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Electric Vehicle Fire Risk Assessment using Fault Tree Analysis

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Abstract: *Soon, the rapid adoption of electric vehicles is inevitable, driven by environmental concerns and climate change awareness. However, this progressive trend also brings forth safety concerns and hazards, notably regarding the risk of EV fires, which have garnered significant media attention. This necessitates the need to study for comprehensive fire risk assessment strategies aimed at preventing and mitigating such incidents.*

Through this approach, the work discerned five major causes: human factors, vehicle factors, management factors, external factors, and unknown factors. Using a meticulous weighted average approach, the annual EV fire frequency for each country was deduced, revealing an average annual EV fire rate of 2.44 × 10-4 fires per registered EV. This metric provides a significant benchmark, reflecting both the probability and inherent risk of such incidents.

As EV adoption surges, this study underscores the importance of comprehensive, data-driven insights for proactive risk management, emphasizing the necessity for vigilant and adaptive strategies. The findings emphasize the pivotal role of this assessment in shaping response strategies, particularly for first responders dealing with EV fires. In essence, this research not only elevates the understanding of EV fire risks but also offer a foundation for future safety measures and policies in the domain

Keywords: Electric vehicle

I. INTRODUCTION

Electric vehicle (EV) fire accidents in India have been increasingly reported as the use of electric vehicles becomes more prevalent. These incidents have raised concerns regarding the safety of EVs and the readiness of infrastructure to handle such situations. While the introduction of electric vehicles marks a significant advancement in the automotive industry, it also brings about challenges, particularly in ensuring the safety of these vehicles. One major contributing factor to EV fire accidents is the lithium-ion batteries used in these vehicles. While these batteries offer benefits such as high energy density and longer driving ranges, they can also be susceptible to thermal runaway and subsequent fire incidents if damaged or exposed to extreme conditions like high temperatures or overcharging. Issues such as inadequate battery management systems, manufacturing defects, and substandard charging infrastructure further increase the risk of fire accidents. The absence of standardized regulations and protocols specific to EVs in India compounds the challenges in ensuring their safety. Fighting EV fires requires specialized training and equipment due to the unique characteristics of lithium-ion battery fires, which can reignite even after initial extinguishment. To address these concerns, efforts are underway to develop and implement stricter safety standards, improve battery technology, and enhance emergency response capabilities. Collaboration between government agencies, automakers, and industry stakeholders is essential to establish guidelines for the safe design, manufacturing, and operation of electric vehicles. Additionally, raising public awareness and educating individuals about EV safety practices is crucial.

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Despite these challenges, the environmental benefits and technological advancements offered by electric vehicles continue to drive their adoption in India. However, ensuring the safety and reliability of EVs remains critical to realizing their full potential as a sustainable mode of transportation in the country.

Fig. 1: Images of Electric Vehicle Fires in India

II. LITERATURE REVIEW

2.1 Foleyet al. [1] study in Urban Science investigates the factors influencing electric vehicle (EV) adoption in Australia. Using a descriptive analysis, the research identifies key determinants: Policy Environment: Government policies and incentives impact EV adoption. Technological Factors: Advancements in EV technology influence consumer preferences. Consumer Perceptions: Concerns like range anxiety affect EV uptake. Socio-Economic Factors: Income levels and urban-rural divide play roles in EV affordability. Environmental Awareness: Climate consciousness drives EV adoption. Infrastructure Availability: Access to charging infrastructure affects adoption rates. Market Dynamics: Availability and pricing of EV models impact consumer choices. These findings contribute to understanding EV adoption and offer insights for promoting sustainable transportation in Australia.

2.2 Bisschop et al. [2] examine the fire safety concerns surrounding lithium-ion batteries in road vehicles. The study likely reviews lithium-ion battery chemistry to assess fire risks. Analysing documented fire incidents involving these batteries. Reviewed regulations governing battery safety standards. They explore about safety technologies used by manufacturers and Evaluated factors contributing to battery fires. Discuss methods for preventing and managing battery fires .Also addresses protocols for responders dealing with battery fires. Their work provides essential insights for enhancing fire safety in electric and hybrid vehicles.

2.3 Shah et al. [3]In their study, delve into methods for predicting thermal runaway in lithium-ion (Li-ion) cells. They review Li-ion battery technology and its applications and Discuss about the potentially hazardous thermal runaway phenomenon in Li-ion batteries and provided predictive model for thermal runaway.

