at up to 54 km/hr (33.6 mph), and (3) being impacted from the rear by a barrier moving at up to 80 km/hr (50 mph).

FMVSS 305 calls for high-voltage batteries to be marked with a yellow triangle containing a jagged black arrow and bordered in black. The marking is not required for electrical isolation barriers that cannot be accessed without tools or for electrical connectors or the vehicle charge inlet. High-voltage cables and components must be identified with an orange covering. The exterior of a vehicle is not required to be marked to show the location of high-voltage cut loops or other means of disconnecting the high-voltage system. The standard does not specify a method for disconnecting the vehicle’s high-voltage power.

FMVSS 305 has been amended nine times since it came into force in 2001. The most recent changes were made to bring US regulations into harmony with the electrical safety requirements of global technical regulations (GTRs) for hydrogen and fuel-cell vehicles (GTR 13) and electric vehicles (GTR 20).⁶⁸

4.2 Global Technical Regulation for Electric Vehicles

Since 1952, the United Nations has led an effort to develop technical regulations for cars and other motor vehicles that can be coordinated, or *harmonized*, worldwide. An agreement signed in 1998, known as the 1998 Agreement, established a process for jointly developing GTRs related to motor vehicles, equipment, and parts.⁶⁹ The United States is a signatory (contracting party) to the 1998 Agreement. A global registry of harmonized regulations was created pursuant to the 1998 Agreement. Contracting parties use their countries’ individual rulemaking processes to incorporate the GTRs into their national laws and regulations.

GTR 20, the first GTR focused on electric vehicle safety, was entered into the global registry on March 14, 2018 (UNECE 2018). GTR 20 is phase 1 of a process of establishing uniform global standards for electric vehicles. Phase 2 concerns thermal propagation tests, venting and management of gases released postcrash, and requirements for warning signals. A working group on electric vehicle safety, established by the World Forum for Harmonization of Vehicle

⁶⁸ FMVSS 305 was amended in 2017 to adopt the normal operation requirements of GTR 13 (82 *Federal Register* 44945) and in 2019 to harmonize with both GTR 13 and GTR 20 (84 *Federal Register* 6758). Work on GTR 13 began in 2005, with the purpose of establishing safety-related performance requirements for hydrogen-fueled vehicles that would achieve levels of safety equivalent to those for conventional internal combustion vehicles (a GTR working party had begun researching existing regulations and standards for alternative fueled vehicles in 1998). GTR 13 covers the safety of high-voltage electrical parts and includes requirements for electrical isolation to protect against electric shock, under both noncrash and postcrash conditions. GTR 13 was issued in 2013 (UNECE 2013; accessed November 12, 2020).

⁶⁹ The full title of the 1998 Agreement is “Agreement concerning the Establishing of Global Technical Regulations for Wheeled Vehicles, Equipment and Parts which can be fitted and/or used on Wheeled Vehicles.” It came into force in 2000.

Regulations (part of the UNECE), is developing the standards. NHTSA participates as the US delegation to the working group.

GTR 20 specifies both in-use requirements (covering normal vehicle use) and postcrash requirements. The in-use requirements address occupant safety for thermal events that can lead to fire, explosion, or smoke. Vehicles are required to provide advance warning of a hazardous situation inside the passenger compartment that will allow egress within 5 minutes, and manufacturers must make documents available describing the warning system (including a risk reduction analysis, diagrams, and engineering documents such as tests).

GTR 20 establishes four measures for determining the safety of electric vehicle occupants, rescue workers, and first responders after a crash. The requirements are to be met by a separate crash test. It is left to individual countries to specify the criteria according to their own crash-test requirements. At least one of the following measures to protect against postcrash electric shock must be met: (1) absence of high voltage (≤ 60 volts within 60 seconds of impact for high-voltage buses); (2) low electrical energy (the total energy of impulse currents must be < 0.2 joules, from components to the vehicle chassis); (3) physical protection; and (4) isolation resistance.⁷⁰

To protect against electric shock from indirect contact, resistance requirements are given for exposed conductive parts (between the parts and the electrical chassis or between simultaneously reachable conductive parts). As with the in-use requirements, the postcrash requirements for electrical isolation resistance specify minimum values between the high-voltage bus and the electrical chassis for powertrains consisting of separate or combined DC and AC buses.

Postcrash requirements for an electric vehicle's rechargeable electrical energy storage system include vehicle-based tests for electrolyte leakage, retention of the battery pack (it must remain attached to the vehicle and not intrude into the passenger compartment), and fire hazards (no evidence of fire or explosion for 1 hour after a crash test). The electrolyte leakage requirement allows no leakage from the battery into the passenger compartment and leakage of no more than 7 percent of the electrolyte (maximum 5.0 liters) outside the passenger compartment for 60 minutes after a crash. (No leakage is allowed if the electrolyte is not a liquid.)

4.3 SAE International Standards

SAE is a US-based professional society that creates standards, organizes technical meetings, and publishes technical papers through voluntary, collaborative efforts.⁷¹ SAE recommended practice J2990 (*Hybrid and EV First and Second Responder Recommended Practice*) addresses the hazards faced by first and second responders to crashes and other incidents (such as garage fires) involving electric vehicles.⁷² The recommended practice was first published in November 2012 and was reissued in July 2019. It emphasizes the chemical, electrical, and

⁷⁰ The *joule* is the unit of work or energy in the International System of Units. One joule = 1 watt-second (the energy released in 1 second by a current of 1 ampere through a resistance of 1 ohm). One kWh = 3.6 million joules, and 1 joule = 2.77778×10^{-7} (0.000000277778) kWh.

⁷¹ SAE originally focused on the American automotive industry but has since expanded globally and into other transportation industries, such as aerospace.

⁷² Recommended practice J2990 can be purchased on the [SAE website](#) (accessed November 12, 2020).

thermal risks associated with the high-voltage systems (including batteries) of electric vehicles and recommends best practices to “help protect emergency responders, tow and/or recovery, storage, repair, and salvage personnel.” SAE J2990 considers only lithium-ion batteries and does not discuss the hazards associated with alternative fuels such as hydrogen (treated in another SAE publication).

4.3.1 Emergency Response Guides

SAE J2990 gives format and content recommendations for the emergency response guides produced by electric vehicle manufacturers. It recommends that manufacturers create quick reference sheets, following the guidance in ISO standard 17840: *Road Vehicles—Information for First and Second Responders* (see section 4.4 for details). It further recommends standardizing the emergency response guides using the ISO 17840 templates for organization and appearance (chapter headings, sequence of chapters, color codes, graphics) and for the design and color of fuel and energy labels.

SAE J2990 notes that manufacturers’ guides “cover many of the necessary areas required for responders, but they vary in style and content . . . [and the] text is often written from an engineering and technical mindset, rather than from a responder’s point of view.” An appendix to SAE J2990 shows a 1-page quick reference guide (figure 19, from the NFPA emergency field guide [NFPA 2018]) that summarizes critical information about fire suppression in hybrid and electric vehicles.

SAE J2990 recommends that emergency response guides “should contain crucial and in-depth information linked to the quick reference sheet” and lists examples of available responder guides, including the NFPA emergency field guide, and how they can be obtained (individual manufacturer websites, commercial platforms that must be purchased, and smartphone applications).⁷³

⁷³ See section 4.5 for information about the NFPA emergency field guide and the emergency response guides from individual manufacturers.

