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A Software/Hardware Framework for Efficient and Safe Emergency Response in Post-Crash Scenarios of Battery Electric Vehicles

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Abstract: The adoption rate of battery electric vehicles (EVs) is rapidly increasing. Electric vehicles differ significantly from conventional internal combustion engine vehicles and vary widely across different manufacturers. Emergency responders (ERs) and recovery personnel may have less experience with EVs and lack timely access to critical information such as the extent of the stranded energy present, high-voltage safety hazards, and post-crash handling procedures in a user-friendly manner. This paper presents a software/hardware interactive tool named Electric Vehicle Information for Incident Response Solutions (EVIRS) to aid in the quick access to emergency response and recovery information. The current prototype of EVIRS identifies EVs using the VIN or Make, Model, and Year, and offers several useful features for ERs and recovery personnel. These features include integration and easy access to emergency response procedures tailored to an identified EV, vehicle structural schematics, the quick identification of battery pack specifications, and more. For EVs that are not severely damaged, EVIRS can perform calculations to estimate stranded energy in the EV's battery and discharge time for various power loads using either EV dashboard information or operational data accessed through the CAN interface. Knowledge of this information may be helpful in the post-crash handling, management, and storage of an EV. The functionality and accuracy of EVIRS were demonstrated through laboratory tests using a 2021 Ford Mach-E and associated data acquisition system. The results indicated that when the remaining driving range was used as an input, EVIRS was able to estimate the pack voltage with an error of less than 3 V. Conversely, when pack voltage was used as an input, the estimated state of charge (SOC) error was less than 5% within the range of 30–90% SOC. Additionally, other features, such as retrieving emergency response guides for identified EVs and accessing lessons learned from archived incidents, have been successfully demonstrated through EVIRS for quick access. EVIRS can be a valuable tool for emergency responders and recovery personnel, both in action and during offline training, by providing crucial information related to assessing EV/battery safety risks, appropriate handling, de-energizing, transport, and storage in an integrated and user-friendly manner.

Keywords: stranded energy; post-crash handling; electric vehicle battery; lithium-ion battery; incident response

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1. Introduction

The burgeoning demand for electric vehicles (EVs), spanning the spectrum from lightweight to heavyweight transportation applications, has precipitated a prolific upsurge in the production of EV models characterized by diverse battery configurations and dimensions [1]. In addition to the conventional safety considerations applicable to internal combustion engine (ICE) vehicles, the aftermath of vehicular accidents or natural calamities such as hurricanes [2] presents distinctive safety hazards specific to battery electric vehicles (BEVs). Following a collision, natural disaster, or any other unforeseen event, individuals within and around the incident site, including first responders, face immediate safety hazards due to the latent energy contained within BEV batteries. In such scenarios, unlike conventional gasoline vehicles, the energy cannot be easily siphoned off, which presents unique risks that must be carefully managed.

The U.S. National Highway Traffic Safety Administration (NHTSA) has delineated the concept of "stranded energy" as the energy persisting within a BEV battery without a secure means of extraction [3]. Broadening this scope, stranded energy encompasses the residual energy residing within a compromised high-voltage battery, the safety status (denoted as "state of safety" or SOS) of which remains indeterminate after an accident or abnormal event [4]. A potentially compromised battery with an unknown level of stranded energy can precipitate a thermal runaway event in the absence of vigilant monitoring, diagnosis, controls, and appropriate handling procedures, thereby posing a risk to life and causing property damage.

In the aftermath of a vehicular collision, an emergency responder (ER) has to expeditiously formulate a strategy to effectively determine safety hazards and mitigate them, not only for their own well-being, but also for the passengers and onlookers within the immediate vicinity. While ERs possess considerable familiarity with ICE vehicles, their exposure to BEVs may be comparatively limited, and they may lack immediate access to the exact information regarding the distinctive characteristics of BEVs as a category or the specific attributes, high-voltage safety intricacies, and post-crash handling protocols applicable to various BEV variants.

Safety risks that are intrinsically associated with stranded BEVs encompass such potential perils as high-voltage circuit shocks and the prospect of battery fires, the latter exacerbated by the substantial reservoir of stranded energy contained within these BEVs, which can reach up to a magnitude of 200 kilowatt-hours (kWh). These unique safety concerns necessitate ERs to exercise heightened vigilance and employ specialized precautions, as some are still developing when addressing incidents involving BEVs [5].

In 2020, the U.S. NHTSA issued a report that focused on post-crash response. This report delved into practical techniques and tools relevant to on-site EV-battery stranded energy and failure detection [3]. Several BEV diagnostic tools have been developed [6–11], and state-of-the-art battery diagnostic methods have been reviewed for EVs [12,13]. Studies have also explored thermal runaway modeling and short-circuit fault diagnosis [14], joint state of charge (SOC) and state of health (SOH) estimation [15], as well as approaches to differentiate discrete sampled data for battery diagnosis [16]. Additionally, Wöhrl et al. [17] presented studies addressing the handling of crashed EVs and providing recommendations. References [18,19] conducted reviews and investigations on EV battery fire accidents, summarizing the lessons learned and offering fire suppression advice applicable to battery or facility design. However, further validation, demonstration, and standardization of these methods and tools in real-life scenarios are still needed before ERs can confidently and effectively use these diagnostic methods and tools in the field.

ERs frequently encounter intricate, vehicle-specific scenarios in the aftermath of EV accidents. Most EV manufacturers offer standardized emergency response guides (ERGs), guided by ISO 17840-1 [20], encompassing post-crash situations [21–23]. These BEV specific guides include comprehensive two-dimensional (2D) imagery that identifies critical safety-related wiring and components, and offers guidance on emergency high-voltage disconnection procedures, among other essential information. Nonetheless, the expeditious retrieval and practical application of these guidelines can pose challenges, especially when dealing with damaged EVs under time constraints and with limited on-site resources. The extensive variety of EV makes, models, and years, along with the associated design complexities, further compounds the difficulties faced by ERs in maintaining awareness, especially considering that a significant portion of ERs in the U.S. are volunteers. According to the U.S. fire administration's statistics, 70% of registered U.S. fire departments are made up of 100 percent volunteer firefighters, and another 15.5% of the U.S. fire departments' staff are made up of over 50% volunteer firefighters. Of active firefighting personnel, only 35% were career firefighters, 53% were volunteer firefighters, and 13% were paid-per-call firefighters [24]. Therefore, there is a critical need for a user-friendly tool that facilitates the rapid identification of specific BEVs and the safety hazards in compromised situations. This tool should offer first responders, second responders, and other incident response personnel vehicle-specific guidance on safely handling and securing BEVs within minutes of their arrival on scene.

In 2023, the application 'The Electric Vehicle Rescue App/EV Rescue' was launched, offering seamless access to manufacturer-developed Emergency Response Guides (ERGs) [25]. This application has proven to be beneficial and has garnered significant interest and appreciation from first and second responders, as well as incident response personnel. In a previous article [26], we highlighted the necessity for such an application to provide safety-critical information specific to stranded EVs readily to emergency responders. The work presented in this paper is inspired by and builds upon our earlier research [26], aiming to address existing gaps in emergency response practices related to EVs involved in accidents.

We propose an open architecture-integrated software and hardware interface tool designed to efficiently provide crucial information to emergency responders (ERs), helping them to safely and efficiently manage post-crash EV situations. This tool encompasses various critical functions tailored to the needs of ERs, including the following: (i) integration and easy access to emergency response procedures tailored to the specific EV on-site, along with the vehicle's structural schematics for ERs; (ii) the quick identification of battery pack specifications; and (iii) the calculation of stranded energy in the EV's battery using real-time input and the estimation of discharge time for various power loads to achieve a safer state.