III. SCOPE

This project encompasses a wide range of areas aimed at understanding, preventing, and mitigating the risks associated with battery fires. The scope of this research includes, but is not limited to, the following key areas:

3.1 Battery Chemistry and Design

- Investigating different battery chemistries (e.g., lithium-ion, solid-state) to identify those with lower fire risks.
- Developing safer battery designs that minimize the likelihood of thermal runaway.
- Studying the impact of battery aging and degradation on fire safety.

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3.2 Thermal Management Systems

- Designing and optimizing thermal management systems to prevent overheating.
- Developing advanced cooling techniques to maintain battery temperatures within safe limits.

3.3 Fire Detection and Suppression

- Creating early detection systems for identifying potential battery failures before they lead to fires.
- Developing effective fire suppression systems specifically tailored for EV battery fires.
- Evaluating the efficacy of different fire extinguishing agents and techniques.

3.4 Standards and Regulations

- Developing and updating safety standards and regulations for EV batteries and systems.

3.5 Consumer Education and Awareness

- Educating consumers about the potential risks and safety practices associated with EVs.
- Providing guidelines for safe charging, storage, and maintenance of EVs.
- Raising awareness about the importance of using certified repair and maintenance service.

IV. FIRE ACCIDENTS OF ELECTRIC VEHICLES

4.1.Ola S1 Pro (March 2022):

Location: Pune, Maharashtra Incident: An Ola S1 Pro electric scooter caught fire while parked. The company attributed it to an isolated thermal incident.

4.2. Pure EV (April 2022):

Location: Chennai, Tamil Nadu Incident: A Pure EV electric scooter caught fire while being ridden. The rider was unharmed. Pure EV began an investigation into the cause.

4.3. Okinawa (April 2022):

Location: Vellore, Tamil Nadu Incident: An Okinawa electric scooter caught fire while charging at home, resulting in two fatalities. Okinawa recalled over 3,000 units to address potential battery issues.

4.4. Jitendra EV (April 2022):

Location: Nashik, Maharashtra Incident: A truck transporting Jitendra electric scooters caught fire, damaging several units. The incident was likely caused by a short circuit.

4.5. Gemopai Electric Scooter (May 2022):

Location: Gujarat Incident: A Gemopai electric scooter caught fire while charging. No injuries were reported, and the company initiated an investigation.

4.6. Hero Electric (June 2022):

Location: Jaipur, Rajasthan Incident: A Hero Electric scooter caught fire while parked. The company stated it was an isolated incident and conducted a thorough investigation.

4.7. Tata Nexon EV (June 2022)

Location: Mumbai, Maharashtra Incident: A Tata Nexon EV caught fire while it was parked and charging. Tata Motors investigated and stated that this was an isolated incident caused by a faulty electrical installation at the charging point.

4.8. Mahindra e-Verito (August 2022)

Location: Delhi Incident: A Mahindra e-Verito caught fire while parked. The vehicle was part of a fleet operated by a government agency. Mahindra launched an investigation to determine the cause and reassured customers about the safety of their EVs.

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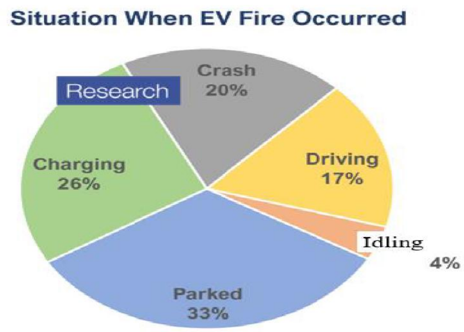

Fig- SITUATION WHEN EV FIRE OCCURRED

V. PROBLEM FORMULATION AND METHODOLOGY

5.1 Fault tree analysis (FTA) is a graphical technique that helps identify the potential causes of a system failure. It's a deductive, top-down approach that uses a logic diagram to break down the root cause of a failure into its contributing factors. FTA can be used for: Safety assessment, identifying failure causes, determining the probability of an accident, and analysing industrial system reliability problems. Here are some steps involved in FTA:

Identify the top event: Start with the undesired event, or "top event", that you want to analyse.

Draw the fault tree: Logically work out the immediate contributory fault conditions leading to the top event.

Calculate probabilities: Once you know the probability of basic events, you can calculate the probabilities of intermediate events.

