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Failure Assessment in Lithium-ion Battery Packs in Electric Vehicles using the Failure Modes and Effects Analysis (FMEA) Approach

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Abstract

The use of batteries in electric cars comes with inherent risks. As the crucial component of these vehicles, batteries must possess a highly dependable safety system to ensure the safety of users. To establish such a reliable safety system, a comprehensive analysis of potential battery failures is carried out. This research examines various failure modes and their effects, investigates the causes behind them, and quantifies the associated risks. The failure modes and effect analysis (FMEA) method is employed to classify these failures based on priority numbers. By studying 28 accident reports involving electric vehicles, data is collected to identify potential failure modes and evaluate their risks. The results obtained from the FMEA assessment are used to propose safety measures, considering the importance of the potential failure modes as indicated by their risk priority number (RPN). The design incorporates safeguards against mechanical stress, external short circuits, and thermal runaway incidents. The findings of this study enhance our understanding of electric vehicle (EV) battery safety and offer valuable insights to EV manufacturers, regulators, and policymakers, aiding them in the development of safer and more reliable electric vehicles.

I. Introduction

In recent years, there has been a growing focus on environmental awareness and the decline of fossil fuels. To tackle this problem, one solution that has gained significant attention is the adoption of electric vehicles, which utilize an eco-friendly energy storage system. Batteries have emerged as a promising energy source for electric vehicles, with lithium-ion batteries being the preferred option. This choice is attributed to their advantageous features, including lightweight design, compact size, ability to function across a wide range of temperatures, rapid charging capability, long lifespan, minimal self-discharge, and absence of hydrogen gas emissions [1].

Moreover, the foremost priority in electric vehicles lies in their safety systems. The use of batteries in such vehicles inherently carries certain risks. Given that batteries are a crucial element in electric vehicles, it is imperative for them to possess a safety system of utmost dependability to safeguard the users. It is worth noting that while lithium-ion batteries have a slower ignition time compared to

fossil fuels, a failure within a battery cell can still generate internal heat, potentially leading to the combustion of the entire battery pack.

Over the last few years, multiple accidents have resulted from battery malfunctions. A prominent example took place in 2013, involving a Tesla Model S vehicle in Washington DC, USA, which ignited following a collision with metal debris [2]. Furthermore, in August 2016, there was another occurrence where a Tesla Model S vehicle experienced an unexpected fire while undergoing a road test in Biarritz, France. This incident unfolded after the car exhibited signs of problems during the charging procedure [3]. Given these accidents, there is an urgent need for a thorough examination of potential battery failures in electric vehicles to improve their safety measures.

The referenced study [4] provides a comprehensive overview of different types of electric vehicle (EV) drivetrains, discussing their architecture and examining the pros and cons of each variant. However, it does not delve into the safety system of EV batteries. The main objective is to present the latest advancements in EV technology, which are continually evolving. Furthermore, the study conducts a comparison of batteries as the primary energy storage solution, considering factors such as energy density, efficiency, specific energy and power, cost, and applicability. The focus of this discussion specifically revolves around the current state of battery technology used in electric vehicles. Additionally, it evaluates the efficiency, power density, fault tolerance, dependability, and cost of electric motors, aiming to identify the most suitable motor type for EVs. The research also thoroughly examines the future challenges and opportunities associated with the widespread adoption of EVs. While government regulations pertaining to EVs remain a significant non-technical obstacle, technical challenges include charging time and battery performance.

A previous study has already conducted an examination of potential failures in electric vehicles. In 2013, Ruddle et al. [5] performed an initial analysis of hazards using fault tree analysis (FTA) and failure modes and effects analysis (FMEA) specifically on the electric powertrain of fully electric vehicles. Their objective was to develop a prognostic health monitoring system. Similarly, in 2014, Schlasza et al. [6] conducted a review of aging mechanisms in lithium-ion batteries for electric vehicles using FMEA methods. In a separate study, Hendricks et al. [7] carried out an FMEA analysis on battery failures, emphasizing how this process facilitates the implementation of enhanced control strategies for mitigating battery failures. Additionally, in 2016, Shoults [8] conducted a comprehensive research study as part of their thesis, focusing on design failure modes and effects analysis in the motor system of electric vehicles. This research resulted in a reduction in risk associated with the motor system by implementing recommended measures to address primary risks in future motor system designs and implementations [8].