The EV Rescue application [25] organizes and requests manufacturer-developed ERGs for BEVs, similar to the National Fire Protection Association (NFPA) [21] but through a mobile interface. However, users are required to identify the EV and look up the related ERGs in the mobile application. Our work simplifies this process by allowing users to input the VIN or the model, make, and year of the vehicle to automatically retrieve and display the specific ERGs interactively. Furthermore, the EV Rescue app cannot identify battery pack specifications once a vehicle is identified, nor can it estimate stranded energy. These are both crucial and dynamic safety-critical pieces of information that are helpful for first responders.

Our comprehensive approach, integrated into the framework, may provide first responders with valuable resources to handle post-accident BEVs effectively and safely. The current prototype tool can operate as a standalone offline executable package or can be accessed via a local webpage with an interface port. For enhanced convenience and to better serve on-site applications, the tool could also be accessed via a quick response (QR) code if a server is available, or in an app format if preferred.

2. Methodology

2.1. EVIRS Framework

Stranded high-voltage batteries present a potential shock hazard for first responders. In worst-case scenarios, a damaged battery may enter thermal runaway, either immediately or later, leading to property damage, serious injury, or death. Therefore, the rapid retrieval of safety-critical information regarding a potentially compromised EV battery pack is essential, highlighting a crucial gap in current emergency response practices.

To effectively capture safety-critical information from a compromised EV, we have conceived, implemented, and presented a software and hardware framework to assist ERs. This framework, named EVIRS, is designed to facilitate the swift retrieval of EV-specific information and contents, enabling rapid decision-making when on-site resources are limited after accidents. EVIRS can be accessed through multiple avenues, including a dedicated website, a mobile application, or standalone software via a QR code mechanism. This accessibility ensures that ERs can quickly access the system at the accident scene, providing them with the necessary guidelines and tools to assess safety and handle stranded EVs and mitigate potential safety risks following an accident or natural disaster. For a visual representation of the proposed EVIRS workflow framework, please refer to Figure 1.

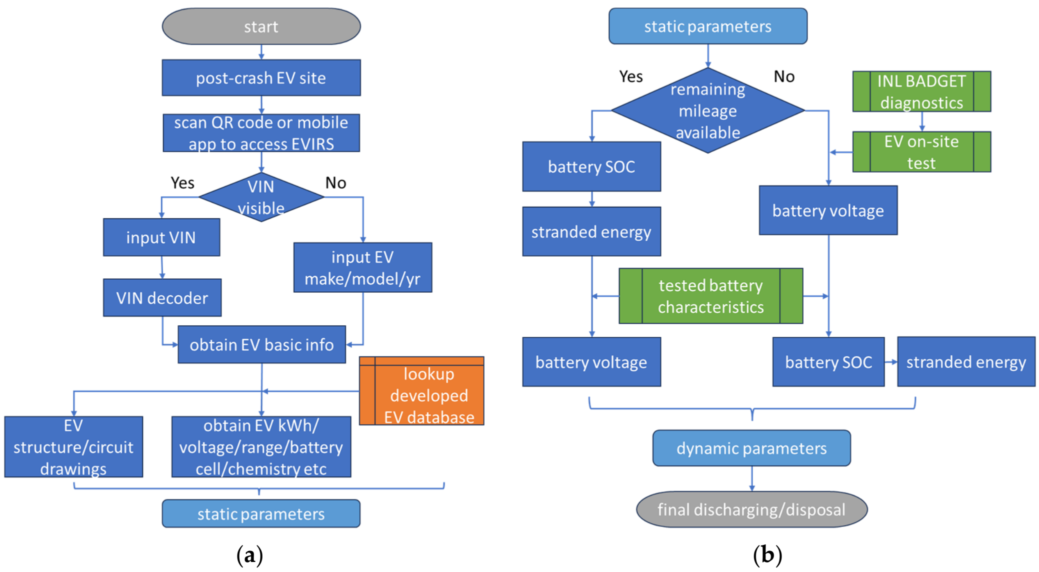


Figure 1. (**a**) EVIRS workflow with different inputs and (**b**) EVIRS calculation flow chart.

As shown in Figure 1a, the initiation of the EVIRS workflow occurs at the post-crash site or any other off-normal situations, where a QR code is scanned, or standalone software is launched to access the EVIRS webpage; access through a mobile app could also be feasible in the future. Subsequently, contingent upon the visibility of the vehicle identification number (VIN), ERs have the option to input the VIN into EVIRS to retrieve basic information about the EV and battery pack. Alternatively, they can manually input details such as the EV's make, model, and year to achieve the same outcome.

The expedient and precise retrieval of EV specific information proves invaluable, given the extensive variety of EV models, diverse designs, and variations in energy content at varying voltages (e.g., 400 V Tesla vs. 800 V Porsche Taycan [27]). To present accurate details pertaining to the EV's range, battery energy, rated voltage (or system architecture voltage), and battery configuration specific to the crashed EV following VIN input, an EV information database was established, as marked in orange in Figure 1a. This database draws its data from a Department of Energy (DOE) data center [27], ensuring the precise search of parameters unique to the crashed EV. These data can be readily obtained from the database, and the platform applies the calculation process once the specific EV model is determined. Importantly, these parameters remain constant and are not indicative of the EV's real-time status; hence, in this paper, they are referred to as static parameters, as indicated in Figure 1a.

In addition to static parameters, numerous essential dynamic parameters are needed to estimate the real-time states, e.g., SOC, pack voltage, the amount of energy stranded, etc., of a battery pack for a particular EV. State estimation may depend on lithium-ion battery chemistry, which can vary with original equipment manufacturers (OEMs), as well as the make, model, and year of the EV. In the context of this paper, we term these measured and/or estimated variables as dynamic parameters, shown in the right flow diagram as Figure 1b, as they exhibit variations contingent upon the specific vehicle's make, model, year, and the battery's state during an off-normal event. The three green boxes in Figure 1b indicate steps involving laboratory or on-site tests to obtain dynamic parameters.

The rapid acquisition of dynamic parameters at the accident site holds paramount significance for ERs to effectively manage the EV following a collision. These variations may result in diverse responses. Figure 1b presents how dynamic parameters could be obtained by using EVIRS. For some minor crashes, often when the airbag is not deployed, the vehicle's remaining mileage or battery SOC are still accessible via the infotainment system. Thus, in this case, it would be easy to calculate the stranded energy based on the static parameters and the battery's remaining mileage or SOC. However, for some accident cases, the EV data may no longer be accessible; thus, tests are needed to obtain live battery voltage data, e.g., by tapping into the CANbus interface (an example case is included in Section 3) on-site or off-site. EVRIS has a compatible diagnostic interface to input the battery's remaining miles, SOC, or voltage data for estimating stranded energy. The built-in database also stores voltage–SOC information for different LiB chemistry compositions, encompassing major EV brands so an accurate estimate of SOC and stranded energy can be obtained. We presented two case studies with a Ford Mach-E EV [28] in Section 3 using characteristic data embedded and preprogramed in EVIRS. Once the specific EV static parameters are obtained, the battery stranded energy and SOC could be obtained with the voltage data input based on the preprogramed EV characteristic datasets, or vice versa. In this way, the dynamic parameters could also be obtained.