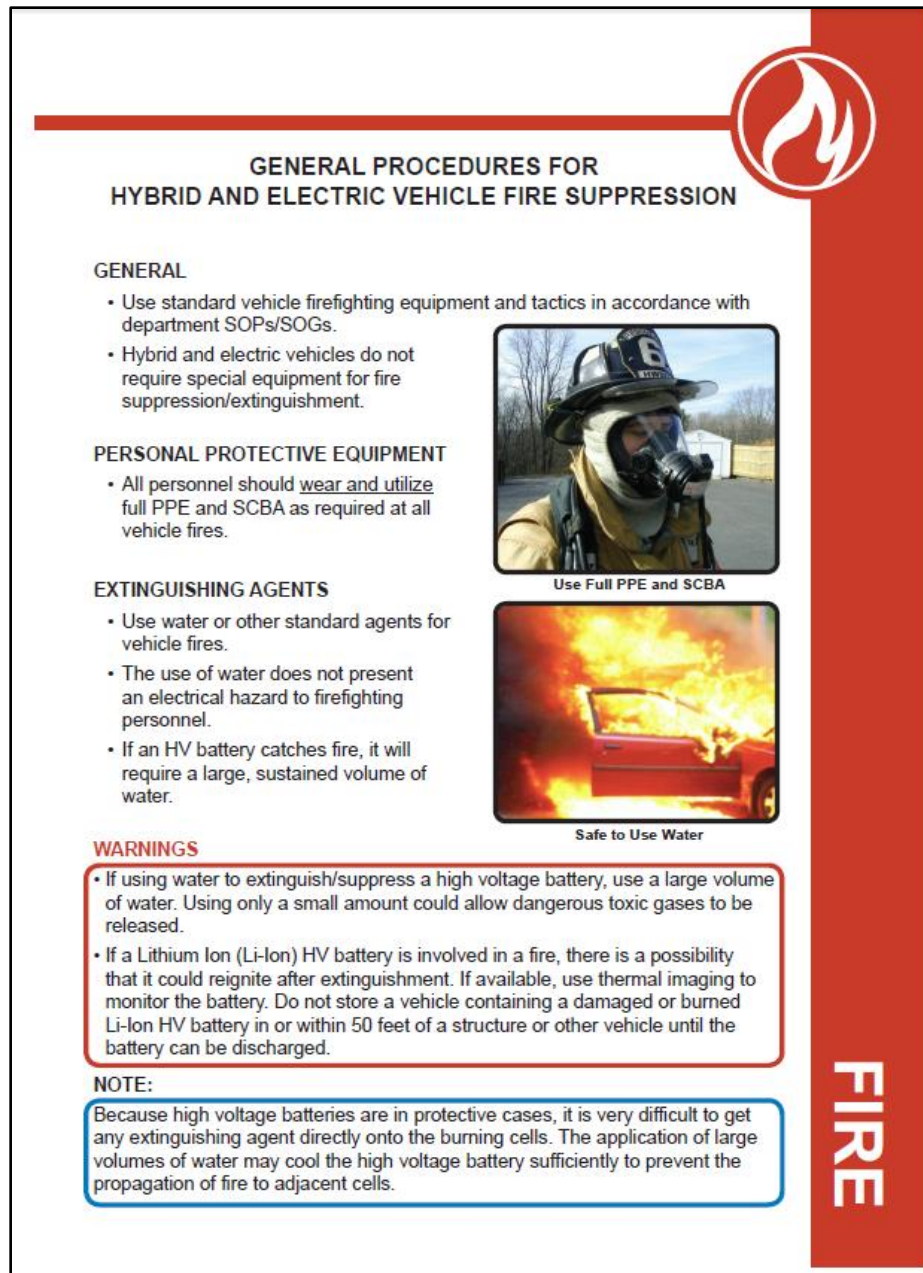


Figure 19. One-page emergency response guide (“quick reference sheet”) for fire suppression in electric vehicles. SOPs/SOGs = standard operating procedures/standard operating guidelines. HV = high voltage. (Source: NFPA)

4.3.2 Disabling High-Voltage Systems

SAE J2990 recommends three methods for disabling (disconnecting) high-voltage systems, noting that the methods “generally do not completely remove high voltage from the vehicle” but are intended “to limit its distribution around a vehicle”: (1) automatic shutdown; (2) switching ignition switch to OFF (which should disconnect the high-voltage system from the high-voltage sources and discharge the system to ≤ 60 volts DC or 30 volts AC within 10 minutes); (3) cut or

disconnect battery cables to discharge the 12-volt system, and cut or disconnect the 12-volt output cable. SAE J2990 further recommends that at least two methods be incorporated into the design of an electric vehicle.

SAE J2990 states that removing an electric vehicle's manual disconnect should not be a primary method for first responders to disable the high-voltage circuits, because (1) the variety of designs makes locating and activating manual disconnects inefficient, (2) first responders do not always have the required PPE, and (3) the manual disconnect might be inaccessible.⁷⁴ The recommended practice includes design considerations for manual disconnects if manufacturers prefer removing them as the method for disabling high-voltage systems.

4.3.3 Postincident Vehicle Inspection

SAE J2990 recommends two inspection stages after a crash or other incident to make certain that the high-voltage system has shut down and is not damaged—one at the incident scene and one at the storage site afterward. The vehicle should remain physically isolated until it has passed inspection. Recommended inspection steps, and what actions to take, are listed in table 1.

Table 1. Postincident inspection steps recommended by SAE J2990.

Step	Action	Notes
1	Inspect for signs of fire or smoldering.	Use thermal camera or infrared temperature probe if possible.
2	Listen for gurgling, bubbling, crackling, hissing, or popping noises from battery.	Sounds can indicate venting of overheated cells or arcing in high-voltage system.
3	If groups of battery cells have separated from battery enclosure, alert responders of potential exposure to high voltage or fire reignition.	Contact equipment manufacturer for depowering recommendations, packaging instructions, and disposal recommendations. If sufficient information is not available, consult latest version of US Department of Transportation/Transport Canada <i>Emergency Response Guidebook</i> for lithium-ion batteries (guide 147) or NiMH (guide 171). ^a
4	If vehicle is submerged, do not remove submerged service disconnect, but turn off ignition if possible. Disable vehicle by chocking wheels, placing in park, and removing ignition key or disconnecting 12-volt battery.	Understand that electric vehicles are designed to be safe in water. Small bubbles emanating from vehicle do not create shock hazard. Water damage to electrical components could lead to reignition. Do not store vehicle that has been submerged indoors until high-voltage energy is depowered.
5	Ensure that high-voltage system is disabled.	Refer to manufacturer's emergency response guide or emergency field guide to verify. At a minimum, disable 12-volt system.
6	Examine mechanical integrity of battery system.	Is enclosure ruptured, cracked, punctured, or dented?
7	Inspect for evidence of fire or heat damage.	Signs include smoke residue or heat damage around battery system and burnt odor from battery system.

⁷⁴ *Manual disconnects*, also called *manual service disconnects*, are devices such as plugs, levers, or switches that emergency responders can manipulate to disconnect an electric vehicle's high-voltage system. The devices are found in various locations—for example, behind the back seat or near a rear tire—depending on the vehicle make and model.

Step	Action	Notes
8	Inspect for evidence of arcing in high-voltage system. Notify tow truck driver of potential hazards and recommendations for isolation.	Carbon traces indicate that isolation of high-voltage system has been lost.
9	Inspect for evidence of external battery leaks. Notify tow truck driver of potential hazards and isolation requirements.	Electrolyte of lithium-ion battery has sweet odor, like ether, that could indicate battery leak. Leaking electrolyte normally creates drops, not puddles.

^a A new edition was published in August 2020. The guidebook is intended for use by firefighters, police, and other emergency personnel who may be first to arrive at the scene of a transportation incident involving dangerous goods. Available online in English and Spanish.

SAE J2990 recommends towing a damaged electric vehicle on a flatbed, to avoid generating voltage from the turning wheels. If the vehicle's wheels must be turned—because it has run off the road, for example—its speed should be kept below 5 mph. After being loaded onto a tow truck, the vehicle's structural integrity should be checked. If the vehicle rolls while it is on the tow truck, the inspection steps listed above should be repeated.

SAE J2990 states that tow operators should arrange to tow the vehicle to an offsite location where it can be isolated. Once there, the vehicle should be inspected again. It should also be inspected for evidence of internal battery leaks, which could lead to short circuits or loss of high-voltage isolation, and the battery should be examined for loss of mechanical integrity. If airbags have deployed, further diagnostic steps should be conducted to assess the integrity of the high-voltage system, such as measuring the battery temperature.

SAE J2990 recommends two barrier methods for an electric vehicle during storage: (1) separate the vehicle from combustibles and structures by 50 feet on all sides, or (2) create a barrier of earth, steel, concrete, or solid masonry around the vehicle.

4.3.4 Hazard Communication

SAE J2990 states that a 24-hour telephone hotline provided by the vehicle manufacturer is “not an appropriate communications medium for first and second responders at this time” (for one thing, subject matter experts are widely dispersed and making them constantly available is not practical). Instead, it recommends that manufacturers should make emergency response guides available in digital format at any time, accessible through links from a website, and that the information should be made readily available to third parties.

4.4 ISO Standard 17840

The ISO is a worldwide federation of national standards bodies. It publishes international standards on thousands of topics, including quality management, environmental management, health and safety, energy, food safety, and information technology. The work is carried out by technical committees. Any member interested in a particular subject can be represented on the corresponding technical committee. The United States is a member body.

ISO standard 17840 (*Road Vehicles—Information for First and Second Responders*) is a set of four documents defining the structure and content of the information that vehicle

manufacturers provide for emergency responders to vehicle fires or crashes.⁷⁵ The standard was created by CTIF, with the collaboration of the European New Car Assessment Programme (Euro NCAP) and Europe's Schengen Information System.⁷⁶

ISO 17840-1 (published in August 2015) standardizes the content and layout of rescue sheets for passenger cars and light commercial vehicles. *Rescue sheets* are short documents that give quick information about a vehicle's construction, intended for use by emergency responders at the scene of a crash. The standard covers conventional (diesel, gasoline), liquefied petroleum gas, compressed natural gas, electric, and hybrid electric vehicles. ISO 17840-2 (published in April 2019) standardizes the rescue sheets for buses, coaches, and heavy commercial vehicles.

ISO 17840-3 (published in April 2019) establishes a template and defines the general content for manufacturers' emergency response guides—longer documents that give in-depth “necessary and useful information” about a vehicle involved in an incident. Emergency response guides are intended for use in conjunction with rescue sheets, generally for training emergency responders on unconventional vehicles. This part of ISO 17840 applies to passenger cars, buses, coaches, and light and heavy commercial vehicles.

ISO 17840-4 (published in June 2018) defines the labels and colors used to indicate the fuel or energy used to propel a vehicle. For example, an orange diamond with a white zigzag in the center indicates high voltage. Use of the labels includes the rescue sheets defined in ISO 17840-1 and -2 and the emergency response guides covered in ISO 17840-3.

The text introducing ISO 17840-3 ties the standard to the quick decision-making required of emergency responders at a crash site, and to the need for emergency responders to avoid risking their own lives while saving others. The template established by the standard is described as “a flowchart for the main actions of first and second responders arriving at an accident scene” and as a means of promoting “the correct action with respect to the vehicle technology concerned.” The template gives headings for the various sections of an emergency response guide (such as “Disable direct hazards/safety regulations” or “In case of fire”) and the order in which they should appear (see figure 20) but leaves it to manufacturers to fill in specific information for each section. Standards for colors and graphics are given, including pictograms for indicating where tanks, batteries, and other components are located in a vehicle. The headings and sequence of sections are the same for both rescue sheets and emergency response guides.

⁷⁵ The standards are available for purchase [online](#) from the ISO or from the [ANSI webstore](#) (both accessed November 12, 2020).

⁷⁶ The NFPA is the US representative organization to CTIF.