Pahuja and Singh [9] utilized FMEA to assess the risk priority number (RPN) of electric vehicle inverters and put forth protective measures. Similarly, Prasad conducted a qualitative risk analysis of failure modes across cell, module, and battery pack levels using FMEA. Within their study, Prasad identified failure modes with high risks, conducted numerical modeling for one of them, and established design guidelines by constructing a failure envelope at the cell and module levels. This envelope aided in determining the level of localized deformation that a given battery can withstand before initiating internal damage, which could potentially result in a short circuit [10].

The main focus of ISO 26262:2018 is to address potential risks associated with the malfunctioning behavior of E/E safety-related systems and their interactions. However, it does not specifically encompass hazards related to electric shock, fire, smoke, heat, radiation, toxicity, flammability, reactivity, corrosion, energy release, and similar hazards, unless these hazards are directly caused by the malfunctioning behavior of E/E safety-related systems [11].

Wang et al. [12] present a comprehensive examination of the thermal runaway phenomenon and the associated fire dynamics in single lithium-ion battery cells and multi-cell battery packs. They discuss relevant aspects of this phenomenon. Similarly, another study [13] focuses on advancements in lithium-ion battery chemistries, different failure modes, methods, and mechanisms, while recommending strategies to mitigate these failures. In 2018, Bubbico et al. [14] conducted an extensive analysis of hazardous scenarios for lithium-ion secondary batteries using FMEA. Additionally, Borujerd et al. performed a Fuzzy-FMEA analysis on an immersion-cooled battery pack (ICBP) in an electric vehicle [15]. The primary contribution of this paper is to highlight the risks associated with electric vehicle battery systems during vehicle operation based on historical data. The research begins by collecting data on electric vehicle accidents and analyzing their causes and effects on the battery. Potential failure modes are identified, and an FMEA analysis is conducted using the accident data. The paper also addresses the risks of fire and smoke in relation to the battery. A comprehensive analysis of potential battery failures is carried out to establish a highly reliable safety system in electric vehicles. The paper explores various potential failure modes and their effects, examines the causes, and calculates the associated risks, prioritizing the failures using the FMEA method. The potential failures are analyzed by considering battery usage, the control system, and the sudden braking of electric vehicles. Moreover, safety action recommendations based on the FMEA analysis are provided. However, it is important to note that this paper's scope is limited to analyzing the operation of the electric vehicle's battery and does not delve into the chemical processes, reactions, or mechanical structure of the battery.

The paper can be summarized in the following manner: In Section 1, an overview of previous research on electric vehicle battery safety analysis is
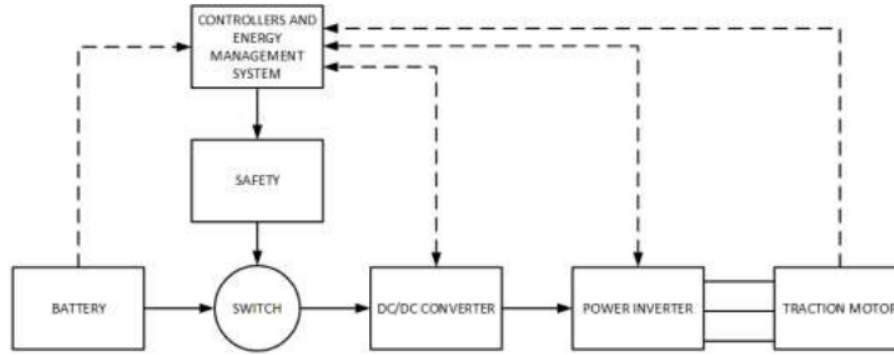
Figure 1. Electric vehicle configuration

provided. Section 2 explains the methodology utilized in this study. The FMEA results and recommendations are presented in Section 3. Lastly, Section 4 provides a summary of the conclusion.