FTA is different from other methods like Failure Modes and Effects Analysis (FMEA), which start with individual components. FTA is useful for analysing multiple failure scenarios and their interactions at the same time. FTA can help organizations anticipate potential problems and mitigate them in advance. For example, in the automotive industry, FTA can help prevent vehicle recalls by identifying potential failures during manufacturing.

5.2 FTA ANALYSIS

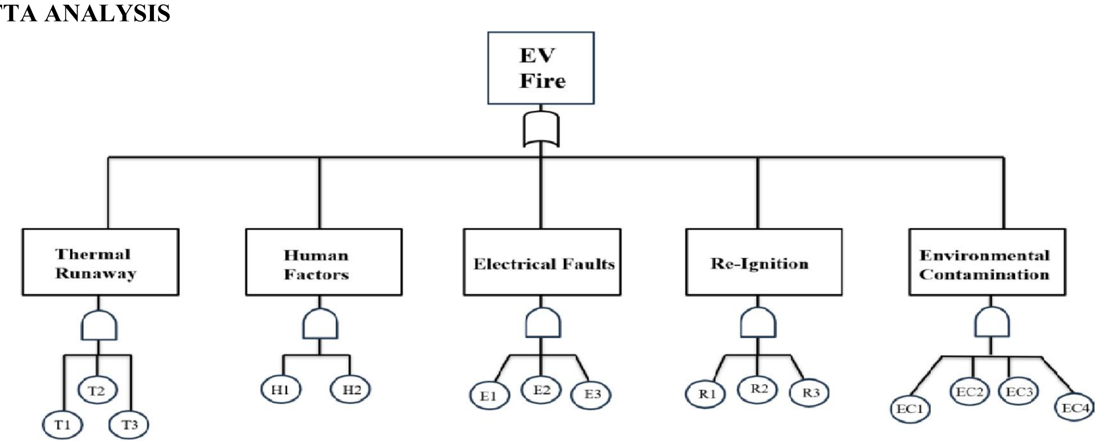

Fig- FAULT TREE ANALYSIS OF EV VEHICLES FIRE

This risk assessment is structured around the fault tree analysis process and encompasses qualitative, quantitative, and control perspectives. In this study, "risk" refers specifically to the risk of vehicle fires and the spread of fires between multiple vehicles. The assessment is based on a literature search and review of relevant materials, including:

Reports and investigations of major EV fires.

Research on the nature and severity of fires in electric EVs and IC engine vehicles.

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Data on fire frequencies in car parks, for EVs, EV charging equipment, and ICEVs.
Fire safety standards for car parks and vehicles; and
Facilities for Fire Brigade intervention in car park fires.
The literature search involved reviewing open sources and fire research publications but was limited by the short timeframe available for the study. It is not intended to be exhaustive or a state-of-the-art review. The study utilized a systematic literature review methodology to ensure an organized, transparent, and reproducible approach for synthesizing research findings and collecting and analyzing data, the adopted systematic literature review methodology provides an overview of the systematic approach followed in gathering and analyzing the literature. This systematic review process relied on secondary data sources, such as conference papers, journal articles, books, and scientific reports.

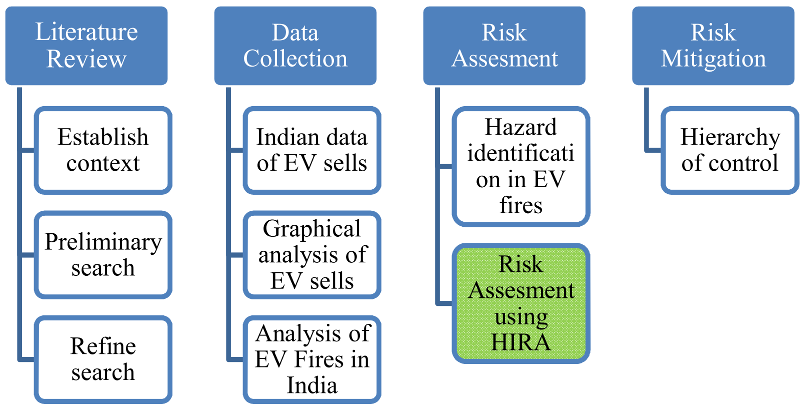

Fig. 2: Steps of mitigation framework.