0.	Rescue sheet(s)
1.	Identification / recognition
RGB: 191,191,191	
2.	Immobilisation / stabilisation / lifting
RGB: 204,255,204	
3.	Disable direct hazards / safety regulations
RGB: 255,204,0	
4.	Access to the occupants
RGB: 102,255,51	
5.	Stored energy / liquids / gases / solids
RGB: 255,255,0	
6.	In case of fire
RGB: 255,0,0	
7.	In case of submersion
RGB: 0,0,255	
8.	Towing / transportation / storage
RGB: 255,204,153	
9.	Important additional information
RGB: 141,179,226	
10.	Explanation of the used symbols

Figure 20. Contents of vehicle rescue sheets and emergency response guides as defined in ISO standard 17840. (Source: CTIF)

In February 2020, Euro NCAP published a protocol for rescue, extrication, and safety testing and assessment (version 1.1), which promotes the use of ISO standard 17840 and incorporates scoring relative to the availability of a manufacturer’s rescue sheets.⁷⁷ The protocol was prepared in coordination with CTIF. It promotes the availability of rescue sheets because “rescue services require detailed but readily-understood information regarding the construction of individual vehicles to extract trapped occupants as quickly and safely as possible,” which “is becoming more pressing as vehicles use different sources of power (e.g. electric/hybrid, hydrogen).”⁷⁸ The Australasian NCAP, which publishes crash test results for vehicles sold in Australia and New Zealand, published version 1.1.1 of a similar protocol in July 2020.⁷⁹

⁷⁷ The protocol is described at www.euroncap.com (accessed November 12, 2020). Points are awarded for using the ISO standard.

⁷⁸ Quotations are from the protocol description at www.euroncap.com (accessed November 12, 2020).

⁷⁹ See the [protocol document](#) (accessed August 11, 2020).

Euro NCAP announced in June 2020 that it had centralized the manufacturers' rescue sheets in a free, downloadable mobile application for emergency responders, called "Euro Rescue." Australasian NCAP launched its own application, "ANCAP Safety," at the same time. In its press release, Euro NCAP stated: "As vehicles have become tougher, more complex and alternatively powered, it has become increasingly crucial that first responders know what they can and can't do at the scene of an accident."⁸⁰

4.5 Industry Guidance for Emergency Responders

The 40-plus manufacturers of electric or other alternatively fueled vehicles voluntarily produce guidelines for firefighters and other emergency personnel who respond to incidents involving their vehicles. Links to the manufacturers' emergency response guides are available on the NFPA website, as well as on individual manufacturers' websites.⁸¹ The NFPA also publishes a 460-page emergency field guide (NFPA 2018) that can be ordered and downloaded from its website. The NFPA recently added to its website a training video for firefighters, titled "Stranded Energy—How Little You Know Might Shock You."⁸² A video prepared for the 2019 North American Heavy Rescue Symposium by the NFPA and others demonstrates best practices for responding to electric vehicle fires.⁸³

4.5.1 NFPA Emergency Field Guide

The NFPA is a nonprofit organization that works to improve fire safety and provides training and education. The organization's emergency field guide is intended as a quick reference to use on scene or as a study aid. It begins by laying out general procedures for the initial response to vehicle crashes, fires, submersion in water, spills, and leak hazards. A separate chapter gives guidance for first aid in case of exposure to battery electrolytes or to natural gas or propane. The bulk of the field guide is devoted to brief, vehicle-specific entries drawn from the manufacturers' emergency response guides but not intended to replace them.

4.5.1.1 General Procedures

Initial response. Procedures are given for identifying the type of vehicle and its fuel and for immobilizing and stabilizing the vehicle. The guide states, "Always assume the vehicle is some type of hybrid, electric or alternatively fueled vehicle until proven otherwise." To immobilize a vehicle, emergency responders should approach it at a 45-degree angle, to stay out of the way in case it moves. The first step in stabilizing a vehicle is to turn off the ignition and disconnect the 12-volt battery. An alternative shutdown method is given if responders cannot access the ignition.

⁸⁰ See [press release](#), June 17, 2020 (accessed November 12, 2020).

⁸¹ Smartphone applications and commercial platforms, such as Moditech, are also available. Some are free, others must be purchased. The [Boron Extrication company website](#) has links similar to the NFPA's (accessed November 12, 2020).

⁸² The video can be viewed on the [training and certification section](#) of the NFPA website (accessed June 5, 2020).

⁸³ The [video demonstrates](#) using a thermal imagery camera to check the temperature of the battery and propping up a vehicle to apply water directly to the battery case. The video was sponsored by the NFPA, the California Department of Forestry and Fire Protection, and the training company Advanced Extrication, with the support of Tesla (accessed June 8, 2020).

Extrication. Steps are given to extricate occupants from inside a crashed vehicle. Separate procedures are given for hybrid and electric vehicles, hydrogen fuel cell vehicles, and gaseous fuel vehicles. All vehicles must be immobilized and stabilized first. For hybrid and electric vehicles, responders should visually check for exposed high-voltage components or cables. Responders are warned to always assume that the high-voltage system is energized. Warnings are also given not to cut orange high-voltage cables (different from the 12-volt battery cables and the low-voltage cut loops that disconnect the high-voltage circuits) and not to penetrate high-voltage components. Further, firefighters are warned that if the 12-volt system cannot be disabled, occupant protection systems, such as airbags, could remain active, even if the high-voltage system is shut down.

The extrication section outlines procedures for handling damaged high-voltage batteries. The guidance—

- Stresses the need for PPE and SCBA.
- Warns of leaking fluids, sparks, smoke, or bubbling noises from the high-voltage battery and instructs responders to vent the vehicle to avoid a buildup of fumes.
- Warns that sparks, smoke, and bubbling noises are signs of a potentially overheating battery, which could result in a delayed fire.
- Warns of a significant shock hazard (and to avoid contact with the battery).

A section on manual service disconnects notes that removing a manual disconnect will not discharge the high-voltage battery.

Fire extinguishment. The general procedures for extinguishing fires in alternative fuel vehicles state that “all personnel should wear and utilize full PPE and SCBA as required at all vehicle fires.” Procedures for hybrid and all-electric vehicles include using standard firefighting equipment and tactics; no special equipment is required for extinguishing electric vehicle fires. The difficulty of extinguishing a high-voltage battery fire depends on (1) the size and location of the battery, (2) the extent of fire in the battery, (3) access to the battery and the “ability of the extinguishing agent to be applied to the battery assembly case,” and (4) whether openings in the battery case allow the extinguishing agent to be applied directly to the burning cells. Points made about extinguishing agents are as follows:

- Use water or other standard agents for electric vehicle fires.
- Water does not pose an electrical hazard to firefighters.
- If a high-voltage battery catches fire, “it will require a large, sustained volume of water” (2,600 gallons or more, depending on the battery’s size and location). Responders should establish a sustained water supply (hydrant or static water source).⁸⁴

The following warnings are emphasized:

- If using only water to extinguish or suppress a high-voltage battery fire, use a large amount. A small amount of water could release toxic gases.

⁸⁴ *Static water source* means a lake, stream, or pond.

- A fire in a lithium-ion battery could reignite. The following steps should be taken:
 - Use thermal imaging if available to monitor the battery (to determine the presence of fire).
 - Do not store a vehicle with a damaged or burning lithium-ion battery within 50 feet of a structure or another vehicle until the battery is discharged.
 - Reignition is accompanied by a “whooshing” or “popping” sound, followed by off-gassing of white smoke or electrical arcs or sparks that reignite with visible flames or fire. Reignition can occur within several hours to a day or more after the fire is extinguished.

The guidance notes the following about fires in high-voltage batteries:

- It is difficult to direct an extinguishing agent onto burning cells because high-voltage batteries are in a protective case. Applying a large volume of water might cool the battery enough to prevent the fire from propagating to adjacent cells. Applying water to a localized area for a long time leads to quicker extinguishment. Water should be applied even after no flame is visible.
- Anticipate longer fire-suppression times if the high-voltage battery is involved. Tests show that suppression can take an hour or longer.

4.5.1.2 Vehicle-Specific Guidance

Nearly 400 pages of the NFPA emergency field guide give specific initial response procedures for 43 makes and 195 models (counting generations of the same model separately) of alternatively fueled vehicles, including trucks, buses, and vans as well as cars. The guidance was prepared by the manufacturers and gathered together in the emergency field guide. The entries are organized alphabetically by manufacturer and then by vehicle model. Each entry is presented in a 2- or 3-page format.

4.5.2 Manufacturers' Emergency Response Guides

As stated earlier, links to the emergency response guides published by the manufacturers of alternative fuel vehicles can be found on the NFPA website. The downloadable guides can be accessed by clicking on “Alternative Fuel Vehicles Safety Training” at the bottom of the NFPA webpage, then clicking on “Emergency Response Guides.” Altogether, 41 manufacturers are listed.⁸⁵ The guides include quick response sheets (2 to 4 pages), which are similar to the vehicle-specific guidance published in the NFPA emergency field guide but not necessarily identical. Some manufacturers also publish longer emergency response guides (such as BMW’s 108-page rescue manual), which are included in the links. The guides are organized by model and year and cover hybrid electric vehicles, BEVs, fuel-cell vehicles, and vehicles powered by

⁸⁵The downloadable guides include two manufacturers (Karma and BYD) that are not listed in the NFPA emergency field guide. The NFPA’s emergency field guide contains vehicle-specific guidance from four manufacturers that are not on the downloadable list (Electric Vehicles International, Ferrari, Smart, and XLhybrids).

compressed natural gas. Seven manufacturers of electric buses, commercial trucks, or vans are included.

The guides generally start with information about how to identify a vehicle, including markings and vehicle identification numbers, then go on to describe various aspects of vehicle operation. The location of high-voltage components is usually shown on diagrams or photographs. Some diagrams label the parts; others rely on color coding and a key printed under the diagram. Information about airbags is often given, including their location and the safety importance of deactivating the 12-volt system that powers the airbags (to prevent the airbags from triggering during an emergency operation). The organization and type of hazard information varies.