II. Materials and Methods

Batteries undergo redox electrochemical reactions to convert the chemical energy stored within their materials into electricity [16][17][18]. In the case of rechargeable batteries, this chemical reaction allows for the process of transforming electrical energy back into chemical energy. Lithium, being a reactive material, can give rise to a phenomenon called lithium plating, which poses a significant risk in the form of internal short circuits [19][20][21]. If one battery cell sustains damage, it can generate heat and potentially lead to thermal leakage in the surrounding cells, resulting in damage to the entire battery pack [9]. For electric vehicles, lithium-based batteries are widely utilized, including Li-ion, LiTiO, LiCoO, Li-MnO$_2$, LiMn$_2$O$_4$, LiFePO$_4$, LiSO$_2$, Li-SOCl$_2$, and LTO.

The key components of an electric vehicle include the battery pack, controller, inverter, motor, and switch [4][22][23]. This paper focuses on observing the safety system, which is separate from the primary driver and main controller. Figure 1 illustrates the safety system block, which receives inputs from the controllers and the energy management system. The controller and energy management system, in turn, receive inputs from the real-time condition of the battery, converter, inverter, and motor. Within the safety system, situation assessment and decision-making processes are conducted. The decisions made involve determining the necessary actions to be taken if an error occurs, posing a threat to the safety of both the system and the users.

FMEA is a method that serves the following purposes [24]:

- Detect potential failure modes, their underlying causes, and the resulting impacts on a particular product or procedure.
- Evaluate the risk linked to the identified failure modes, impacts, and causes, and prioritize concerns to guide corrective actions.
- Determine and implement corrective measures to address the most critical issues.

RPN is a dimensionless metric of a risk attributed to a process or a component. RPN is calculated using three parameters: 1. The severity of failure (SEV), 2. The frequency of failure occurrence (OCC), and 3. The detection of failure (DET). Each factor is assessed on a scale of 1-10, allowing for quantitative or qualitative descriptions [5]. The RPN calculation is as equation (1),

$$RPN = SEV * OCC * DET \qquad (1)$$

SEV criteria, as defined by SAE J1739 [25], are provided in Table 1. The likelihood of failure occurrence (OCC), according to SAE J1739 [25], is presented in Table 2. The capability of the existing design to identify the cause of failure (DET), sourced from SAE J1739 [25], can be found in Table 3.

Table 1.
Severity of effect criteria [25]

Effect	Criteria	Rank
Dangerous without prior notification	The failure mode compromises safe operation without providing any prior indication.	10
Dangerous with prior notification	The failure mode compromises safe operation with prior indication.	9
Very high	Total loss of the main function.	8
High	Degradation of the main function.	7
Moderate	Loss of secondary function.	6
Low	Loss of secondary function with degradation of comfort.	5
Very low	The disturbance is seen or heard, with more than 75 %of users aware of the flaw.	4
Minor	The disturbance is seen or heard, with 50 %of users aware of the flaw.	3
Very minor	The disturbance is seen or heard, with less than 25 %of users aware of the flaw.	2
None	No effect.	1

Table 2.
Possible failure rates [25]

Effect	Criteria	Rank
Very high: failure is almost unavoidable	≥1 in 2	10
	1 in 3	9
High: repeated failures	1 in 8	8
	1 in 20	7
Moderate: occasional failures	1 in 80	6
	1 in 4×10^2	5
	1 in 2×10^3	4
Low: relatively few failures	1 in $1,5 \times 10^4$	3
	1 in $1,5 \times 10^5$	2
Remote: failure is unlikely	≤1 in $1,5 \times 10^6$	1

The process of conducting the FMEA assessment in this paper is illustrated in Figure 2. One crucial step in this process is the collection and analysis of historical data on electric vehicle accidents. This study gathered 28 accident reports from various news sources, which are summarized in Table 4. The collected data is instrumental in determining the RPN score. Due to limited historical data on electric vehicle accidents, the scoring process will be qualitative, based on the perspective of the experts and referencing SAE J1739 guidelines.

For a failure mode to be included in the shutdown logic, it must have an RPN score equal to or greater than 20 and a severity score equal to or greater than 7. The cutoff value for the RPN score is set at 20 due to the low occurrence score resulting from incomplete historical data. The cutoff value for the severity score is set at 7 based on SAE J1739, which considers a severity score of 7 to indicate high damage and main function degradation in the system.