2.2. Retrieving Information and Database Development

2.2.1. Retrieving EV VIN and Battery Information

Accessing VIN information represents the most-efficient approach for acquiring precise EV details related to the vehicle involved in the collision. The NHTSA has furnished a vehicle VIN database resource application programming interface (API) [29] and a VIN decoder [30]. The prototype EVIRS software developed in this study seamlessly integrates NHTSA's data resource with the established VIN coding rules of prominent OEMs, facilitating VIN decoding. This process enables the retrieval of fundamental EV information directly from the VIN, encompassing details such as the model, make, and year of the vehicle. Taking the INL-owned EV as an example with its VIN of 3FMTK1SS4MMA19662, inputting the VIN into EVIRS returns the EV year as 2021, the make Ford, and the model Mustang Mach-E, which will be used in the later calculation steps to demonstrate EVIRS's functionality.

In cases where the VIN of the crashed EV is not visible or safely accessible, EVIRS offers an alternative solution. Users can manually input information about the vehicle manufacturer, model, sub-model, and year. This input aids in the retrieval of basic EV information, ensuring the accurate calculation of different battery specific parameters. In the case that ERs do not know the specific sub-model of the post-crash EV, EVIRs can still proceed and use EV information corresponding to popular sub-models; for example, EVRS will list "standard", "long-range", and "performance", and will provide all 3 sub-models' information for Tesla Model 3 if the sub-model is not manually input.

With the specific EV VIN or information obtained, e.g., the accurate EV brand, model, and information regarding the crashed EV specific to the year of manufacture, the EV range and battery energy can be retrieved, referring to the U.S. Department of Energy (DOE) alternative-fuels data center [27], and the EV battery's rated voltage, motor, power, and other information can also be retrieved in the individual EV OEM's website. In order to conveniently retrieve data and properly index, a Structured Query Language (SQL) database is developed to integrate the EV model, year, battery energy, rated range, etc.—including up to five popular EV brands for demonstration purposes and hundreds of tuples/records. For convenient data retrieval, the developed database has been integrated in EVIRS and properly indexed. A more detailed database will be discussed in Section 2.2.3.

2.2.2. EV-Specific Guideline and Retrieval of Structure Information

In addition to fundamental EV information, ERs require access to structural drawings of the EV to comprehend the battery's location, the configuration of battery circuits with color codes (both high and low voltage), the location of disconnection points, and any associated emergency response guidelines pertinent to the specific crashed EV. The NPFA website hosts most of the popular EV models' emergency response guidelines, including up to 70 EV maker brands [21]. For instance, taking the INL-owned 2021 Ford Mustang Mach-E EV as an example, the Ford Mustang Mach-E emergency response guidelines are helpful for ERs and include structural drawings, the battery and disconnection location, instructions on towing the Ford EV, as well as special response solutions in case an EV is on fire or is submersed. However, when ERs are handling the EV post-crash on-site, searching the specific EV's information among various EV makers, models, years, and locating the right information in a relatively short amount of time could be time consuming and less user friendly.

To overcome the above barrier and better support ERs, EVIRS encompasses a comprehensive repository of vehicle structure details, disconnection point locations, concise emergency guidelines, and related documents, referring to NHTSA, NPFA's data information [20], and individual OEM's website. These resources, including EV structure/circuit image portfolios and emergency guideline PDF files, have been harmonized, resized, and systematically cataloged within a database, and cross-referenced with each specific EV sub-model and year dataset for efficient retrieval, locating, and reference. The resource repository can be expanded to include additional 2D/3D graphics, targeted video content, "dos and don'ts" guidance, etc., for on-site safe handling and off-site education and training purposes for ERs.

2.2.3. Database Development

Based on the information-retrieving, calculation, and dataset-organizing methods described in the previous subsections (Sections 2.2.1 and 2.2.2) and Figure 1, the database for the EVIRS tool has been developed with primary/foreign keys, tuples, attributes, and associated database entity relationship diagrams, as shown below in Figure 2.

Figure 2 shows that the proposed database mainly includes an EV_data table, EV_model table, EV_image_portfolio, and EV_guideline_portfolio, in addition to a VIN-decoding supportive API, plus a sub-module with tested characteristics and an associated calculation function.

(a) First, the EV_model table interacts with the VIN-decoding API to implement the VIN input and basic EV information retrieval, including EV make, model, and year data. A unique EV_model_ID is set as the primary key of this database table for indexing purposes while it is also the foreign key for the EV_data table to link data between EV_model table and EV_data table.

(b) Second, the EV_model table stores the main EV data, including the sub-model, motor information, EV mileage range, rated battery energy in kWh, rated battery pack ampere capacity in Ah, rated battery pack voltage, battery chemistry type, and basic EV make, model, and year data obtained from the EV_model table. A unique EV_data_ID primary key ensures that the data information stored in the database is specific to each EV sub-module, referring to the right vehicle the ER is handling after a crash. Because additional image files showing a vehicle's circuit structures and document files containing responder guidelines specific to a vehicle are also needed, as discussed in Section 2.2.2, two foreign keys of EV_image_ID and EV_guideline_ID are also used to refer to two other tables that store images and document files as separate portfolios.

(c) Third, the EV_image_portfolio database stores EV photos, structures and circuit figures, and transportation instructions. These image files are indexed by EV_image_ID as the primary/foreign keys, referring to the EV_data table, and implemented in SQL.

(d) Similarly, the EV_guideline_portfolio database stores the EV emergency response and QR guide documents. These PDF files are indexed by the EV_ guideline _ID linking to the EV_data table as well.

(e) Lastly, battery chemistry, voltage, and capacity data in EV_data table act as the further inputs and are combined with the cell voltage–SOC test characteristics to further compute the battery pack voltage details based on the battery cell voltage and capacity data of different battery chemistry types. More details will be present in Section 2.3.

In the proposed database, most of the static information—including the EV make, model, year, battery energy, chemistry, circuit, and associated emergency guideline—are retrieved, calculated, properly indexed, and become conveniently accessible.

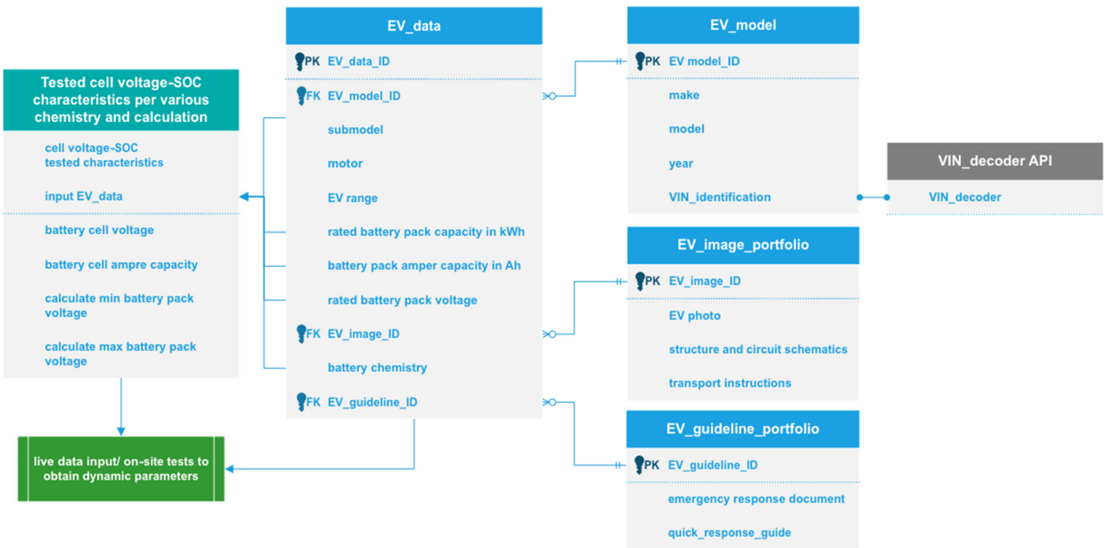


Figure 2. The EVIRS database diagram.