The NTSB reviewed the manufacturers' response guides and assessed whether they covered 11 categories of information deemed critical to emergency personnel who respond to high-voltage battery fires. Only the subset of 36 manufacturers whose vehicles use high-voltage lithium-ion batteries was considered. What constituted critical information was determined from the NTSB's review of the regulations and standards related to the risks faced by emergency responders (see sections 4.1 to 4.4), as well as from its investigation of the emergency response to four electric vehicle fires (see section 2).

Table 2 lists the criteria the NTSB used to determine whether (yes or no) an emergency response guide covered a particular item of critical information for first and second responders. Determining whether the response guides included elements found in the NFPA emergency field guide and its vehicle-specific guidance was part of the review. Table 3 gives the results of the review.

Table 2. Criteria for yes/no determination of critical information in manufacturers' emergency response guides, with corresponding column of table 3.

Criteria for Yes/No Determination	Table 3 Column
Does format of guide conform to ISO standard 17840? Format follows organizational structure and order of information in ISO 17840.	2
Does guide contain elements in NFPA guide for that vehicle? Elements in NFPA guide include identifying vehicle, immobilizing vehicle, disabling vehicle, warnings (high voltage, airbag, silent movement), and extricating occupants.	3
Does guide contain vehicle-specific instructions for disconnecting high-voltage battery from rest of vehicle? Examples include use cut loops, remove plugs, pull levers, remove fuses, disconnect 12-volt battery.	4
Does guide include information on vehicle stabilization and use of PPE? Stabilization examples include placing vehicle in park or chocking wheels. PPE examples include wearing SCBA for fighting vehicle fires and high-voltage protective gear when handling high-voltage components.	5
Does guide include general information about high-voltage battery damage or fire? Examples include warnings that (1) damaged batteries can vent toxic gas, (2) high-voltage battery fires require copious amounts of water, and (3) high-voltage batteries can ignite after being extinguished.	6

Criteria for Yes/No Determination	Table 3 Column
Does guide contain vehicle-specific information about fighting high-voltage battery fire? Examples include (1) specific locations to apply water and (2) procedures for applying water to extinguish fire and cool battery. Some guides state that occupant compartment must be vented, or that fire or heat can ignite components near battery.	7
Does guide contain information about submerged vehicle? Examples include statement that vehicle does not pose risk of electric shock, or procedures to mitigate risk.	8
Does guide contain information about postincident recovery or towing of damaged vehicle? Examples include that flatbed should be used for transport and vehicle should be monitored for reignition.	9
Does guide contain information about storing damaged electric vehicle? Examples include that vehicle should be isolated outdoors, 50 feet from other fire sources.	10
Does guide contain specific information about mitigating risks of stranded energy? Examples include procedures for minimizing risks of battery reignition; also information for contacting manufacturer.	11
Does guide contain information about vehicle's high-voltage battery? Examples include peak voltage of battery pack or battery storage capacity.	12

Vehicle models that use NiMH rather than lithium-ion batteries were excluded from the review (NiMH batteries do not contain a flammable electrolyte). The number of vehicle models produced by different manufacturers varied from just 1 to more than 20. When a manufacturer published response guides for several vehicle models and model years, the most recent model was selected, with priority given to BEVs over PHEVs (the five PHEVs listed in table 3 contain lithium-ion batteries). If a parent company (such as Toyota) published a guide covering multiple manufacturers or brands (such as Lexus and Toyota) as well as a guide for each specific brand, both types of guide were reviewed.

Table 3. Presence or absence of critical information in emergency response guides for 36 electric vehicles equipped with high-voltage lithium-ion batteries.

1 Vehicle make and model	2 ISO 17840 format	3 Elements of NFPA vehicle-specific guides	4 Vehicle-specific instructions for HV disconnect	5 Stabilization and PPE information	6 General information on HV battery damage or fire	7 Vehicle-specific instructions for HV battery fire	8 Submerged vehicle information	9 Damaged EV recovery/towing information	10 Damaged EV storage information	11 Information on mitigating stranded energy risk	12 HV battery characteristics	13 Notes
Acura MDX Sport Hybrid EV	No	Yes	Yes	No	No	No	Yes	Yes	Yes	No	Yes	--
Audi A8 TFSI e	No	Yes	Yes	No	No	No	No	No	No	No	No	--
Azure Transit Connect Van EV ^a	No	Yes	Yes	No	Yes	No	No	Yes	No	No	Yes	--
BMW i3 EV 2015–2018 and BMW Multi-Vehicle 2017	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	--
Buick LaCrosse and Regal Hybrid EV 2012–2016	No	Yes	Yes	No	No	No	Yes	No	No	No	Yes	--
BYD K9M Series Bus EV	No	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Vehicle has automatic fire suppression system.
Cadillac ELR Extended-Range EV 2014–2016	No	No	Yes	No	Yes	No	Yes	No	No	No	Yes	--
Chevrolet Spark EV 2014–2016	No	No	Yes	No	Yes	No	Yes	No	No	No	Yes	--
Chrysler 2017 Pacifica Hybrid	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	--
Fiat 500e EV 2013–2018	No	Yes	Yes	Yes	Yes	No	Yes	No	No	No	Yes	--
Fisker Karma PHEV 2011–2012 ^a	No	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	No	--
Ford 2018 Focus EV	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Guide gives manufacturer contact information.
Gillig Bus EV 2016–2018	No	No	Yes	No	Yes	No	No	No	No	No	Yes	--
GMC Sierra Hybrid EV 2016–2018	No	No	Yes	No	Yes	No	Yes	No	No	No	Yes	--

1 Vehicle make and model	2 ISO 17840 format	3 Elements of NFPA vehicle- specific guides	4 Vehicle- specific instructions for HV disconnect	5 Stabilization and PPE information	6 General information on HV battery damage or fire	7 Vehicle- specific instructions for HV battery fire	8 Submerged vehicle information	9 Damaged EV recovery/ towing information	10 Damaged EV storage information	11 Information on mitigating stranded energy risk	12 HV battery characteristics	13 Notes
Honda Clarity EV 2017–2018	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	--
Hyundai Ioniq EV 2017–2018	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Guide instructs firefighters to monitor battery with thermal camera before leaving scene.
Infiniti Q50 Hybrid 2014–2018	No	Yes	Yes	Yes	Yes	N	Yes	No	No	No	Yes	--
Karma Revero 2017–2018	No	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	Yes	--
Kia Soul EV 2015– 2018	No	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	Yes	--
Lexus LC500h 2018	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	--
Lincoln MKZ Hybrid 2013–2018	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Guide gives manufacturer contact information.
Mercedes-Benz	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Guide contains 1-page rescue cards for all Mercedes-Benz passenger cars.
MINI Countryman PHEV 2017–2018	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	--
Mitsubishi Outlander PHEV 2018	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Guide instructs to flood vehicle with water.
Nissan Leaf EV 2018	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	--
Nova Bus LFSe EV 2016–2019	No	Yes	Yes	Yes	No	No	No	No	No	No	Yes	--
Porsche AG Taycan Data Sheets 2019	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Guide gives source for additional information.
Proterra Catalyst E2 EV Bus 2017–2018	No	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Guide says to focus water at vents, use thermal camera until all heat sources are extinguished.

1 Vehicle make and model	2 ISO 17840 format	3 Elements of NFPA vehicle- specific guides	4 Vehicle- specific instructions for HV disconnect	5 Stabilization and PPE information	6 General information on HV battery damage or fire	7 Vehicle- specific instructions for HV battery fire	8 Submerged vehicle information	9 Damaged EV recovery/ towing information	10 Damaged EV storage information	11 Information on mitigating stranded energy risk	12 HV battery characteristics	13 Notes
Scion iQ EV 2013 ^b	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Guide gives advice for offensive fire attack (flood battery with water) or defensive attack (let it burn out).
Smith Newton Step Van 2012–2017 ^a	No	No	Yes	No	No	No	No	No	No	No	No	--
Subaru Crosstrek Hybrid 2019	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Guide recommends not flooding battery and allowing it to burn itself out.
Tesla Model 3 EV 2017–2018	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Guide states 3,000 gallons of water applied directly to battery may be needed. Consider allowing to burn; can take 24 hours to extinguish.
Toyota Prius PHEV 2012–2015	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Guide recommends allowing fire to burn itself out.
Van Hool Bus (fuel cell)	No	No	Yes	No	No	No	No	No	No	No	No	Bus has both hydrogen fuel cell and lithium-ion batteries.
Volkswagen e-Golf EV 2014–2018	No	No	Yes	No	No	No	No	No	No	No	No	Only 3-page quick response guide is provided.
Volvo XC60 PHEV 2018	No	No	Yes	No	No	No	No	No	No	No	No	--
TOTAL Yes	0	28	36	24	28	2	26	21	17	0	30	--
TOTAL No	36	8	0	12	8	34	10	15	19	36	6	--

NOTE: EV = electric vehicle; HV = high voltage.
^a Manufacturer is no longer in business.
^b Scion was discontinued in 2016.

As shown in table 3, most (28) of the manufacturers' guides contain elements of the vehicle-specific guidance that is part of the NFPA's emergency response guide. However, none of the manufacturers follow the format or order of elements in ISO 17840 in their guides, as recommended by SAE J2990.⁸⁷ All manufacturers give vehicle-specific information for disabling the high-voltage system—which means disconnecting the high-voltage circuits from the rest of the vehicle, not deenergizing the high-voltage battery itself. Various devices and procedures are described, such as cut loops for severing the connection between the high-voltage system and the rest of the vehicle, or plugs that can be manually lifted out to disconnect the high-voltage system. The guides generally include diagrams or photos of the disconnect procedures, accompanied by written instructions.

Two-thirds (24) of the manufacturers' guides give information about stabilizing a damaged vehicle and also describe the PPE appropriate for various emergency situations. All but 10 guides contain information about submerged vehicles, such as that the chassis will not be energized if the vehicle is under water (and is therefore safe to touch). Twenty-one give information about towing the vehicle—for example, that a flatbed truck should be used.