III. Results and Discussions

The performance of a Li-ion battery can be affected by various factors, with temperature and working voltage being the two primary parameters that exert the most significant influence among these
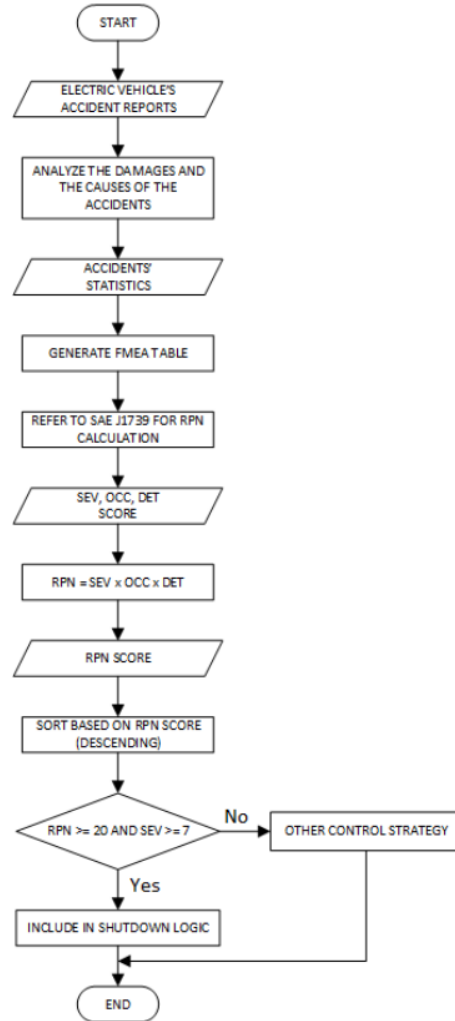

Figure 2. EV assessment using FMEA flow chart

Table 3.
Detection of effect criteria [25]

Effect	Criteria	Rank
Absolute uncertainty	The existing design control lacks the ability to identify a potential cause or mechanism and the resulting failure mode.	10
Very remote	The current design control has an extremely low probability of detecting a potential cause or mechanism and the resulting failure mode.	9
Remote	The likelihood of the current design control detecting a potential cause or mechanism and the resulting failure mode is highly unlikely.	8
Very low	The chances of the current design control detecting a potential cause or mechanism and the resulting failure mode are extremely minimal.	7
Low	The likelihood of the current design control identifying a potential cause or mechanism and the subsequent failure mode is relatively low.	6
Moderate	The current design control has a moderate chance of identifying a potential cause or mechanism and the resulting failure mode.	5
Moderately high	There is a moderately high probability that the current design control will identify a potential cause or mechanism and the resulting failure mode.	4
High	There is a high probability that the current design control will identify a potential cause or mechanism and the resulting failure mode.	3
Very high	There is a highly favorable probability that the current design control will identify a potential cause or mechanism and the resulting failure mode.	2
Almost certain	It is almost certain that the current design control can identify a potential cause or mechanism and the resulting failure mode.	1