2.3. Battery Characteristics Tests and EVIRS Calculations

After obtaining all EV static-parameter information, as discussed above, for ERs, it is also vital to obtain live data demonstrating the dynamic status of the EV after a crash—e.g., battery SOC, real-time pack voltage, and battery stranded energy—in order to enable the determination of how to perform post-crash handling, to provide appropriate diagnostic tools to evaluate the EV battery status, and to find guidance on discharging, towing or final disposal.

2.3.1. Tests of Battery Characteristics in Different Chemistry Types

To acquire real-time SOC, stranded energy, and battery voltage data from a crashed vehicle, it is imperative to establish battery voltage–SOC characteristics. The characteristics also vary significantly across different battery chemistries, necessitating the creation of characteristic curves for each chemistry type.

Experimental tests were conducted at the INL battery test center [31] to obtain the cell battery voltage–SOC characteristic curves using a Maccor 4000 series tester (Maccor, Tulsa, OK, USA). Modern EVs use varying cathode chemistry compositions in LiBs, including nickel cobalt aluminum (NCA), nickel manganese cobalt (NMC), and lithium ferro-phosphate (LFP), and the tests focus on gr/NCA, gr/NMC, and gr/LFP chemistries in full cell settings. The voltage–SOC relationship was established by testing batteries with different chemistries at low charge and discharge rates at 30 °C. To ensure the accuracy and repeatability of test data, each battery undergoes a gradual discharge at a "C/20" rate, with voltage continuously monitored as the depth of discharge decreases from 100 to 0%. This process results in over 7000 measured voltage data points per battery, spanning a 20 h discharge period at the rate of C/20. The low current rate minimizes polarization and provides a quasi-equilibrium voltage that closely approximates the open circuit voltage (OCV) of a battery. For method demonstration purposes, we used this method to establish the voltage–SOC relationship. This serves as a reasonable approximation of the OCV-SOC relationship, which is typically generated by allowing relaxation time at different SOC setpoints. However, classical OCV-SOC plots can be utilized to improve the accuracy of estimation during the implementation stage.

Figure 3 displays the battery voltage test curves in relation to SOC for the gr/NCA, gr/NMC, and gr/LFP battery chemistries within their operational voltage windows. The SOC was established by scaling the cumulative capacity with the nominal cell capacity in Ah. Employing these test data, we can determine the minimum and maximum voltages for the entire battery package, which will be used for calculation later in Section 2.3.2.

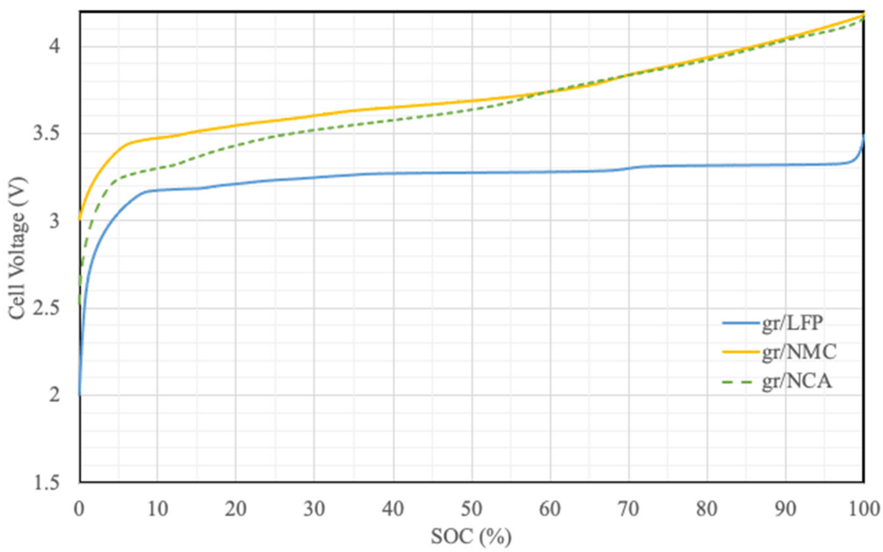


Figure 3. Battery voltage–SOC characteristics with different chemistry types.

Also, Figure 3 indicates that different chemistries lead to distinctively different voltage–SOC characteristics. For example, in comparing the NMC and LFP curves, the NMC cell voltage increases from 3.5 to 4.2 V, with SOC in the range of 10–100%, while the

LFP cell voltage increases only slightly, from 3.2 to 3.5 V, with SOC from 10 to 100%. With these voltage characteristics, the LFP battery pack normally would have much less voltage variation than an NMC pack for SOC normally operating between 10 and 100%; on the other hand, the LFP battery pack would need more battery sub-modules in series to achieve the same pack voltages as an NMC or NCA. Thus, to ensure that the ER obtains accurate live status-related dynamic information for the post-crash EV, identifying the correct battery chemistry type and characteristics, as well as static parameters, is crucial to maintain the accuracy of the output information for the ERs. Note that there are different variants of NMC battery chemistries, e.g., NMC111, NMC622, and NMC811. For demonstration purposes, Figure 3 presents NMC811 characteristics, but EVIRS can also host other NMC battery types or other relevant future battery chemistry properties. For convenient computing, NCA, NMC, and LFP battery voltage-versus-SOC curves are integrated into the proposed EVIRS to support easy ER access on-site.

2.3.2. Calculation of Battery Pack Parameters

Static information concerning the EV model, make, year, rated battery energy information, etc., which is derived from the database as discussed in Section 2.2, plays a crucial role in the subsequent computation of battery pack and cell specifications. These data serve as a fundamental prerequisite for facilitating the next step in the process: the on-site measurement and assessment of stranded energy. Assuming that the EV's model, year, manufacturer, sub-model, range, battery energy, and voltage information has been successfully obtained via the database, the following steps are implemented:

Step (a): Calculate battery pack ampere-hour capacity.

With the rated battery-energy and voltage data, the battery pack ampere-hour capacity could be calculated as below:

$$Q_{\text{rated}}(\text{Ah}) = \frac{1000 \times E_{rated}(\text{kWh})}{V_{rated}(\text{V})} \tag{1}$$

where Q_{rated} is the rated battery pack ampere-hour capacity in Ah; E_{rated} is the rated battery pack energy in kWh; and V_{rated} is the rated battery pack voltage or system architecture voltage in V. Still taking the 2021 Ford Mustang Mach-E EV as an example, with its VIN of 3FMTK1SS4MMA19662, EV range of 230 miles, battery rated energy of 75.7 kWh, rated voltage of 400 V, and following the Step (a) and Equation (1), this EV has the calculated battery pack ampere-hour capacity of around 190 Ah.

Step (b): Obtaining battery chemistry and battery pack voltage range.

