Safety21

INNOVATING FOR SAFETY

US DOT National
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482 Transforming Transportation Policy and Planning for Safety

Chris Hendrickson, PI Orchid 0000-0002-9812-3580,
Corey Harper Co-PI Orchid 0000-0003-1956-5258,
Karen Lightman Co-PI Orchid 0009-0005-7689-1449

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Final Report – July 31, 2025

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16. Abstract

The project goal is to influence transport policy to improve safety. We have produced a policy brief with specific recommendations to improve safety for battery electric vehicles. As background for this policy analysis, we have published a literature review on battery electric vehicle safety. We have also published a journal editorial with specific recommendations for needed research and activity to improve roadway safety. We have continued work on the effectiveness of partial automation in vehicles. We have presented results at professional meetings and involved five students in our research work. We have continued to work with partners to achieve the PennSTART testing and training facility for automated vehicles.

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Battery electric vehicle safety; roadway safety research; PennSTART	No restrictions.

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1. Introduction: Project Overview

This project builds upon five previous years of research, which has informed policymakers of disruptive transportation technology trends and provided guidance on policies to take advantage of opportunities and mitigate risk. The activity focus switched from mobility to safety research with the initiation of Safety21. The work builds upon relevant research conducted by Safety21.

The project accomplished several tasks:

- Research on safety policy improvements for battery electric vehicles was pursued using interviews of knowledgeable experts and relevant literature. Audiences will be USDOT, USDOE and State officials. Safety concerns of interest include battery fires, vehicle sound, and vehicle weight.
- Project participants continued to work with Regional Industrial Development Corporation (RIDC) in the planning for Pennsylvania Safety Transportation and Research Track (PennSTART).
- Project participants engaged in a variety of technology transfer and outreach activities.

Project personnel included:

Chris Hendrickson, Principal Investigator, is the Hamerschlag University Professor Emeritus, Director of the Traffic 21 Institute at Carnegie Mellon University, member of the National Academy of Engineering, and Editor-in-Chief of the ASCE Journal of Transportation Engineering Part A (Systems). His research, teaching, and consulting are in the general area of engineering planning and management, including, transportation systems, design for the environment, construction project management, finance, and computer applications.

Corey Harper, Co-Principal Investigator, is an Assistant Professor at CEE and Heinz School of Information Systems and Public Policy at Carnegie Mellon University. In his role as the director of the Future Mobility Systems Lab, he leads a team of researchers who explore the infrastructure, policy, and equity implications of emerging transportation technologies (e.g., autonomous vehicles and micromobility). The equity analysis side of his team applies equity metrics to assess how policy and regulation could affect the distributional equality of transportation resources. The modeling and simulation side of his group is focused on incorporating new mobility modes (e.g., micromobility and e-commerce) into regional traffic demand models to promote better long-range planning of the transportation system.

Karen Lightman, Co-Principal Investigator, is Executive Director of Safety21 as well as the Executive Director of Metro21: Smart Cities Institute at CMU. Karen is an internationally recognized leader in building and supporting communities based on emerging technologies. Her diverse background spans the consumer, military, healthcare, manufacturing, and automotive sectors. Karen is ranked by *EETimes* as one of the top 25 "Women in Tech." She is a passionate advocate and spokesperson for technology solutions to real-world problems and has held several board positions and is currently treasurer on the board of the MetroLab Network. She has a BA from the University of Vermont and a MS in Public Policy and Management from Carnegie Mellon University's Heinz College.

Several undergraduate and graduate Carnegie Mellon students assisted the primary personnel, including:

- Bright Aungsuthar, MS Student, Engineering
- Lex Capestany, Undergraduate, Engineering
- Sanjeev Naiac, Undergraduate, Engineering
- Jiacheng Wang, PhD Student, Engineering
- Haoming Yang, PhD Student, Engineering

Data Management

This project involved literature review and meetings with transportation stakeholders. No datasets were developed and used in this work.

2. Battery Electric Vehicle Safety Literature Review and Analysis

Media reports regularly express concern about the safety of battery electric vehicles (BEV). However, there is little comprehensive analysis of the comparative safety of BEV relative to comparable ICE vehicles. This task is intended to (1) survey existing literature, including relevant regulations and changes in safety risks over time, (2) identify research gaps, and (3) consider appropriate policies to improve the safety of BEVs.

Sales of battery electric vehicles have continued to grow in the United States. BEV are now becoming a significant fraction of vehicles on the road. In the interest of promoting roadway safety, the special characteristics of BEV need to be considered in roadway safety policy.

The literature survey taken advantage of database tools such as TRID and Google Scholar. A taxonomy of potential risks has been developed and literature relevant to each risk categorized.