Twenty-eight of the manufacturers' guides warn about the hazards, including fire, posed by damaged high-voltage batteries. However, only two manufacturers give vehicle-specific instructions for fighting a high-voltage battery fire (Mitsubishi recommends flooding a damaged vehicle with water; Proterra, which manufactures an electric bus, instructs firefighters to focus water at the battery enclosure). Subaru recommends not flooding a battery but letting it burn itself out. Toyota also recommends letting a battery fire burn out by itself. Hyundai and Proterra recommend monitoring a damaged battery using a thermal camera. Generally missing from the guidance is specific information about where to apply water to a burning high-voltage battery and how to determine when it is safe to stop applying water, such as appropriate temperature thresholds.

None of the manufacturers give specific instructions, such as a list of procedures, for minimizing the dangers posed by stranded energy, including the risk of battery reignition. Six do not provide any information about such battery characteristics as peak voltage.

⁸⁷ See section 4.4.

5 Analysis

This safety report begins with investigations by the NTSB of four electric vehicle fires. Three of the fires (Lake Forest, Mountain View, and Fort Lauderdale) resulted from high-speed, single-vehicle collisions that damaged the vehicles' high-voltage lithium-ion batteries. The fourth fire (West Hollywood) was caused by internal failure of the vehicle's high-voltage lithium-ion battery during normal driving operations.

The three crashes were much more severe and resulted in greater damage to vehicles and batteries than the conditions under which electric vehicles are crash-tested to meet federal safety standards (FMVSS 305 and FMVSS 208). Two of the crashes involved vehicles traveling at well above the posted speed limit (82 mph in Lake Forest and 116 mph in Fort Lauderdale). In the Mountain View crash, the vehicle hit a nonoperational crash attenuator at highway speeds (71 mph). All three crashes caused extensive damage that extended into the protected area of the high-voltage battery case, rupturing the case and damaging the battery modules and individual cells.

The Mountain View and Fort Lauderdale crashes resulted in the deaths of vehicle occupants. FMVSS 305 requirements (to prevent electrolyte spillage, retain electrical storage or conversion devices, and ensure electric safety) are evaluated after an electric vehicle is crash-tested under the conditions described in FMVSS 208 (focused on occupant protection at impact speeds ranging from 30 to 50 mph). Both occupants survived the Lake Forest crash, illustrating that crashes at higher impact speeds that cause severe battery damage and fire can be survivable.

As part of its analysis, the NTSB examined national and international standards established to maximize the safety of electric vehicles. Particular attention was paid to the guidance supplied by electric vehicle manufacturers for first and second responders to vehicle crashes and high-voltage battery fires. The examination focused on high-voltage lithium-ion batteries. The analysis identified two primary safety issues:

- Inadequacy of vehicle manufacturers' emergency response guides for minimizing the risks to first and second responders posed by high-voltage lithium-ion battery fires in electric vehicles.
- Gaps in safety standards and research related to high-voltage lithium-ion batteries involved in high-speed, high-severity crashes.

Below, we discuss the findings of the investigation and present recommendations for improving the safety of first and second responders who deal with high-voltage lithium-ion battery fires in electric vehicles.

5.1 Guidance for Emergency Responders

The NTSB reviewed the guidance documents prepared for emergency responders by 36 manufacturers of electric vehicles powered by high-voltage lithium-ion batteries. The results, tabulated in table 3, section 4.5.2, show that the guidance is strong in certain respects but lacking in others, particularly as regards specific instructions for fighting high-voltage lithium-ion battery

fires and for addressing the risks posed by stranded energy. Each subsection below draws conclusions related to one critical aspect of the guidance, followed by a subsection containing recommendations for improving the guidance and for disseminating information to first and second responders about the risks and the guidance described in this report.

5.1.1 High-Voltage Disconnect

Emergency responders face a risk of electric shock from the energy stored in damaged high-voltage lithium-ion batteries. To protect against electric shock, safety standards require isolating an electric vehicle's high-voltage battery system from the chassis, giving minimal values for isolation resistance. They also require specific markings for high-voltage systems and orange coverings to identify high-voltage cables and other components.

To lessen the high-voltage risks in damaged electric vehicles, manufacturers include methods of isolating the high-voltage system by disconnecting the high-voltage circuits between the lithium-ion battery and the powertrain. First responders who consult any of the emergency response guides reviewed by the NTSB will find instructions on how to isolate an electric vehicle's high-voltage lithium-ion battery (refer to column 4, table 3). Each of the emergency response guides includes a graphic illustration of the disconnect method for that vehicle, and in all the electric vehicles covered by the guides, the color orange is used to identify high-voltage components. The methods of disconnecting high-voltage circuits vary by vehicle manufacturer—federal standards (FMVSS 305) do not mandate a uniform method. As noted earlier, although the disconnects will isolate a high-voltage lithium battery, they will not remove energy from the battery itself.

SAE J2990, which addresses the hazards faced by first and second responders to crashes and other incidents involving electric vehicles, recommends that manufacturers incorporate at least two methods of disconnecting the vehicles' high-voltage systems. The recommendation lists the following methods: (1) automatic shutdown; (2) switching the ignition switch to OFF (to disconnect the high-voltage system from the high-voltage sources and discharge the system to ≤ 60 volts DC or 30 volts AC within 10 minutes); (3) cut or disconnect battery cables to discharge the 12-volt system, and cut or disconnect the 12-volt output cable. SAE J2990 states that using a manual disconnect (such as pulling a plug) should not be the primary method for first responders to disable a vehicle's high-voltage circuits. That is because (1) the variety of designs makes locating and activating manual disconnects inefficient, (2) first responders do not always have the required PPE, and (3) the manual disconnect mechanism might be inaccessible.

The disabling methods incorporated by manufacturers include manual service disconnects and cut loops that can be severed to disconnect the high-voltage system and isolate it from the rest of the vehicle. A few manufacturers prefer operating the manual disconnect as the method of disabling the high-voltage system. If physical disconnects are not available or are inaccessible, some manufacturers recommend pulling a particular fuse, or removing all fuses. For several models, the guidance states that the vehicle's high-voltage system will automatically disconnect if the airbags deploy. For other models, emergency responders are told that pressing the start/stop button will automatically trigger a high-voltage disconnect.

All the vehicles in the three postcrash battery fires investigated for this report were equipped with emergency disconnect devices. Under the circumstances, however, none of the first responders to the fires employed any of the devices. In the Lake Forest case, the high-voltage cut loop was in the area of severe fire and impact damage at the front of the SUV. The Mountain View crash resulted in the cut loop (also at the front of the vehicle) being completely torn away. During the inspection after the Fort Lauderdale crash, firefighters told NTSB investigators that the fire made the cut loop at the front of the car inaccessible, even if they had known where to look for it.⁸⁸ In the West Hollywood fire, which did not follow a crash, first responders successfully cut the vehicle's high-voltage disconnect loop, though they expressed confusion about the relation between the high-voltage system and the 12-volt system that powered the vehicle's computer. The NTSB concludes that manufacturers' emergency response guides provide sufficient vehicle-specific information for disconnecting an electric vehicle's high-voltage system when the high-voltage disconnects are accessible and undamaged by crash forces. The NTSB further concludes that crash damage and resulting fires may prevent first responders from accessing the high-voltage disconnects in electric vehicles.

5.1.2 Fire Suppression

The NFPA emergency field guide states that large, sustained volumes of water are required to extinguish a high-voltage battery fire: "it could require over 2,600 gallons, depending on the size and location of the battery." The guidance also highlights the difficulty of applying extinguishing agents directly onto burning cells because of the batteries' protective cases. It further states that applying a large volume of water might cool the battery enough to prevent the fire from propagating to adjacent cells. A high-voltage lithium-ion battery is designed to resist water, but water is critical for cooling overheated cells to stop thermal runaway and further combustion (as discussed in the next section).

In the four NTSB investigations, the total amount of water used to suppress the high-voltage lithium-ion battery fires ranged from 300 gallons in Fort Lauderdale and West Hollywood to 1,000 gallons in Mountain View and to over 20,000 gallons in Lake Forest. In the Fort Lauderdale incident, the battery fire was intense, but a rupture in the battery case between the front seats allowed water into the case, which helped extinguish the fire. In the West Hollywood battery fire, which did not result from a crash, the flames were extinguished quickly, but firefighters had to apply water for a further 30 minutes to stop the battery from smoking. In the Mountain View case, the flames were also extinguished quickly, but more water had to be applied when the battery fire reignited. In the Lake Forest case, firefighters applied large quantities of water, but they could not extinguish the fire until they elevated the vehicle and applied water directly to the battery on the underside.

According to the NTSB's review of the emergency response guides available to first and second responders, most manufacturers provide general information about damaged high-voltage batteries and the danger of fire, including that such fires require large amounts of water to extinguish. However, manufacturers generally do not give vehicle-specific information for fighting a high-voltage lithium-ion battery fire (refer to column 7, table 3), such as where and how

⁸⁸ Cut loops can be in the front or the rear, or in both front and rear, as in Tesla model S cars built after June 2013 (such as the vehicle in the Fort Lauderdale fire).

to apply water in order to extinguish and cool the battery. In the Lake Forest fire, firefighters searched online for assistance, but they did not apply enough water directly onto the battery case in the beginning to cool the high-voltage battery, which ended up requiring 2 hours and 20,000 gallons of water to extinguish. In the West Hollywood fire, firefighters contacted the manufacturer directly once the flames had died down because they could not determine where to apply water to stop the vehicle from smoking. While searching for a way to apply water to the battery, firefighters used a metal pry bar to remove body panels from the vehicle, a procedure that posed a risk of electric shock and that guidance documents warn against.