By using decoded VIN data that specify the year, make, model, and sub-model information and relying on DOE [27] or publicly available information, it becomes feasible to discern the prevalent battery chemistry, namely gr/NCA, gr/NMC, or gr/LFP. These matured chemistries are well-studied and the lab test data are available through INL or other reliable sources [31]. This chemistry information is stored within the EVIRS database for major OEM EVs for demonstration purposes.

The battery pack's minimum and maximum voltage (voltage range) are essential parameters to obtain battery pack actual post-crash voltage based on SOC. Normally, the maximum battery pack voltage is the rated battery pack voltage while the minimum battery voltage still needs to be determined. For a specific battery chemistry type, knowing the battery cell voltage characteristic curve by test, the battery pack minimum and maximum voltage can be calculated as:

$$V_{(\text{min,max})} = V_{\text{cell}(\text{min,max})} \cdot N_{series} = V_{\text{cell}(\text{min,max})} \cdot \frac{V_{rated}}{V_{\text{cell}(\text{max})}} \tag{2}$$

where $V_{(\min,\max)}$ is the minimum or maximum total battery pack voltage in V; $V_{\mathrm{cell}(\min,\max)}$ is the minimum or maximum battery cell voltage in V which can be obtained by test based on the battery chemistry type as shown in Figure 3 and Section 2.3.1; N_{series} is the number of cells in series to form a battery pack and approximated using $\frac{V_{rated}}{V_{\mathrm{cell}(\max)}}$ as this information is not readily available; and V_{rated} is the rated battery pack voltage in V, which could be obtained as discussed in Section 2.2.1. For instance, still referencing the Ford Mustang Mach-E with VIN 3FMTK1SS4MMA19662, this VIN input in the database will return the rated voltage of 400 V, battery chemistry type of gr/NMC [32], and other information specifically to the 2021 Ford Mustang Mach-E. Based on Figure 3 and Equation (2), it is feasible to further calculate and obtain the minimum and maximum battery pack voltages of 288 and 400 V for this ford EV, respectively. Note that the 288 V minimum battery pack voltage corresponds to 0% SOC, which is not recommended to be in real-world EV battery charging/discharging operation.

2.3.3. Estimating Battery Stranded Energy and Voltage

Stranded energy and battery voltage represent critical dynamic parameters crucial for ERs to determine the remaining energy stored in a vehicle after a crash. There are two approaches for estimating stranded energy and voltage data following an accident:

(a) In the event of an EV accident where the infotainment system remains relatively intact, a convenient method for computing stranded energy involves obtaining the live SOC displayed on the infotainment system, retrieving the battery specifications for the identified EV through EVIRS, and multiplying the SOC by the identified nominal battery energy. For some EV models where SOC is not available but the remaining mileage is displayed, it is also feasible to obtain the real-time battery SOC with the remaining mileage displayed on the infotainment system divided by the original EV range, a static parameter obtained from EVIRS database which was discussed in Section 2.2. This estimated SOC can then be employed to calculate the stranded energy based on the rated battery energy, with the calculation equation as below:

$$E_{\mathrm{SE}} = \mathrm{SOC} \times E_{rated} = \frac{M_{remain}}{M_{rated}} \times E_{rated} \tag{3}$$

where E_{SE} is the actual stranded energy stored in the crashed vehicle; M_{remain} and M_{rated} are the real-time remaining mileage and rated full EV range, respectively; and E_{rated} is the rated EV battery energy in kWh. The rated full EV-range parameter M_{rated} and the rated EV battery capacity E_{rated} are static parameters that would be obtained as discussed in Section 2.2 and retrieved from the database.

For live battery pack voltage estimation, it would be feasible to calculate the live battery pack voltage data with the known real-time SOC as the input, in addition to looking up the test curves of Figure 3, as discussed in Section 2.3.1. The live battery pack voltage can be calculated as below:

$$V_{live} = V_{\min} + \frac{\left[f_{(\mathrm{V}_{cell\_live},\mathrm{SOC})} - V_{\mathrm{cell}(\min)}\right]}{\left[V_{\mathrm{cell}(\max)} - V_{\mathrm{cell}(\min)}\right]} \times (V_{max} - V_{min}) \tag{4}$$

where V_{max}, V_{min}, $V_{cell(max)}$, and $V_{cell(min)}$ are the maximum and minimum total battery pack or battery cell voltages in V, respectively, which can be obtained referring to Equation (2). The function $f_{(\mathrm{V}_{\mathrm{cell\_live}},\mathrm{SOC})}$ is the live value return by looking up the voltage–SOC test curves of Figure 3 based on the known real-time SOC as the input and the confirmed battery chemistry type, as discussion in Section 2.3.1. For the Ford Mustang Mach-E with VIN 3FMTK1SS4MMA19662 as an example with a rated mileage of 230 miles and battery chemistry of gr/NMC, based on Equation (2), the minimum and maximum battery pack voltages and battery cell voltages are 288 V, 400 V, 3 V, and 4.2 V, respectively. When the live remaining mileage is 140 miles, equating to an SOC of 60.8%, the calculated live battery pack voltage referring to Equation (4) will be 367.5 V. We acknowledge that the calculation accuracy of Equations (3) and (4) depends significantly on the accuracy of the BMS in estimating remaining miles and/or SOC. Given that the intended purpose is to obtain a coarse estimate of stranded energy, we anticipate that some degree of inherent error in the BMS estimation will be acceptable.

(b) Conversely, there are instances where the EV infotainment system fails to provide information regarding the remaining range. In such scenarios, it becomes imperative to conduct on-site battery diagnostic measurements to acquire live battery voltage data. Referring to Figure 3 and Equation (3), with a known battery chemistry, the amount of energy stranded can also be determined based on the measured voltage, which can be directly obtained through the EV Controller Area Network (CAN) or similar interface if those interfaces are undamaged. In Section 3 below, an illustrative example of an experimental test will be presented to validate the proposed EVRIS workflow, featuring the Ford Mach-E as a case study.

3. Results and Discussion

3.1. Validation with Ford Mach- E

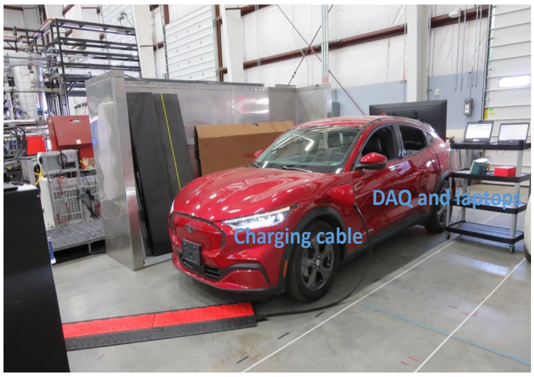
This section will present a use case of a Ford Mach-E to demonstrate the EVIRS workflow and some of its capabilities. It will also verify the framework and calculation accuracy of EVIRS by comparing the computing output from EVIRS versus the laboratory measurements of the battery pack voltage. The 2021 Ford Mach-E EV parameters are listed below, in Table 1, where the EV year, maker, model, body type (SUV), and fuel type (electric) information can be retrieved from VIN, while the EV range, battery energy, voltage, and chemistry type are based on EVIRS database retrieval or calculation.

Table 1. 2021 Ford Mach-E parameters.