5.3 EV Numbers in India: Graphical representations of the growth in EV numbers in India, based on digitalized vehicle records from the centralized Vahan 4 system, are depicted in Figure 3. The data illustrate a significant increase in EV numbers, rising from 124,681 in 2020 to 1,433,545 EVs in 2023. Additionally, Figure 3 highlights the changing ratio of EVs to total vehicles in India, which escalates from 0.0067 in 2020 to 0.0631 in 2023. However, it is noteworthy that the proportion of electric vehicles remains relatively low compared to petrol and diesel vehicles. This is attributed to factors such as the availability of less efficient batteries in India and recent fire incidents.

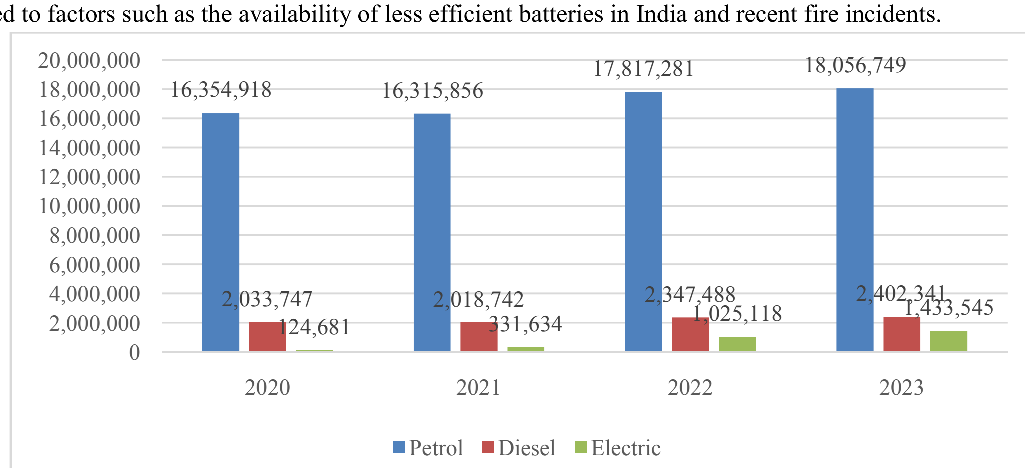

Fig. 3: Vehicle registered during calendars years -2020 to 2023

5.4 EV Fires in India: Electric vehicle fires in India have sparked safety anxieties, particularly with recent occurrences like A high-end Volvo C40 Recharge SUV igniting on a highway in Chhattisgarh (Economic times).A compact electric

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car, possibly a Mahindra E20, erupting in flames on the streets of Bengaluru (The Times of India).Tata Nexon EV bursts in flames: First EV fire for Tata (The Times of India).Battery of electric two-wheeler explodes while charging in Delhi. These incidents underscore the importance of stricter regulations and enhanced safety protocols for EVs in India. The Defence Research & Development Organisation (DRDO), assigned by the Union Road Transport and Highways Ministry to investigate EV (electric vehicle) fire incidents, has uncovered significant issues in the batteries. Sources familiar with the investigation suggest that these problems stem from flaws in the battery packs and modules' designs. It is speculated that electric two-wheeler manufacturers such as Okinawa Auto tech, Pure EV, Jitendra Electric Vehicles, Ola Electric, and Boom Motors might have opted for cost-cutting measures by utilizing lower-grade materials, leading to these defects. (India TV)

Potential causes of EV fires include:

Poor battery quality: Flawed battery cells can significantly elevate fire risk.

Battery design imperfections: Faulty designs can lead to overheating and potential fires.

Inadequate Battery Management System (BMS): The BMS is responsible for maintaining battery temperature and voltage. A malfunctioning BMS could fail to prevent overheating.

While these incidents receive significant attention, it is important to remember that EV fires are statistically uncommon compared to conventional gasoline vehicle fires. However, they do raise legitimate safety concerns for India's burgeoning EV industry.

VI. HIERARCHY OF CONTROL

Ensuring the prevention of recurring accidents should be a primary objective during incident inspections and safety investigations. Utilizing the Hierarchy of Controls can offer a structured approach to identifying and implementing the most impactful corrective actions.

Elimination controls: This measure eradicates the risk of EV fires completely and provides the utmost level of safety. It is considered the most effective control method, such as removing defective EV charging points.

Engineering controls: Engineering controls mitigate the risk of EV fires by implementing alterations to engineering systems, such as categorizing EV charging stations within buildings as 'Special Hazard' according to building codes, with features like compartment or fire suppression systems. These measures safeguard human, the environment, and the public from potential hazards linked to specific processes, tasks, or activities.