Thus, in addition to hampering efficient extinguishing of high-voltage lithium-ion battery fires, the lack of clear, vehicle-specific firefighting information can lead to confusion or inadvisable action on the part of first responders, even when general guidance is available. The NTSB concludes that the instructions in most manufacturers' emergency response guides for fighting high-voltage lithium-ion battery fires lack necessary, vehicle-specific details on suppressing the fires.

The NTSB notes that in France, Renault (not included in the guidance documents reviewed for this report because its vehicles are not imported to the United States) has worked with fire and emergency services to design inlet ports through which, in case of fire, water can be applied directly to the lithium-ion batteries in its electric vehicles. According to a company website, firefighters can extinguish a battery fire in less than a minute using the access ports.⁸⁹

5.1.3 Thermal Runaway and Battery Reignition

Damaged high-voltage lithium-ion batteries pose a risk to emergency responders because of the potential for thermal runaway, which can cause a battery to ignite, or reignite. The risk of thermal runaway in electric vehicles powered by high-voltage lithium-ion batteries became evident in 2011, when a Chevrolet Volt caught fire 3 weeks after a crash test.

The high-voltage energy stored in lithium-ion batteries and the flammability of the batteries' electrolyte create the potential for thermal runaway and fire. Thermal runaway begins with overheating in individual battery cells that degrades their electrical isolation and can be in progress even when flames are not visible outside the battery. SAE J2990 recommends using a thermal camera or infrared temperature probe to inspect a damaged battery. Emergency responders are also counseled to use their senses when inspecting a damaged electric vehicle—to listen for noises from the battery (gurgling, bubbling, crackling, hissing, or popping), which can indicate that overheated cells are venting or that the high-voltage system is arcing; and to notice whether a burnt odor is coming from the battery, which is evidence of fire or heat damage.

SAE J2990 warns that if a high-voltage lithium-ion battery is involved in a fire, “there is a possibility that it could reignite after extinguishment.” The NFPA's emergency field guide also warns that a fire in a high-voltage lithium-ion battery could reignite and recommends that emergency responders use thermal imaging to monitor the battery. The guide states that reignition is accompanied by a “whooshing” or “popping” sound, followed by off-gassing of white smoke or

⁸⁹ See [article](#) dated May 16, 2018, on the Groupe Renault website: “Electric Vehicles: Groupe Renault Works Hand in Hand with Fire Services” (accessed June 1, 2020).

electrical arcs or sparks that reignite, with visible flames or fire. The guidance states that reignition can occur within several hours to a day or more after the fire is extinguished. The NFPA advises firefighters to continue applying water (even after they can no longer see a flame) to sufficiently cool the battery pack—it could take an hour or more—so as to reduce the risk of reignition.

All but 8 of the 36 manufacturers' emergency response guides reviewed for this report contain general information about high-voltage battery damage, including that high-voltage batteries can reignite after being extinguished. Tesla's guidance for the model S specifically states that about 3,000 gallons of water are needed to cool the high-voltage lithium-ion battery, that reignition can occur, and that the battery must be completely cooled before it is released to secondary responders. The vehicles in both the Lake Forest and Mountain View crashes experienced at least six battery reignitions after the vehicle fires were extinguished. The battery in the Fort Lauderdale crash reignited three times. (The battery in the West Hollywood fire did not reignite.) Emergency responders in all three cases either consulted the emergency response guides online or contacted the manufacturer directly. Yet firefighters and tow truck drivers were unable to prevent the reignitions. The NTSB concludes that thermal runaway and multiple battery reignitions after initial fire suppression are safety risks in high-voltage lithium-ion battery fires.

5.1.4 Stranded Energy

The NTSB concludes in section 5.1.1 that the manufacturers' emergency response guides contain sufficient information for first responders to disconnect an electric vehicle's high-voltage system, provided the disconnects are accessible and are undamaged by crash forces. However, even if an electric vehicle's high-voltage system is disconnected, energy will remain trapped in a damaged high-voltage lithium-ion battery. The stranded energy poses a risk of electric shock to emergency responders and creates the potential for thermal runaway that can result in reignition and fire.

Battery reignition can be caused by thermal or mechanical means. In a thermal reignition, the battery is not sufficiently cooled and thermal runaway results, as in the Lake Forest fire. Mechanical reignition results when parts of a battery or other conductive debris cause a short circuit in cells that contain stranded energy. For example, if a damaged electric vehicle is shifted, twisting of the wreckage can create new electrical connections that can then release energy and cause reignition. After the Fort Lauderdale fire, the battery reignited twice—once while the wreckage was being loaded onto a tow truck, and again when a chain passed over the battery after the vehicle had been loaded onto the truck.

In the three high-speed, high-severity crashes that the NTSB investigated, the vehicles' high-voltage lithium-ion batteries reignited at least 15 times in total. The reignitions were evidence that stranded energy remained in undamaged parts of the high-voltage batteries. In the inspection of the battery system after the Fort Lauderdale crash and fire, the voltage in battery modules 1 through 5 ranged from 69.9 to 167.3 volts DC, well above the safe limits for human exposure (50 to 60 volts DC). The inspection of the high-voltage battery after the West Hollywood fire found that module 14 had experienced internal failure and that all other modules remained charged.

Technicians at a local service center operated by the manufacturer, which took possession of the vehicle, removed the battery and discharged the stranded energy by 50 percent.⁹⁰

After the Mountain View crash, engineers twice attempted to remove stranded energy from the vehicle's high-voltage energy system. On scene, they halted their attempt when they encountered signs of reignition. After the vehicle had been moved to the more-controlled environment of a tow yard, the engineers made a second attempt to remove stranded energy from the battery, using a connector on the battery's outside. However, the connector was contaminated by water and debris, and attempts to deenergize the battery failed. Efforts to measure the voltage were inconclusive.

After the Lake Forest crash and fire, much of the high-voltage lithium-ion battery remained intact, but confirming that the battery contained stranded energy was not possible because the module connection terminals were inaccessible. In the Chevrolet Volt example from 2011, sufficient stranded energy remained after a crash test that the battery caught fire while the vehicle was in storage 3 weeks later. In two international examples of high-voltage lithium-ion battery fires in electric vehicles reviewed for this study, a BMW model i3 and a Mitsubishi Outlander also experienced reignitions. Although none of the battery fires investigated or reviewed for this safety report resulted in electric shock to vehicle occupants or emergency responders, an energized high-voltage lithium-ion battery always presents such a risk. The NTSB concludes that the energy remaining in a damaged high-voltage lithium-ion battery, known as stranded energy, poses a risk of electric shock and creates the potential for thermal runaway that can result in battery reignition and fire.

Firefighters have no method of determining whether stranded energy is present in a damaged high-voltage lithium-ion battery or of removing energy from the battery pack.⁹¹ Engineers or other specialists can use the battery management system to check for remaining voltage if the system is operational, and some batteries have built-in discharge ports. However, in three of the four NTSB investigations discussed in this report, the high-voltage battery system was damaged in a crash, preventing access to the battery management system or to the discharge ports. In addition, the status of a damaged battery is unknown and must be treated as a high-voltage safety risk.

In all four NTSB investigations, emergency response guides for each vehicle were available to the first responders from both the NFPA website and directly from the vehicle manufacturer. The NTSB's review of emergency response guides from 36 manufacturers found that all contained vehicle-specific information for mitigating high-voltage risks, such as the location of the high-voltage battery and methods for disconnecting the high-voltage system. However, none of the guides offered information for mitigating the risks of stranded energy, such as a list of procedures for minimizing the chance of battery reignition or specific instructions for where and how to apply water to cool a high-voltage battery. One method of removing the stranded

⁹⁰ As noted earlier, the charge was reduced to 50 percent to allow safe long-distance transportation of the battery and also to preserve evidence.

⁹¹ Existing methods of deenergizing a battery (such as accessing the terminals manually or flooding the battery pack with a conductive solution) are not within an emergency responder's scope and typically take an impractically long time.

energy from a high-voltage lithium-ion battery is to separate it from the vehicle and discharge it in a saltwater bath.

The NFPA's recent training video addressing high-voltage battery systems and stranded energy highlights the challenges to emergency responders.⁹² The NFPA warns responders that they should always assume that the high-voltage system is energized. First responders therefore must assume that stranded energy is present in a damaged electric vehicle, and they require vehicle-specific information on how to manage—and minimize—the associated risks for battery reignition and fire.⁹³ Secondary responders, including tow operators and storage facility operators, must also assess and mitigate the risks associated with high-voltage lithium-ion batteries. As noted earlier, in the Fort Lauderdale recovery effort, a chain that passed over the high-voltage battery caused it to reignite. After the Lake Forest crash, when the vehicle ignited while being moved onto a flatbed tow truck, the tow truck operator suffered minor injuries. The NTSB concludes that high-voltage lithium-ion batteries in electric vehicles, when damaged by crash forces or internal battery failure, present special challenges to first and second responders because of insufficient information from manufacturers on procedures for mitigating the risks of stranded energy.

Storing an electric vehicle with a high-voltage lithium-ion battery is problematic when the vehicle is damaged or a battery fire has occurred. The battery fires investigated by the NTSB reignited multiple times, even days after a crash, placing other vehicles and nearby structures at risk for fire. The Chevrolet Volt that reignited 3 weeks after a crash test damaged four nearby vehicles. The NFPA and vehicle manufacturers recommend leaving a 50-foot clearance around a stored, damaged electric vehicle to prevent fire damage to nearby vehicles or structures in case the battery reignites. (The guidance in SAE J2990 gives an alternate solution: create a barrier of earth, steel, concrete, or solid masonry around the vehicle.) The storage facilities for the vehicles involved in the NTSB-investigated crashes and fires in Lake Forest, Mountain View, and Fort Lauderdale could not accommodate a 50-foot radius around the damaged vehicles. If more than one electric vehicle with a risk for fire reignition were stored at the same facility, providing sufficient space to mitigate the risks of a subsequent fire would most likely be impossible. The NTSB concludes that storing an electric vehicle with a damaged high-voltage lithium-ion battery inside the recommended 50-foot-radius clear area may be infeasible at tow or storage yards.