Year	Maker	Model	Body Type	Fuel Type	EV Range (miles)	Rated Energy (kWh)	Module/Pack Capacity, Ah	Rated Pack Voltage (V)	Chemistry
2021	Ford	Mach-E	SUV	Electric	230	75.7	189	400	Gr/NMC

Figure 4 presents the laboratory setup, including a Level 2 charging system with charging control and a Hikoi power analyzer, as shown in Figure 4a, and the Ford Mach-E, scope, and data acquisition (DAQ) system as shown in Figure 4b. For the test, a Level 2 charger, up to 11 kW, is used to charge the Ford Mach-E battery from less than 10% SOC to 100% SOC. The battery voltage DAQ system is set up in the rear seat inside the Ford Mach-E (hidden in Figure 4b), with one end connected to the Ford Mach-E CAN interface port, and the other end using laptops to record the real-time battery voltage measurement data that will be compared to the calculated battery voltage from EVIRS software for validation purposes. The Hioki power analyzer was used to measure charging power, charger-side voltage, and current, facilitating the real-time monitoring of the vehicle's charging and discharging status during lab tests.

(**a**)



(**b**)

Figure 4. Lab validation of EVIRS using the Ford Mach-E. (**a**) Level 2 charging system with charging control and a Hikoi power analyzer, and (**b**) Ford Mach-E with DAQ system connected.

A laptop computer running Ford's FDRS diagnostic software (2024 version) was connected to the 2021 Ford Mach-e using Ford's VCM-3 interface connected to the diagnostic connector located in the driver-side foot well. Battery pack voltage and battery pack SOC signals were displayed and recorded once per minute. These diagnostic data are referred to in short in this paper as CAN data, reflecting the fact that the data originate as sensor or calculated values in vehicle controllers, and are communicated over one or more of the vehicle CAN networks.

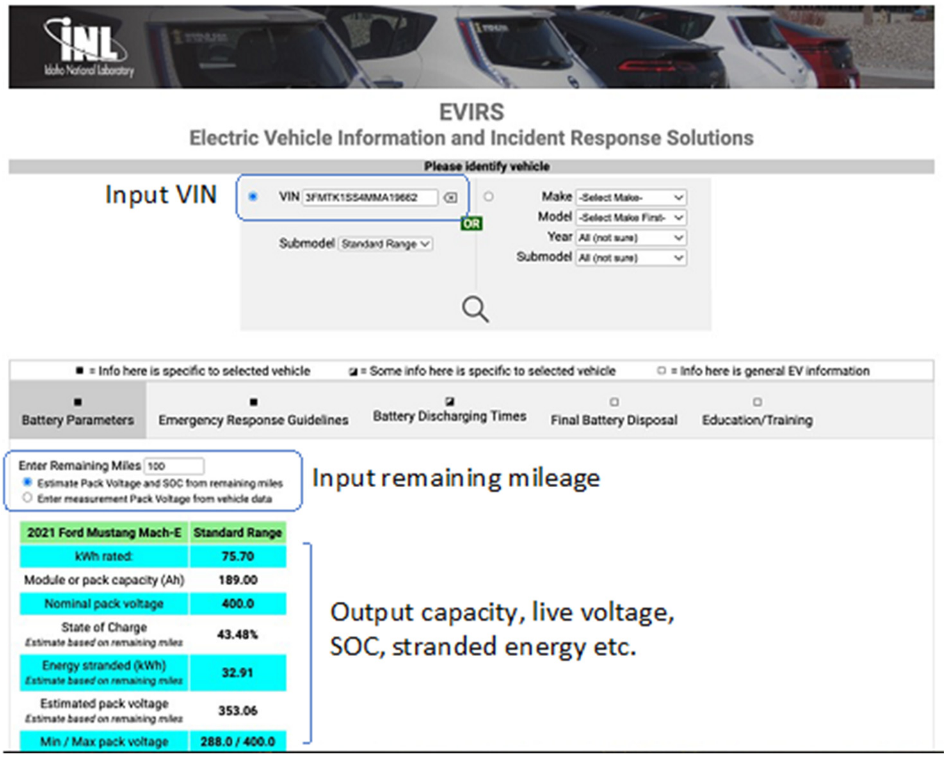
3.2. EVIRS Calculation Result and Lab Verification

As discussed in Section 2.3.3, the two options of the live data input in EVIRS depend on the information available at the crash site: (1) if the mileage or SOC data from the EV infotainment system are still accessible, the remaining mileage is input or (2) the voltage data are input using on-site live voltage measurement through a vehicle CAN interface. EVIRS software is configured to incorporate either of these options as an input, and to output such key stranded battery pack energy details as kWh stranded and voltage in V. Figure 5 demonstrates EVIRS input and part of the output details, based on remaining mileages data in Figure 5a or the voltage measurement input in Figure 5b. As discussed in Section 2.2.1, two options, to input either VIN or model, year, etc., are also demonstrated in Figures 5a and 5b, respectively.

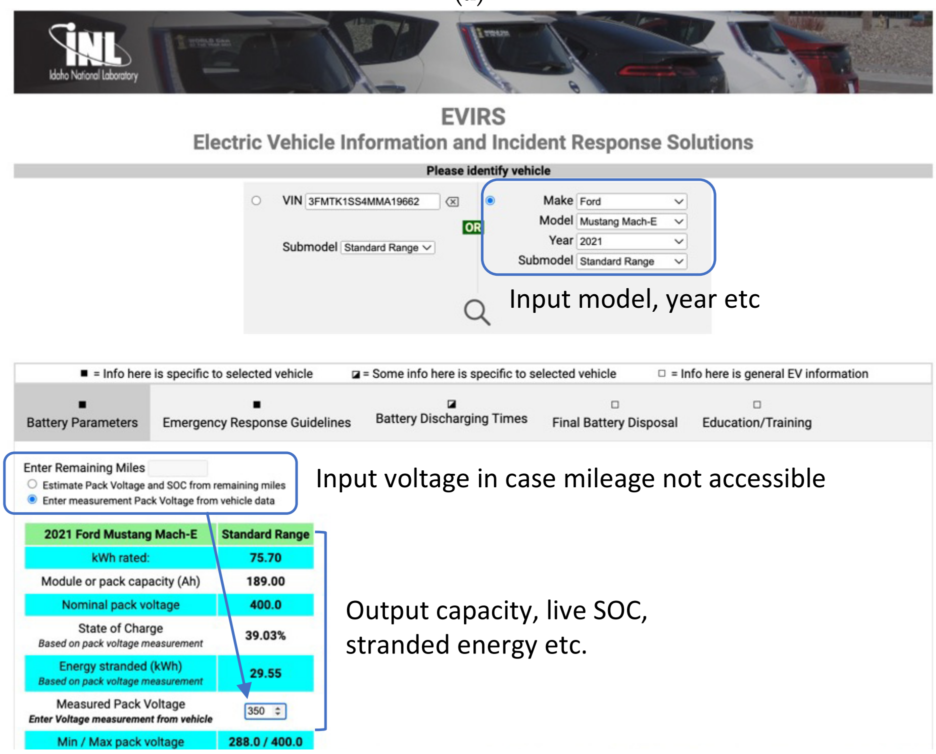
(a) Input mileage (SOC) validation

Lab testing is carried out to verify EVIRS's estimation accuracy. There are two input options of EVIRS; thus, both input–output algorithms must be verified. This subsection validates EVIRS' estimation accuracy based on input mileage (SOC). Table 2 presents the comparison of EVIRS' calculated battery pack voltage versus the lab test results. For a 2021 Ford Mach-E EV in the lab, as shown in Figure 4, with a rated range of 230 miles, the input parameters of the remaining miles are selected as 40, 60, 80, 100, 120, 140, 160, 180, and 200 miles, as shown in Table 2. With the inputs into EVIRS, as shown in Figure 5a for the calculation, EVIRS will return the estimated battery SOCs, as listed in the second row of Table 2, as well as the estimates of stranded energy and battery pack voltage, as shown in the third and fourth rows of Table 2.