Administrative controls: These measures depend on human behaviour and decision-making, including oversight, to mitigate risks. When implemented alone, they are generally less effective in risk reduction. For instance, emergency planning and operational protocols fall under this category."

VII. OBSERVATION

During conducting a risk assessment for fire hazards in electric vehicles (EVs), several critical observations were made to identify potential risks and develop effective mitigation strategies. Here are key areas of focus:

7.1. Battery Risk Factors

Thermal Runaway: Assess the likelihood of thermal runaway, a process where a battery cell overheats uncontrollably, leading to potential fires or explosions.

Battery Chemistry: Evaluate the type of battery chemistry used (e.g., lithium-ion, solid-state) and its associated fire risks. Lithium-ion batteries, for example, are more prone to thermal runaway.

Cell Defects: Inspect for manufacturing defects or damage in battery cells that could increase the risk of fire.

Battery Aging: Consider the impact of battery aging on fire risks, as older batteries may be more susceptible to failure.

7.2. Charging Infrastructure

Overcharging Risks: Evaluate the risk of overcharging, which can lead to excessive heat generation and potential battery fires.

Charger Compatibility: Ensure that the EV's charging system is compatible with the charging station to prevent electrical faults.

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Electrical Overload: Assess the potential for electrical overloads in the charging system that could cause fires.

7.3. Vehicle Design and Engineering

Battery Placement: Consider the location of the battery pack within the vehicle and its exposure to potential impacts or environmental conditions.

Cooling Systems: Examine the effectiveness of the vehicle's cooling systems in preventing overheating of the battery pack.

Material Flammability: Evaluate the flammability of materials used in the vehicle’s construction, particularly those surrounding the battery.

Structural Integrity: Assess the vehicle's ability to protect the battery during a crash or collision.

7.4. Environmental and External Factors

Extreme Temperatures: Consider the vehicle's exposure to extreme temperatures, which can increase the risk of thermal runaway.

Water Ingress: Assess the risk of water ingress into the battery pack, which can cause short circuits and fires.

Collision and Impact: Evaluate the risk of fire following a collision or impact, especially if the battery is compromised.

7.5. Operational and Usage Patterns

Driving Habits: Consider aggressive driving patterns that could lead to excessive heat generation in the battery.

Frequent Fast Charging: Assess the impact of frequent fast charging on battery health and its potential to increase fire risks.

Maintenance Practices: Evaluate the adequacy of vehicle maintenance in preventing conditions that could lead to fire hazards.

7.6. Regulatory Compliance and Safety Standards

Adherence to Standards: Review the vehicle’s compliance with international safety standards related to battery safety and fire prevention.

Testing Protocols: Ensure that the vehicle has undergone rigorous testing under various conditions to identify potential fire hazards.

7.7. Emergency Response and Containment

Fire Suppression Systems: Evaluate the presence and effectiveness of onboard fire suppression systems.

Emergency Response Plans: Consider the availability and effectiveness of emergency response plans in case of a fire, including evacuation procedures and first responder training.

Containment Measures: Assess the design and effectiveness of measures to contain a fire within the battery pack, preventing it from spreading to other parts of the vehicle.

7.8. Incident History and Data Analysis

Historical Data: Review historical data on EV fires to identify common causes and risk factors. Incident Reporting: Analyses any past incidents involving the specific vehicle model to identify recurring issues or design flaws.

Root Cause Analysis: Conduct root cause analyses of any past fires to determine underlying factors and prevent future occurrences.

Risk analysis was done after the hazards were located. The various activities were categorized as Extreme, High, Medium, or Low based on the likelihood and potential outcomes. These are shown in Table The extreme risk category activities that are shown in red are not acceptable and action are needed now. The risk which is marked in orange colour are needed to analyse and find the strategy to reducing the risk. The risk which are marked in yellow colour are tolerable, but efforts must be made to reduce risk without expenditure that is grossly disproportionate to the benefit gained. The risks which are marked in green colour have the risk level so low that it is not required for taking actions to reduce its magnitude any further. The risks that are indicated in orange require analysis and the development of a risk-reduction plan. The risks shown in yellow are need minor changes, but precautions must be taken to lower the risk without incurring costs that are enormous compared to the potential rewards. The dangers that are highlighted in green have a risk level so low that no further action is necessary to lessen their magnitude.