Table 4.
Electric vehicle accident case data example

Date	Location	Type	Cause	Damage				Source
				Fire or smoke	Mechanical stress	Short circuit	Over heat	
17/11/10	Oslo-Copenhagen	A Future EV	Operating	1	0	1	0	[29]
01/06/11		Chevrolet Volt	*Crash testing*	1	0	0	0	[30]
01/12/11	US	Fisker Karma	Component defect	1	1	1	0	[31]
01/05/12	Texas	Fisker Karma	-	1	0	0	0	[32]
01/05/12		e6	Collision	1	0	1	0	[33]
01/08/12	California	Fisker Karma	-	1	0	0	1	[34]
01/09/12		Dodge Ram 1500 Plug-in Hybrid	Operating	0	0	0	1	[35]
29/10/12		Toyota Prius PHEV	Flood, submerged in water	1	0	1	0	[36]
01/03/13		Mitsubishi i-MiEV	Charge-discharge test	1	0	0	0	[37]
01/03/13		ander P-HEV	-	0	0	0	1	[38]
01/10/13	Washington	Tesla S	Collision	1	1	0	0	[39]
18/10/13	Mexico	Tesla S	Collision	1	0	0	0	[40]
06/11/13	Tennessee	Tesla S	Collision	1	0	0	0	[41]
15/11/13	California	Tesla S	Charging	1	0	0	0	[42]
01/09/15	Texas	Nissan Leaf	-	1	0	0	0	[43]
01/01/16	Norway	Tesla S	Charging	1	0	1	0	[44]
15/08/16	France	Tesla S 90D	Test-drive	1	1	0	0	[3]
03/11/16	Indianapolis	Tesla Model S	Collision	1	1	0	0	[45]
25/08/17	California	Tesla X	Collision	1	0	0	0	[46]
07/12/17	Germany	VW e-Golf	-	1	0	0	0	[47]
16/03/18	Thailand	Porsche Panamera E-brid	Charging	1	0	0	0	[48]
10/05/18	Florida	Tesla Model S	Collision	1	1	0	0	[49]
16/06/18	Los Angles	Tesla S	Operating	1	0	0	0	[50]
22/08/18	New Jersey	Tesla Model S	Collision	1	1	0	0	[51]
10/09/18	Poland	Tesla Model S	Battery overheat	1	1	0	1	[52]
18/12/18	California	Tesla Model S	Battery overheat	1	0	0	1	[53]
18/02/19	California	Tesla Model X	Collision	1	1	0	0	[54]
24/02/19	Vermont	Tesla Model X	Collision	1	1	0	0	[55]

Figure 3. Electric vehicle damages according to Table 4
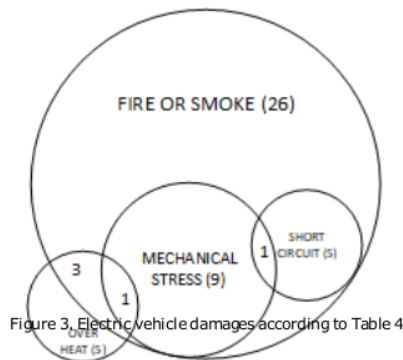
variables. The battery has a specified operating range for temperature and voltage based on its electrochemical materials. Operating the battery outside of this range can lead to reactions such as internal heating (self-heating) and internal short circuits. When a cell experiences internal heating, it can cause a temperature and pressure increase within the battery, which can trigger thermal runaway in other battery cells. This phenomenon has the potential to destroy all cells. The accidents related to battery incidents are summarized in Table 4.

A. Internal short circuit

A battery cell possesses three key characteristics: working voltage, working current, and capacity. The charge and discharge process in Li-ion batteries involves an electrochemical conversion of chemicals to electricity and vice versa. It is important to avoid overcharging a battery cell. When overcharging occurs, lithium ions from the cathode continually migrate to the anode, leading to chemical instability. Additionally, there is an increase in material resistance at the cathode, causing the incoming

energy to be converted into heat, which results in internal heating [26].

During an overcharge of the anode, the copper material undergoes oxidation and dissolves into the electrolyte solution. As the charging process continues, the copper material will deposit onto the anode. Repeated over-discharge can lead to the growth of metal dendrites inside the battery. These dendrites have the ability to penetrate the separator, potentially causing an internal short circuit [20].

Excessive electron flow within the cell can result in internal short circuits. These internal short circuits, in turn, cause the battery to heat up internally, potentially leading to thermal runaway. The presence of metal particles within the cell can cause damage, including the formation of metal dendrites due to excessive chemical reactions [27].

B. Battery storage and operation at high temperature

Damage to the battery can occur in the SEI layer and/or through electrolyte evaporation at high temperatures. When the SEI layer is damaged, typically at temperatures around 120 °C, the anode material can function as an electrolyte, leading to the production of explosive compounds. Additionally, electrolyte evaporation can cause an increase in pressure within the cell, surpassing the limit of the cell envelope [26].

C. External mechanical disturbance

External mechanical interference manifests as external pressure and mechanical stress on the battery cell. Instances such as dropping the battery, colliding with other objects, or creating a hole in the casing can trigger chemical reactions within the cell, leading to internal heating. Moreover, when lithium ions react with ambient air, an exothermic reaction occurs, releasing heat energy [26].