In the lab tests, for comparison, the Ford Mach-E battery is charged to SOCs corresponding to the values of those listed in the second row of Table 2; then the battery pack voltages are measured through the CAN interface and recorded in the fifth row of Table 2. The sixth and seventh rows present the absolute and percentage differences between the EVIRS' calculated voltage in the fourth row and the lab voltage-measured values in the fifth row. It is observed that for a range of 40 to 200 input miles, the EVIRS calculation test voltage differences are all below 3V and less than 1%, as shown in the sixth and seventh rows of Table 2, which validates the EVIRS computing accuracy in providing the EV post-crash information to ERs.



(**a**)



(**b**)

Figure 5. EVIRS calculation demonstration with input of (**a**) remaining mileages or (**b**) battery voltage.

Table 2. EVIRS verification of battery voltage with input of remaining miles.

Input Remaining Miles	**40**	**60**	**80**	**100**	**120**	**140**	**160**	**180**	**200**
Calculated SOC by EVIRS (%)	17.4	26.1	34.78	43.5	52.2	60.9	69.6	78.3	86.9
Calculated remaining stranded energy (kWh)	13.2	19.7	26.3	32.9	39.5	46.0	52.7	59.2	65.8
Calculated voltage by EVIRS (V)	340.4	344.6	348.8	353.0	359.9	367.5	375.1	382.7	390.3
Lab-tested battery pack voltage (V)	343.5	347.5	350	353.5	358	366	373.5	381.5	389.5
Calculation test voltage differences (error in V)	3.08	2.86	1.15	0.44	1.9	1.5	1.6	1.2	0.8
Calculation test voltage differences (error in %)	0.9%	0.8%	0.3%	0.1%	0.5%	0.4%	0.4%	0.3%	0.2%

(b) Input voltage validation

This subsection verifies EVIRS for cases in which the input of battery voltage is needed. This could also be a practical necessity in cases where EV mileage or SOC data are not accessible. In this scenario, battery voltage may be measured at the EV crash site or a secondary staging area and input to EVIRS, as shown in Figure 5b. EVIRS will calculate battery SOC, stranded energy, etc., for ERs to reference. For verification purposes, in the lab tests, the EVIRS-calculated battery pack SOC is compared to the measured SOC test data of the input of battery voltage. Table 3 presents the verification test data. For the 2021 Ford Mach-E, the normal battery voltage operation range is from 330 to 400 V, based on our vehicle tests, although the theoretical minimum voltage estimates 288 V according to the battery cell characterization curve in Figure 3. This is for the optimum battery life cycle purpose as OEMs initialize the default factory setting, and most of the OEMs also recommend avoiding long-time operation under 10% SOC. In this test, the input voltages to EVIRS are set as 340, 345, 350, 355, 360, 365, 370, 375, 380, 385, and 390 V. With these input into EVIRS, as shown in the screenshot of Figure 5b for calculation, EVIRS will output the calculated battery SOC and stranded energy, as shown in the second and third rows of Table 3.

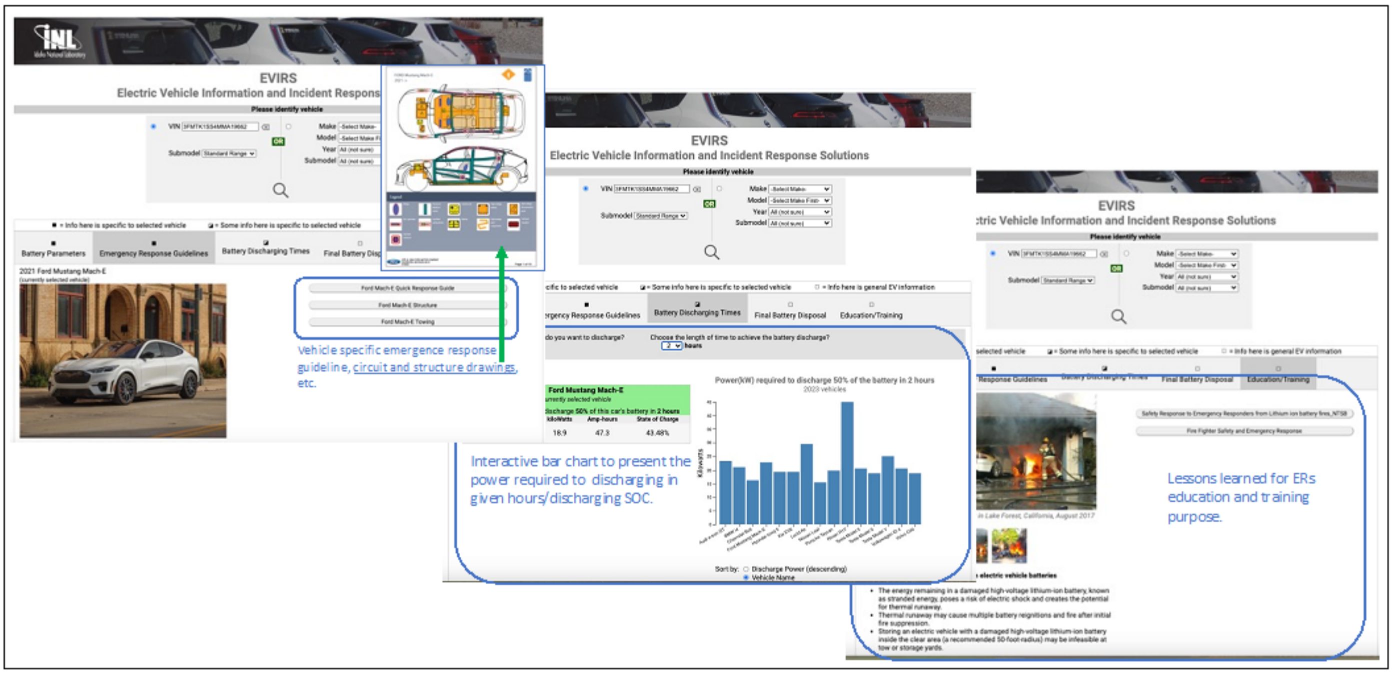
Table 3. EVIRS verification of SOC with input of battery voltage.

Input Voltage from Test (V)	340	345	350	355	360	365	370	375	380	385	390
Calculated SOC by EVIRS (%)	23.0	31.0	39.0	46.5	52.3	58.0	63.7	69.4	75.2	80.9	86.6
Calculated remaining stranded energy (kWh)	17.4	23.5	29.5	35.2	39.6	43.9	48.2	52.6	56.9	61.2	65.6
Lab-tested battery SOC (%)	13.3	20.1	34.8	47.5	54.5	59.7	66.3	71.5	77.0	82.4	87.5
Calculation test SOC differences (%)	9.8	10.9	4.2	0.9	2.2	1.7	2.5	2.1	1.9	1.5	0.9

In the lab tests, for comparison, the Ford Mach-E battery is charged to voltages equating to the values listed in the first row of Table 3; then, the battery pack SOC data are read through the CAN interface and recorded on the fourth row of Table 3. The fifth row presents the absolute differences between EVIRS' calculated SOC in the second row and the lab-measured voltage values in the fourth row. It is observed that most of the EVIRS calculation test SOC differences are below 5%, except for the first two data points (with SOCs less than 30%), and the maximum EVIRS calculation test SOC difference is 10.92%. The discrepancy between the SOCs calculated by EVIRS and those provided by the CAN interface could be attributed to several factors: (i) inherent estimation inaccuracies in the vehicle's BMS algorithm, which are unknown, and (ii) higher voltage swings in the low SOC range and battery-aging effects contributing to inaccurate software regression, among others. LiBs contain less energy at lower SOCs, and the associated heat release rate is reported to be lower at lower SOC [33]. Therefore, a slightly higher error in estimating SOC and stranded energy below 30% SOC may not be significant from an overall safety standpoint.