VIII. RESULT AND INTERPRETATION

Different activities are identified related fire hazards in electric vehicles like charging, parking, driving, and maintenance. Each activity has number of potential hazards and risk associated with them. During the charging thermal runaway hazard is possible which has a risk to Passengers and first responders can be at significant risk due to fire explosion and toxic emission. Adequate BMS and thermal sensors should be used to avoid such risk. Electric hazards have a risk of Electric shock due to high voltage batteries and not proper charging points and can be avoided by not using faulty charging points. Avoiding direct contact with battery. There is possibility of explosion during the charging due to overcharge or not using original chargers and has risk of permanent disability or death. If advanced BMS and early detection sensors, automated shutdown are implemented in electric vehicles such type of risk can be reduced.

While the activity like parking there is possibility of overheating which me cause burning or personnel injury. Overheating may be a reason for thermal runaway or fire. By avoiding open parking in summer days risk can be reduced significantly. Parking conditions is major reason of fire in electric vehicles in India. During the summer days there is huge possibility of fire and explosion due to overheating of batteries. Providing advanced battery management systems and early detection sensors can reduce such risk.

During the driving, impact is major reason for fire in electric vehicles and there is risk of explosion of battery, and it may cause permanent disability to a person driving it. Crash-Resistant Battery Enclosures should be used to reduce the risk. Leakages from battery during driving have a significant risk to damage RESS and leakage of hazardous substances is possible. Crash resistant battery enclosure and PPE during handling can reduce such risk. Battery rapture and explosion possibilities are also they are during driving off road or mechanical impact to battery. Such activity has high risk.

During the maintenance electric hazard is possible and has a risk of electric shock due to high voltage batteries and not proper charging sockets and can be reduced by avoiding direct handling of batteries, using PPE while maintenance.

Environmental contamination is also possible during maintenance due to leakage of battery or fuel cells. it can cause health effects, water pollution, air pollution and by avoiding dispose of hazardous material directly to environment can reduce the risk significantly.

IX. RECOMMENDATION

9.1 Enhanced Battery Safety:

Advanced Battery Chemistry: Research and development of safer battery chemistries, such as solid-state batteries, which offer improved thermal stability.

Improved Battery Management Systems (BMS): Implement more sophisticated BMS that can accurately monitor and predict thermal runaway and take proactive measures to prevent it. Robust Battery Design: Design battery packs with better thermal management systems, including improved cooling and insulation.

9.2 Charging Infrastructure Safety:

Safe Charging Systems: Develop charging systems with built-in safety features to prevent overcharging, overheating, and electrical faults. Infrastructure Monitoring: Implement monitoring systems for charging infrastructure to detect potential hazards and trigger alerts.

9.3 Vehicle Design and Safety Systems:

Improved Crash Protection: Design EV structures to protect battery packs from damage during collisions.

Fire Suppression Systems: Integrate onboard fire suppression systems that can quickly contain and extinguish battery fires. Early Warning Systems: Develop advanced sensors and algorithms to detect early signs of thermal runaway and alert drivers.

Emergency Response Training: Specialized Training: Provide specialized training for firefighters and emergency responders on how to handle EV fires.

Standardized Procedures: Develop standardized procedures for extinguishing EV fires, including the use of appropriate extinguishing agents and techniques.

9.4 Regulatory Frameworks:

Stricter Regulations: Implement stricter regulations for EV battery safety and fire prevention.

Regular Inspections: Conduct regular inspections of EV batteries and charging infrastructure.

X. FUTURE SCOPE

This study has provided valuable insights into fault tree analysis of electric vehicles in India. There are several factors for future scope which can enhance EV fire safety in India. Some potential future research direction includes:

1. Advanced Battery Design and Management

Solid-State Batteries
Battery Management Systems (BMS)
Thermal Management
Redundant Safety Mechanisms

2. Vehicle Design and Engineering Enhancements

Crash-Resistant Enclosures
Reinforced Battery Casings
Strategic Battery Placement
Fire-Resistant Materials
Integrated Fire Suppression Systems

3. Enhanced Charging Safety

Smart Charging Systems
Temperature Control During Charging
Standardized Charging Protocols

4. Stringent Testing and Quality Control

Rigorous Testing Standards
Quality Assurance in Manufacturing
Regular Safety Audits

5. Regulatory and Industry Standards

Mandatory Safety Certifications
Continuous Update of Standards
Regulatory Oversight

6. Emergency Response Preparedness

Training for First Responders
Guidelines for Safe Disposal

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