The regular operation of electric vehicles, including driving on uneven road surfaces, subjects the lithium-ion batteries to external mechanical loads. Over time, these loads can lead to mechanical failure in the batteries due to heightened stress and deformation in the electrode materials. As a result, the electrode active materials may lose their ability to store lithium ions, leading to potential short circuits [28].

D. External short circuit

During an external short circuit, the two terminals of the battery are connected to a conductor with a resistance of less than 50 mΩ. In a battery pack consisting of numerous fully charged cells, a short circuit can lead to the flow of high currents. The occurrence of a rapid chemical reaction causes a rise in temperature and pressure within the cell, which can ultimately lead to a cell explosion [26].

Figure 3 explains common damages in electric vehicles based on Table 4. According to the diagram, fire and smoke damage are related to mechanical stress and short circuits. This aligns with the explanation in [26][28], which states that external mechanical stress can cause the battery to experience an internal short circuit, resulting in internal heating of the battery, as explained in [26]. The data also supports the explanation in [26], which describes the mechanism of battery explosions due to external short circuits.

This paper focuses on the effects of electric vehicle operation on the battery, recognizing the importance of batteries during electric vehicle operation. Six potential failure modes are identified in this study: 1) Mechanical stress on the battery; 2) External short circuit; 3) Overcurrent; 4) Fire event; 5) Thermal event; 6) Overdischarge. Mechanical stress on the battery, external short circuit, thermal event, and fire event are identified because these failure modes occur in electric vehicle accidents, as indicated in Table 4. Overcurrent is identified because we are dealing with an electrical system, while overvoltage is not considered since this paper solely focuses on electric vehicle operation and not the charging condition. Overdischarge is considered because the battery state of charge (SOC) decreases during operation, and the risk of overdischarge is likely. The FMEA assessment is provided in Table 5.

According to the explanation in [26][28], mechanical stress can lead to an internal short circuit, which results in excessive electron flow within the cell. This excessive flow generates Joule heating and increases the temperature, potentially leading to thermal runaway [26][27]. Such an event poses a sudden danger to both the vehicle and its occupants. Mechanical stress can occur when the cell is

Table 5.
FMEA assessment

Potential failure mode	Potential failure effects	SEV	Potential causes	OCC	Current process controls	DET	RPN
Mechanical stress	Possibly contributing to thermal runaway	10	Collision, battery is compressed, punctured, or crushed	2	Collison detection, battery pack casing	7	140
Fire event	Fire, toxic gases	10	Battery overheating, overpressure	1	Temperature sensor	3	30
External short circuit	Overtemperature or overpressure, cells ruptured	9	Grounding failure, motor underload	1	Load sensor in motor, underload protection in motor	3	27
Overcurrent	Overtemperature	7	Cell under-voltage, external short circuit	1	Current monitoring, temperature sensor	3	21
Overheat	Battery aging	7	EV operation, environmental exposure	1	Cooling system	2	14
Over-discharge	Cell under-voltage	2	EV operation, poor battery health	1	SOC prediction, regenerative braking	2	4

compressed, punctured, or crushed, which is likely to happen in the event of a vehicle collision.

Based on electric vehicle accident reports published from 2011 to 2019, as described in Table 4, collisions are the most common cause of electric vehicle accidents. A significant number of these accidents were attributed to failures in autonomous systems within the vehicle. The accident records indicate that the causes of these failures are still uncertain, and the current process control measures are flawed.

If a fully charged multi-cell battery experiences an external short circuit, it can lead to the generation of significant peak currents within individual cells. This, in turn, can result in overheating, overpressure, and the potential release of hazardous fumes or cell rupture [26]. While this failure can compromise the safe operation of the battery, passengers may be alerted to the presence of toxic gas due to its distinct odor.

A standard test protocol for simulating an external short circuit involves connecting the terminal of a cell to a conductor with a resistance of less than 50 mΩ. In an electric vehicle context, an external short circuit can occur when the battery pack is connected to the motor underload. To mitigate the risk of such occurrences, it is advisable to incorporate underload protection in the motor and employ a load sensor to monitor the load and ensure safe operation.