3.3. Additional Supplemental Information for Emergency Responders and Recovery Personnel

In addition to the information obtained as shown in Figure 5, Tables 2 and 3, for identified vehicles, EVIRS also integrates emergency response guidelines and structural information, referring to NPFA's data information [21] and individual OEM's website, as discussed in Section 2.2.2 and presented here in Figure 6a. For ERs' convenience, the circuit and structure see-through figures specific to the crashed vehicles could help ERs to efficiently identify the high-voltage battery circuit and avoid shocking or other safety risks during post-crash handling.



(**a**) (**b**) (**c**)

Figure 6. Additional supplement information in EVIRS for ERs: (**a**) EV's emergency response guidelines and structure information; (**b**) estimated discharge power needed for various EVs; (**c**) web tab reserved for education and training purposes. For more details, visit https://github.com/IdahoLabResearch/EVIRS/blob/main/EVIRS%20Demonstration.mp4 (accessed on 10 February 2025).

Upon initial safety assessment, knowing the discharge power load and time requirements to de-energize a battery pack below a certain SOC threshold is crucial for improving battery safety and preventing secondary events during transportation or storage. This information enables ERs and recovery personnel to better coordinate tools, logistics, and facilities for either on-site or off-site discharging. EVIRS seamlessly integrates these power and time calculations as shown in Figure 6b. For the Ford Mustang Mach-E, with a battery energy of 75.7 kWh (as shown in Figure 5), discharging 50% SOC in 2 h would require 18.9 kW of power, as indicated in the left table of Figure 6b. For convenience, the interactive bar chart also displays discharging power requirements for other major EV models, facilitating comparison and reference.

Additionally, EVIRS can incorporate sources and lessons learned for education and training purposes, as shown in Figure 6c [23,34]. The photo in Figure 6c shows a battery EV reignition accident due to the thermal runaway and stranded energy issue in 2016 in the U.S. Some safety instructions and notes are also provided on this EVIRS page and more education and training contents will be added in the future. Additional functionalities and features can be incorporated into EVIRS, such as enhanced 3D see-through images of EV structures, training videos, and step-by-step action guides for various accidents and abnormal scenarios. The software can also identify compliant hardware components needed in emergency situations for specific EVs and their implementation strategies, provide lessons learned, and offer indexing for easier information retrieval through existing and future emergency response guidelines. A more detailed video demonstration could be found at the following link: https://github.com/IdahoLabResearch/EVIRS/blob/main/EVIRS%20Demonstration.mp4 (accessed on 15 November 2024)

4. Conclusions

When confronted with a post-crash situation involving a BEV, emergency responders (ERs) must act swiftly and safely to manage the incident, ensuring the safety of themselves, passengers, and bystanders. Due to limited time and on-site resources, it is essential for responders to quickly identify the EV, retrieve relevant safety critical emergency response guides and action items, estimate stranded energy, and take appropriate measures to handle the damaged EV, thereby preventing potential catastrophic events.

To better assist ERs and recovery personnel, this paper showcases EVIRS, a comprehensive software and hardware framework in prototype form. EVIRS can be accessed via a QR code, website link, and standalone executive software package or deployed through a mobile application. It can swiftly retrieve critical specifications of crashed EVs, including battery energy content and voltage, by reading the EV VIN or the information regarding the EV make, model, and year. Modern EVs are rapidly expanding in models and typically feature battery packs ranging from 50 to 200 kWh, with voltages between 400 and 800 V. The rapid identification of an EV and its battery pack information is crucial for effective and safe incident management. EVIRS present OEMs with developed emergency response guides in a user-friendly and interactive manner, enabling first responders to quickly access the EV's architecture, high and low voltage circuitry, cut loops, and disconnection points. This system eliminates guesswork and reduces the time needed to look up vehicle-specific information in its existing, tedious form, enabling first responders to focus more on addressing the emergency.

Additionally, EVIRS is battery chemistry agnostic and can estimate stranded energy using various methods, such as accessing intact dashboard information or directly interfacing with the vehicle's CAN interface to retrieve voltage measurements. This information is vital for assessing the safety level of an EV. For example, safety precautions, handling, and storage protocols may differ significantly depending on whether the vehicle's battery is fully charged and retains substantial stranded energy or is nearly depleted with minimal stranded energy. For an identified EV, after determining the SOC and stranded energy, EVIRS can quickly estimate the discharge power required to reach a specified SOC set point within a given timeframe to aid in the on-site or off-site discharging decision.

The primary function of EVIRS is to provide quick and user-friendly access to validated methods and techniques related to potentially compromised EVs, which have been developed, tested, and approved by OEMs and researchers. Some of the functionalities of EVIRS, such as estimating stranded energy, are particularly useful in scenarios where an EV is not on the verge of or engulfed in fire. However, proven methods for handling such critical situations can be integrated into EVIRS, enabling responders to access this information promptly. While the primary focus of this effort has been on EVs, HEVs and PHEVs can also be incorporated into the EVIRS framework. This working prototype software, EVIRS, has so far incorporated five popular EV brands/models including Tesla, Hyundai, Nissan, Ford, and Chevrolet into its relevant database. This process can be repeated to include other current and future EV brands or models, enhancing its comprehensiveness and utility. The existing features of EVIRS have been demonstrated using a 2021 Ford Mach-E EV, as outlined in this report, which verifies its capabilities; however, additional field validation in dynamic driving conditions is necessary to fully validate its functionality.

Enhancements to EVIRS encompass robust hardware–software integration for real-time battery data acquisition, leveraging these data in cloud-based fault detection models and algorithms, and delivering actionable insights to emergency responders. Additionally, the system can be expanded to maintain an accident data repository and utilize artificial intelligence and machine learning technologies to automate the identification and diagnosis of EV and battery issues, thereby improving operational safety and efficiency.

5. Patents

An open source software disclosure is filed for this work. Data and codes are stored at the following link: https://github.com/IdahoLabResearch/EVIRS (accessed on 15 November 2024).

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

API	Application programming interface;
BADGE	Battery diagnostic evaluation;
BEV	Battery electric vehicle;
CAN	Controller Area Network;
DAQ	Data acquisition;
DOE	U.S. Department of Energy;
DOT	U.S. Department of Transportation;
EVIRS	Electric Vehicle Information for Incident Response Solution;
ER	Emergency responder;
EV	Electric vehicle;
ICE	Internal combustion engine;

INL	Idaho National Laboratory;
LiB	Lithium-ion battery;
LFP	Lithium ferro-phosphate;
NCA	Nickel cobalt aluminum;
NFPA	National Fire Protection Association;
NMC	Nickel manganese cobalt;
NHTSA	U.S. National Highway Traffic Safety Administration;
OEM	Original equipment manufacturer;
QR	Quick response;
SOC	State of charge;
SOH	State of health;
SOS	State of safety;
VIN	Vehicle identification number

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