5.1.5 Format Issues

Emergency response guides must be clear about the vehicle-specific procedures and evaluation criteria necessary to minimize the risk of ignition or reignition of a damaged high-voltage lithium-ion battery. The fire/rescue organization CTIF developed ISO standard 17840 (*Road Vehicles—Information for First and Second Responders*) as a four-part standard addressing all vehicle types, including passenger cars, light commercial vehicles, buses, and heavy commercial vehicles (see section 4.4 for details). Part 3 of the standard, published in April 2019, contains a template for emergency response guides that is applicable to various types of vehicles, including electric vehicles. The template defines the layout and general contents of emergency response guides, with the goal of establishing a standard format for clarity and ease of use by first

⁹² The video can be viewed on the [NFPA's training and certification website](#) (accessed June 5, 2020).

⁹³ The NFPA video highlights the need for responders to consider the type, quantity, and location of batteries in a damaged electric vehicle.

and second responders. The aim is that responders will have the information they need to make quick, correct decisions in case of fire, vehicle submersion, or fluid leakage. The standard spells out the headings for the various sections of an emergency response guide (such as “Disable direct hazards/safety regulations” or “In case of fire”), but leaves it to manufacturers to fill in specific information for each section of the guide.

The NTSB found that none of the electric vehicle manufacturers organize their emergency response guides according to the format laid out in ISO standard 17840, as recommended in SAE J2990. The ISO standard is intended to support the quick and safe rescue of vehicle occupants as well as the safety of emergency responders. The benefits of standardized guidance documents also extend to enhancing the training of emergency responders. If manufacturers used the ISO standard 17840 template to present emergency response information, it could increase response efficiency, improve emergency responders’ understanding of actions to take when confronting a damaged electric vehicle and its high-voltage lithium-ion battery, enable consistent training of emergency responders, and minimize the risks to emergency responders associated with high-voltage energy systems, because the information would be presented in a consistent manner for all vehicles and contain equivalent levels of vehicle-specific detail. The NTSB therefore concludes that electric vehicle manufacturers should use the ISO standard 17840 template to present emergency response information. Euro NCAP, in coordination with CTIF, is incorporating scoring relative to the availability of a manufacturer’s emergency response guide and its compliance with ISO standard 17840.⁹⁴ The NTSB concludes that action by NHTSA, similar to that taken by Euro NCAP, to incorporate scoring relative to the availability of a manufacturer’s emergency response guide and its adherence to ISO standard 17840 and SAE standard J2990 into the US NCAP, would be an incentive for manufacturers of vehicles sold in the United States with high-voltage battery systems to comply with those standards.

5.1.6 Recommendations for Improving Guidance and Disseminating Information

The NTSB found that the guidance provided by electric vehicle manufacturers to first and second responders is lacking in important respects (as shown by the “no” entries in table 3, section 4.5.2)—particularly as regards the safety risks of fighting fires that involve high-voltage lithium-ion batteries and the dangers posed by the stranded energy in a damaged high-voltage lithium-ion battery. The NTSB identified that nearly all the manufacturers’ emergency response guides contain general information about the risks posed by the high-voltage lithium-ion batteries in electric vehicles—such as that damaged batteries can ignite or reignite—but that only two guides offer vehicle-specific information for suppressing a high-voltage battery fire. Critical information includes where to apply water to extinguish a battery fire in an electric vehicle and when it is safe to stop applying water, such as when temperature thresholds are reached.

Of further concern is that none of the reviewed guides give emergency responders any information about how to handle the risks posed by the stranded energy in a damaged high-voltage lithium-ion battery. Firefighters who participate in the initial emergency response and tow truck drivers who move a damaged electric vehicle from the scene can all be exposed to the risks of stranded energy. Storing an electric vehicle with a damaged high-voltage lithium-ion battery is an

⁹⁴ The scoring is based on the availability of the short versions of manufacturers’ emergency response guides, known as rescue sheets.

additional problem. The guidance documents generally limit their advice to calling the manufacturer for instructions or leaving at least 50 feet of clearance around the vehicle. The NTSB considers that advice impractical at best. Given the SAE's recommendation to also consider isolating a damaged electric vehicle inside a barrier of earth, steel, concrete, or masonry, manufacturers might consider including such an alternative in their guidance.

One obvious way of making the guidance information readily accessible to emergency responders would be to present it in the form of a checklist, similar to the list in table 1, section 4.3.3 (the postincident steps recommended in SAE J2990). The NTSB agrees with SAE and others that having the emergency response guides published in a clear, consistent format would improve their usefulness to emergency responders as well as minimize the risks to responders associated with high-voltage lithium-ion batteries. The NTSB also urges vehicle manufacturers to include in their emergency response guides information specific to each vehicle so that firefighters and tow truck drivers can efficiently and safely act in emergencies involving electric vehicles that are powered by high-voltage lithium-ion batteries.

The NTSB therefore recommends that the manufacturers of electric vehicles equipped with high-voltage lithium-ion batteries model their emergency response guides on ISO standard 17840, as included in SAE recommended practice J2990, and incorporate vehicle-specific information on (1) fighting high-voltage lithium-ion battery fires; (2) mitigating thermal runaway and the risk of high-voltage lithium-ion battery reignition; (3) mitigating the risks associated with stranded energy in high-voltage lithium-ion batteries, both during the initial emergency response and before moving a damaged electric vehicle from the scene; and (4) safely storing an electric vehicle that has a damaged high-voltage lithium-ion battery.⁹⁵

The electric vehicle market is expanding, and NHTSA's NCAP rates the performance of new vehicle models against various safety measures. The NTSB concluded in section 5.1.5 that incorporating scoring into the NCAP relative to the availability of a manufacturer's emergency response guide and its adherence to the relevant ISO and SAE standards would be an incentive for manufacturers of vehicles sold in the United States with high-voltage battery systems to comply with those standards. The incentive would apply to both current and new manufacturers of electric vehicles, and adherence would enhance the safety of first and second responders by improving the emergency response guides provided by manufacturers. The NTSB therefore recommends that when determining a vehicle's US NCAP score, NHTSA factor in the availability of a manufacturer's emergency response guide and its adherence to ISO standard 17840 and SAE recommended practice J2990.

⁹⁵ The manufacturers (including subdivisions or subsidiary brands) subject to this recommendation are as follows: BMW Group (BMW and MINI); BYD Motors; FCA Group (Chrysler and Fiat); General Motors Company (Buick, Cadillac, Chevrolet, and GMC); Ford Motor Company (Ford and Lincoln); Gillig; Honda Motor Company (Honda and Acura); Hyundai Motor Company; Karma Automotive; Kia Motors Corporation; Mercedes-Benz USA; Mitsubishi Motors; Nissan Motor Company (Infiniti and Nissan); Nova Bus, Inc.; Porsche Cars North America; Proterra, Inc.; North American Subaru; Tesla, Inc.; Toyota Motor North America (Lexus and Toyota); Van Hool NV; Volkswagen Group of America (Audi and Volkswagen); and Volvo Car Corporation. Three companies whose emergency response guides were reviewed for this report have gone out of business: Azure Dynamics, Fisker, and Smith. Toyota discontinued its Scion brand in 2016.

It is vital that first and second responders be aware of the risks associated with the high-voltage lithium-ion batteries in electric vehicles. The NFPA and other organizations have been working to disseminate such information. The NTSB is particularly encouraged that the dangers of stranded energy have begun to be publicized, as in the NFPA's new training video and recent journal article (Roman 2020). Nevertheless, some firefighters and tow truck drivers may not fully understand the risks entailed in fighting a high-voltage battery fire or in transporting a damaged electric vehicle, or they may not know where to find guidance information. An example of responders' concerns that reflect a lack of clear understanding occurred during efforts to suppress the final battery reignition after the Mountain View crash. Firefighters applied water sporadically, fearing electric shock from the water stream—a potential risk the NFPA has studied and discounted.

The professional associations that represent or operate training programs for first and second responders include, in addition to the NFPA, the International Association of Fire Chiefs, representing the leadership of firefighters and emergency responders worldwide; the International Association of Fire Fighters, a labor union representing full-time firefighters and emergency medical personnel in the United States and Canada; the National Alternative Fuels Training Consortium, a nationwide training organization that develops curriculums and implements training, outreach, and education on the use of alternative fuel vehicles; the National Volunteer Fire Council, which represents volunteer fire, emergency medical, and rescue services and administers the National Traffic Incident Management Responder Training Program; and the Towing and Recovery Association of America, which, in partnership with the Federal Highway Administration, operates the National Driver Certification Program for tow truck operators. The NTSB therefore recommends that the NFPA, the International Association of Fire Chiefs, the International Association of Fire Fighters, the National Alternative Fuels Training Consortium, the National Volunteer Fire Council, and the Towing and Recovery Association of America inform their members about the circumstances of the fire risks described in this report and the guidance available to emergency personnel who respond to high-voltage lithium-ion battery fires in electric vehicles.