As mentioned in [26], an external short circuit can result in overcurrent and overheating in the circuit. However, it is important to note that overcurrent can also be caused by the battery cell being undervolted. When the battery voltage is lower than the normal range, the motor requires a higher current to operate, which can lead to overcurrent. To monitor the vehicle's state and detect such failures, electric vehicles are equipped with current and temperature sensors. These sensors play a crucial role in identifying abnormal conditions.

Based on the electric car accident reports published from 2011 to 2019, as presented in Table 4, fire incidents are the most common type of damage that occurs in electric vehicle accidents. This failure typically arises when the control system fails to prevent it or when the battery cells experience extreme conditions such as over-temperature (above 100 °C) or overpressure. The severity of this failure is heightened by the fact that the passengers are not alerted to the potential danger.

During a fire incident, the battery cells can generate gases as a result of electrochemical processes, leading to the build-up of excessive heat and pressure within the cells. To mitigate this risk, it is crucial for the vehicle to be equipped with sensors capable of detecting and monitoring the accumulation of excess heat and pressure within the battery pack. These sensors play a vital role in ensuring the early detection of potentially hazardous conditions and enabling appropriate preventive measures to be taken.

Batteries have been reported to experience solid electrolyte interphase (SEI) layer decomposition in Li-ion cells with a positive electrode made of lithiated cobalt oxide, which typically starts at 60 °C [56] and continues up to approximately 120 °C [57]. The extent of this failure depends on the temperature and duration of exposure to such conditions. As a result of this failure, there can be a reduction in battery capacity [26].

To address heat-related concerns, electric vehicles are equipped with cooling systems that regulate the temperature of the battery. These cooling systems play a crucial role in maintaining the optimal operating temperature range of the battery, mitigating the risk of thermal damage, and ensuring the overall performance and longevity of the battery. Research in [15] focused on conducting an FMEA assessment for the installation and management of problematic parts in an immersion-cooled battery pack (ICBP).

If the battery is completely discharged, there is a possibility of an internal short circuit occurring [59]. During deep discharge, the copper material in the anode may oxidize and eventually dissolve into the electrolyte solution [26]. When the battery is depleted, the voltage level drops and the cell may experience under-voltage. In an electric vehicle, the motor's power is determined by the voltage and current. If the battery voltage is low, the motor require a higher current to generate power. This can lead to an external short circuit within the system and potentially cause overheating in the battery or motor [26].

To manage the battery's performance, an electric vehicle is equipped with a battery management system (BMS). The BMS monitors the vehicle condition, provides diagnostics, data collection, and manages communication [15]. In this paper, the safety system is separated from BMS, as illustrated in Figure 1, following the ISA standard of functional safety [59]. Some electric vehicles also feature a range extender and regenerative braking, which can provide additional charge to the battery during operation. According to [60], a serial regenerative braking method offers the best opportunity to reduce total energy consumption by up to 15 %

The fault tree analysis is presented in Figure 2. Based on the diagram, five primary events can lead to the shutdown of an electric vehicle: compressed cell, motor underload, environmental exposure, low state of charge (SOC), and grounding failure. When the battery cell undergoes compression, puncture, or crushing, it experiences mechanical stress. An external short circuit occurs when the motor is under load. Environmental exposure also contributes to thermal runaway. Additionally, a battery with a low SOC can cause the cell to be under-voltage, leading to a shutdown.

Following the information provided in Table 6, the top four identified probable failure scenarios would trigger a safety shutdown as the required action due to their high severity. Additionally, the installation of fuses is recommended for external short circuits and overcurrent situations. According to [14][27], electric vehicle battery systems should be equipped with at least one safety feature, including a fuse. Additionally, the national highway traffic safety administration (NHTSA) emphasizes the importance of installing fuses for overcurrent protection. Fuses serve as a

safeguard against excessive current flow and help prevent damage to the circuitry. It is recommended to 39e appropriate fuse installations in electric vehicles to ensure the safety and protection of the electrical system [26].

To ensure passenger awareness and safety, a visual warning system on the dashboard and an audible warning will be implemented. The warnings will be prioritized based on the event, with mechanical stress being the highest priority, followed by fire event, external short circuit, overcurrent, overheat, and finally, over-discharge. By providing a warning, the failure mode can have a lower severity score according to SAE J1739 guidelines provided in Table 1 [25].

In the case of a fire event, the smoke sensor will activate to alert passengers of a potential fire in the battery system. Overheat failure will activate the cooling fan to assist the cooling system in managing temperature, and over-discharge failure will be prevented through the implementation of a regenerative braking mechanism that provides extra charge to the battery.

This paper utilizes six sensors as input for the shutdown logic, as illustrated in Figure 4. The selection of these sensors is based on the basic events identified in the fault tree analysis in Error! Reference source not found.. The pressure sensor and smoke sensor are employed to detect mechanical stress in the battery. Pressure detection is a risk reduction measure to prevent a catastrophic failure due to build-up pressure in the battery [14]. The addition of a smoke sensor in this paper is to detect when the battery begins to emit gases as a result of build-up pressure. The load sensor is used to detect motor underload, SOC monitoring is implemented to

Table 6.
Recommended actions

Potential failure	Actions recommended
Mechanical stress	Warning, safety shutdown
Fire event	Warning, smoke sensor, safety shutdown
External short circuit	Warning, fuse installation, safety shutdown
Overcurrent	Warning, fuse installation, safety shutdown
Overheat	Warning, turn on the cooling system
Over-discharge	Warning, regenerative braking

identify a low SOC condition, current monitoring is employed to detect current surges resulting from grounding failure, and the temperature sensor is utilized to detect increases in battery temperature due to operation or environmental exposure.

The logic of the shutdown system employs AND gates to ensure that events are not triggered by false alarms and the shutdown procedure is only activated during real emergencies. For example, during normal operation, the battery may experience mechanical stress, such as vibrations or pressure increases. However, as long as this mechanical stress does not lead to the emission of dangerous smoke from the battery, a shutdown procedure is not necessary, and the existing battery protection control is deemed sufficient.

IV. Conclusion

The objective of this research was to examine the potential failure scenarios that could occur in lithium-ion battery packs used in electric vehicles. The study investigated the impacts, causes, and existing process controls associated with six
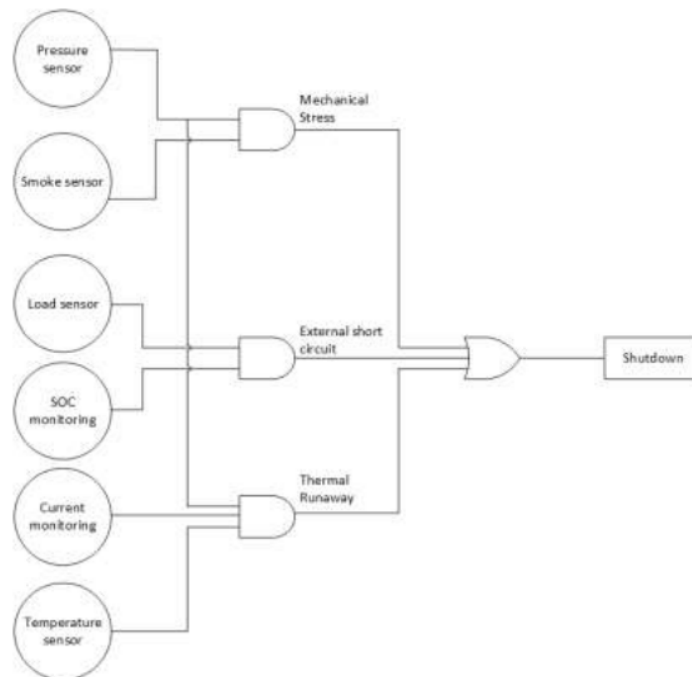
Figure 4. Shut down logic

identified failure modes. To prioritize these modes, the risk priority number (RPN) was calculated for each potential failure. Based on the analysis using failure mode and effects analysis (FMEA), the top four failure modes were mitigated by implementing a shutdown system and incorporating fuses. The remaining two failure modes were addressed through the implementation of a safety alert system and taking appropriate safety actions.

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