5.2 Standards and Research

The need to evaluate the risks associated with high-voltage lithium-ion battery fires, stranded energy, and postcrash (or postincident) vehicle storage is beginning to be recognized. In 2017, NHTSA published a report addressing safety issues in the high-voltage lithium-ion battery systems of electric vehicles and identified crash and postcrash damage as a gap in regulations and safety standards (Stephens and others 2017). Since that report, NHTSA has initiated research projects into battery management systems and stranded energy. For example, Rask and others (2020) reviewed the risks and hazards associated with the stranded energy remaining in high-voltage lithium-ion battery systems. The research focused on undamaged vehicle battery failures or vehicles damaged in survivable crashes (FMVSS 208 level). The mitigation strategies (which included manufacturer-developed battery discharge tools) assumed access to battery connections, which, as seen in the NTSB-investigated crashes, might not be feasible on scene or not possible at all after a high-speed, high-severity crash. Further, the current federal standard (FMVSS 305), the efforts of the United Nations working group on electric vehicle safety (GTR 20), and the emergency response guidance detailed in SAE J2990 do not currently address high-speed, high-severity crashes resulting in damage to a high-voltage lithium-ion battery and the

associated stranded energy in the high-voltage system. The NTSB concludes that although existing standards address damage sustained by high-voltage lithium-ion battery systems in survivable crashes, as defined by federal crash standards, they do not address high-speed, high-severity crashes resulting in damage to high-voltage lithium-ion batteries and the associated stranded energy.

NHTSA is best positioned to facilitate research in the United States on high-speed, high-severity vehicle crashes that result in damage to high-voltage lithium-ion batteries and to communicate findings to the international electric vehicle community. One goal of the Rask and others (2020) study was to develop a prototype tool that would enable nonexperts, such as tow truck drivers, to assess and possibly deenergize a high-voltage battery system after a crash. However, the prototype tool would require either a functional battery management system or a direct connection to internal battery modules through a high-voltage port. The battery management system or the ports, or both, are likely to be damaged in a crash or in a thermal runaway event (as seen in the NTSB investigations discussed in this report), making access to them problematic or impossible. Existing deenergizing devices take hours or days to remove the stranded energy from an undamaged high-voltage lithium-ion battery. The NTSB therefore recommends that NHTSA convene a coalition of stakeholders to continue research initiated by NHTSA on ways to mitigate or deenergize the stranded energy in high-voltage lithium-ion batteries and to reduce the hazards associated with thermal runaway resulting from high-speed, high-severity crashes. NHTSA should publish the research results.

6 Findings

1. Manufacturers' emergency response guides provide sufficient vehicle-specific information for disconnecting an electric vehicle's high-voltage system when the high-voltage disconnects are accessible and undamaged by crash forces.
2. Crash damage and resulting fires may prevent first responders from accessing the high-voltage disconnects in electric vehicles.
3. The instructions in most manufacturers' emergency response guides for fighting high-voltage lithium-ion battery fires lack necessary, vehicle-specific details on suppressing the fires.
4. Thermal runaway and multiple battery reignitions after initial fire suppression are safety risks in high-voltage lithium-ion battery fires.
5. The energy remaining in a damaged high-voltage lithium-ion battery, known as stranded energy, poses a risk of electric shock and creates the potential for thermal runaway that can result in battery reignition and fire.
6. High-voltage lithium-ion batteries in electric vehicles, when damaged by crash forces or internal battery failure, present special challenges to first and second responders because of insufficient information from manufacturers on procedures for mitigating the risks of stranded energy.
7. Storing an electric vehicle with a damaged high-voltage lithium-ion battery inside the recommended 50-foot-radius clear area may be infeasible at tow or storage yards.
8. Electric vehicle manufacturers should use the International Organization for Standardization standard 17840 template to present emergency response information.
9. Action by the National Highway Traffic Safety Administration, similar to that taken by the European New Car Assessment Programme, to incorporate scoring relative to the availability of a manufacturer's emergency response guide and its adherence to International Organization for Standardization standard 17840 and SAE International recommended practice J2990 into the US New Car Assessment Program, would be an incentive for manufacturers of vehicles sold in the United States with high-voltage lithium-ion battery systems to comply with those standards.
10. Although existing standards address damage sustained by high-voltage lithium-ion battery systems in survivable crashes, as defined by federal crash standards, they do not address high-speed, high-severity crashes resulting in damage to high-voltage lithium-ion batteries and the associated stranded energy.

7 Recommendations

As a result of its investigation, the National Transportation Safety Board makes the following new safety recommendations:

To the National Highway Traffic Safety Administration:

When determining a vehicle's US New Car Assessment Program score, factor in the availability of a manufacturer's emergency response guide and its adherence to International Organization for Standardization standard 17840 and SAE International recommended practice J2990. (H-20-30)

Convene a coalition of stakeholders to continue research initiated by your organization on ways to mitigate or deenergize the stranded energy in high-voltage lithium-ion batteries and to reduce the hazards associated with thermal runaway resulting from high-speed, high-severity crashes. Publish the research results. (H-20-31)

To the manufacturers of electric vehicles equipped with high-voltage lithium-ion batteries: (BMW Group; BYD Motors; FCA Group; General Motors Company; Ford Motor Company; Gillig; Honda Motor Company; Hyundai Motor Company; Karma Automotive; Kia Motors Corporation; Mercedes-Benz USA; Mitsubishi Motors; Nissan Motor Company; Nova Bus, Inc.; Porsche Cars North America; Proterra, Inc.; North American Subaru; Tesla, Inc., Toyota Motor North America; Van Hool NV; Volkswagen Group of America; and Volvo Car Corporation):

Model your emergency response guides on International Organization for Standardization standard 17840, as included in SAE International recommended practice J2990, and incorporate vehicle-specific information on (1) fighting high-voltage lithium-ion battery fires; (2) mitigating thermal runaway and the risk of high-voltage lithium-ion battery reignition; (3) mitigating the risks associated with stranded energy in high-voltage lithium-ion batteries, both during the initial emergency response and before moving a damaged electric vehicle from the scene; and (4) safely storing an electric vehicle that has a damaged high-voltage lithium-ion battery. (H-20-32)

To the National Fire Protection Association, the International Association of Fire Chiefs, the International Association of Fire Fighters, the National Alternative Fuels Training Consortium, the National Volunteer Fire Council, and the Towing and Recovery Association of America:

Inform your members about the circumstances of the fire risks described in this report and the guidance available to emergency personnel who respond to high-voltage lithium-ion battery fires in electric vehicles. (H-20-33)

BY THE NATIONAL TRANSPORTATION SAFETY BOARD

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Report Date: November 13, 2020

Appendix: Lithium-Ion Battery Fires in Aircraft

Lithium-ion batteries can power aircraft systems as well as automobiles. In 2013, the NTSB conducted three investigations of lithium-ion batteries as installed aircraft equipment and hosted a forum on lithium-ion batteries in transportation. In 2020, the NTSB issued a safety recommendation report addressing the transportation of lithium-ion batteries by air.

Investigations

The NTSB investigated a January 7, 2013, battery fire in the auxiliary power unit of a Japan Airlines Boeing 787-8 in Boston.¹ The plane was parked at a Boston airport when maintenance personnel saw smoke and fire coming from the battery case of the aircraft's auxiliary power unit. The NTSB concluded that the probable cause of the fire was an internal short circuit in the power unit's lithium-ion battery, which led to thermal runaway that cascaded to adjacent cells and the release of smoke and fire. NTSB safety recommendations addressed assessing and managing the risk of short circuit and fire in lithium-ion batteries.

The NTSB assisted the Japan Transport Safety Board with its investigation of a battery incident on an All Nippon Airways Boeing 787 on January 16, 2013.² The Japan Transport Safety Board concluded that a cell in the aircraft's main battery had most likely suffered a short circuit, resulting in thermal runaway that destroyed the battery and led to emergency landing and evacuation of the aircraft. The NTSB also assisted the General Civil Aviation Authority of the United Arab Emirates with its investigation of the cargo fire and crash of a United Parcel Service Boeing 747-400F on September 3, 2013, in the desert outside Dubai. The General Civil Aviation Authority's investigation concluded "with reasonable certainty that the location of the fire was in an element of the cargo that contained, among other items, lithium batteries."³

Forum

In April 2013, the NTSB convened a public forum titled "Lithium Ion Batteries in Transportation."⁴ Panels discussed the design, development, and performance of lithium-ion batteries; regulations and standards associated with the manufacture of lithium-ion batteries, consumer and industry use, and transportation of the batteries as cargo; and the application and safety aspects of lithium-ion battery technology in various transportation modes.

¹ For further information, see NTSB (2014) Also, https://www.nts.gov/investigations/Pages/boeing_787.aspx.

² For further information on the Nippon Airways fire, see the Japan Transport Safety Board's report: *Emergency Evacuation Using Slides, All Nippon Airways Co., Ltd., Boeing 787-8, JA804A, Takamatsu Airport, At 08:49 JST, January 16, 2013*. Aircraft Serious Incident Investigation Report AI2014-4 (Tokyo, Japan: JTSB) (accessed November 12, 2020).

³ For further information, see the United Arab Emirates report: *Uncontained Cargo Fire Leading to Loss of Control Inflight and Uncontrolled Descent Into Terrain*, Final Air Accident Investigation Report, Boeing 747-44AF, N571UP, case 13/2010 (Dubai, United Arab Emirates: Air Accident Investigation Sector) (accessed November 12, 2020).

⁴ See the NTSB [event summary](#).

Safety Recommendation Report

In May 2020, the NTSB issued a safety recommendation report titled *Standards for Lithium-Ion Battery Shipments by Air* (NTSB 2020b). The report followed an accident on June 3, 2016, in which a FedEx delivery truck and all its cargo were destroyed by fire while the driver was delivering four large-format lithium-ion batteries to a business in Brampton, Ontario, Canada. No injuries were reported. The batteries had been transported from Sarasota, Florida, in two US-registered cargo planes. The probable cause of the fire was determined to be an electrical short circuit in one of the batteries, causing a thermal runaway that ignited the battery and its packaging. The NTSB concluded that if the thermal runaway had occurred on an airplane, the accident could have resulted in significant damage to or loss of the airplane. The NTSB made recommendations to the Pipeline and Hazardous Materials Safety Administration to remove special provisions and exemptions from testing for low-production or prototype lithium-ion batteries that are transported by air.

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