Outputs of the work include a Carnegie Mellon policy brief and a published peer-reviewed paper. The policy brief was produced in cooperation with the Scott Institute for Energy Innovation at Carnegie Mellon University. The works are available online: and in the appendix:

Harper, Corey, Chris Hendrickson, and Karen Lightman (with the assistance of Sanjeev M. Naiek, Sorawich Aungsuthar and Haoming Yang), 2025, 'Improving Safety for Battery Electric Vehicles,' A Policy Brief, Safety21 and Scott Institute, Carnegie Mellon University. (https://safety21.cmu.edu/wp-content/uploads/2025/02/BEV-Policy-Guide_Feb-2025.pdf)

Harper, Corey, Chris Hendrickson, and Karen Lightman (with the assistance of Sanjeev M. Naiek, Sorawich Aungsuthar and Haoming Yang), 2025, 'Policy Insight- Improving EV Fire Safety,' Safety21, Carnegie Mellon University. (https://safety21.cmu.edu/wp-content/uploads/2025/07/One-Pager_BEV-Safety-Policy_2025.pdf)

Naiek, Sanjeev M., Sorawich Aungsuthar, Corey Harper, and Chris Hendrickson. "Battery Electric Vehicle Safety Issues and Policy: A Review." *World Electric Vehicle Journal* 16, no. 7 (2025): 365. (https://www.mdpi.com/2032-6653/16/7/365).

3. PennSTART Participation

Project Co-PI Karen Lightman was the primary project contact for PennSTART activities. She actively participated in PennSTART planning committee meetings as described below. The PennSTART facility is currently in design and business planning.

As described on the PennSTART website,[1] 'Pennsylvania Department of Transportation (PennDOT), the Pennsylvania Turnpike Commission, the Regional Industrial Development Corporation (RIDC) of Southwestern PA, Carnegie Mellon University and Westmoreland County are partnering to plan and design the Pennsylvania Safety, Transportation and Research Track, or PennSTART — a state-of-the-art facility envisioned to benefit emergency

[1] https://PennSTART.org/

responders, transportation technology companies, and research institutions while supporting the local economy.

PennSTART's aim is to address safety, training, and research needs in six key areas: traffic incident management (TIM); tolling and intelligent transportation systems (ITS) technology; work zones; commercial vehicles; transit vehicles; and AV and other emerging technologies.

The facility will be built at and adjacent to the RIDC Westmoreland site in Mount Pleasant.'

Prof. Rajkumar serves on the 8-member *PennSTART Operating Committee*, which is the Governing Board for PennSTART. Karen Lightman, Executive Director of Metro21 and Safety21, serves on the *Training Subcommittee* and *the Technical Subcommittee* for PennSTART. These committees meet regularly and actively to operationalize the initial phase of PennSTART. The Technical Subcommittee engaged an engineering firm to manage the design phase of the project in the fall of 2024 and tree clearing took place in spring/early summer 2025. New track construction started in 2024 and the is anticipated to break ground in the fall of 2025 and to be in operation in 2026.

Organizations that are working with RIDC on PennSTART include PennDOT, Pennsylvania Turnpike Commission (PTC), RIDC, Westmoreland County, and the Westmoreland County Community College. Additional organizations will be included as an AV Connected Corridor between Westmoreland and Hazelwood Green deployed.

In collaboration with PennSTART partners RIDC, PennDOT and PTC, the PennSTART project has started to be promoted and socialized. A webpage was launched on the RIDC website. Other activities include Traffic Incident Management (TIM) training – to date there have been fourteen trainings held onsite at PennSTART and six more planned in 2025.

4. Technology Transfer and Outreach Activities

Project personnel conducted a variety of technology transfer and outreach activities during the course of July 1, 2024 to June 30, 2025. These included:

- Project PI Chris Hendrickson co-authored an editorial outlining research gaps and possible policy improvements for roadway safety. Available online and in the appendix**:** Hendrickson, C., Rilett, L.R. and Sinha, K., 2025. Improving US Roadway Safety and Safety Research. *Journal of Transportation Engineering, Part A:*

Systems, *151*(4), p.01825001. (https://ascelibrary.org/doi/epdf/10.1061/JTEPBS.TEENG-9015)

- Seminar: 'Some Lessons Learned from the Key Bridge Collapse', Chris Hendrickson Safety21 Smart Safety Connection Seminar, Number – 90, Location – Pittsburgh PA and virtual via zoom, September 6, 2024
- Poster: 'Safety21 Policy Briefs', Chris Hendrickson, Safety21 Deployment Partners Consortium Symposium, Number – 120, Location – Pittsburgh PA, Date – Nov. 15, 2024
- Conference: *Transportation Engineering and Safety Conference 2024 Conference* to discuss PennSTART at the Transportation Engineering and Safety Conference, hosted by Penn State College of Engineering. Joined by others on the PennSTART technical committee team, Karen Lightman gave an overview of this Safety21 project, highlighting the safety issues related to battery electric vehicles. Location – Penn State University Main Campus, PA, 500 participants, December 11-12, 2024.
- Seminar: 'Workforce Development' Chris Hendrickson, Workforce Development Workshop, Pactrans, 50 participants, Seattle WA, May 19, 2025.
- Display: 'Battery Electric Vehicles,' Chris Hendrickson, Scott Institute Carnegie Mellon University, 200 participants, April 23, 2025.
- Summit: 'Safety Summit,' Chris Hendrickson and Karen Lightman, Safety21, Washington DC, 200 participants, March 27, 2025.
- Summit: 'National Summit on AV Leadership,' Karen Lightman, Safety21, Washington, DC, 125 participants, June 5, 2025.

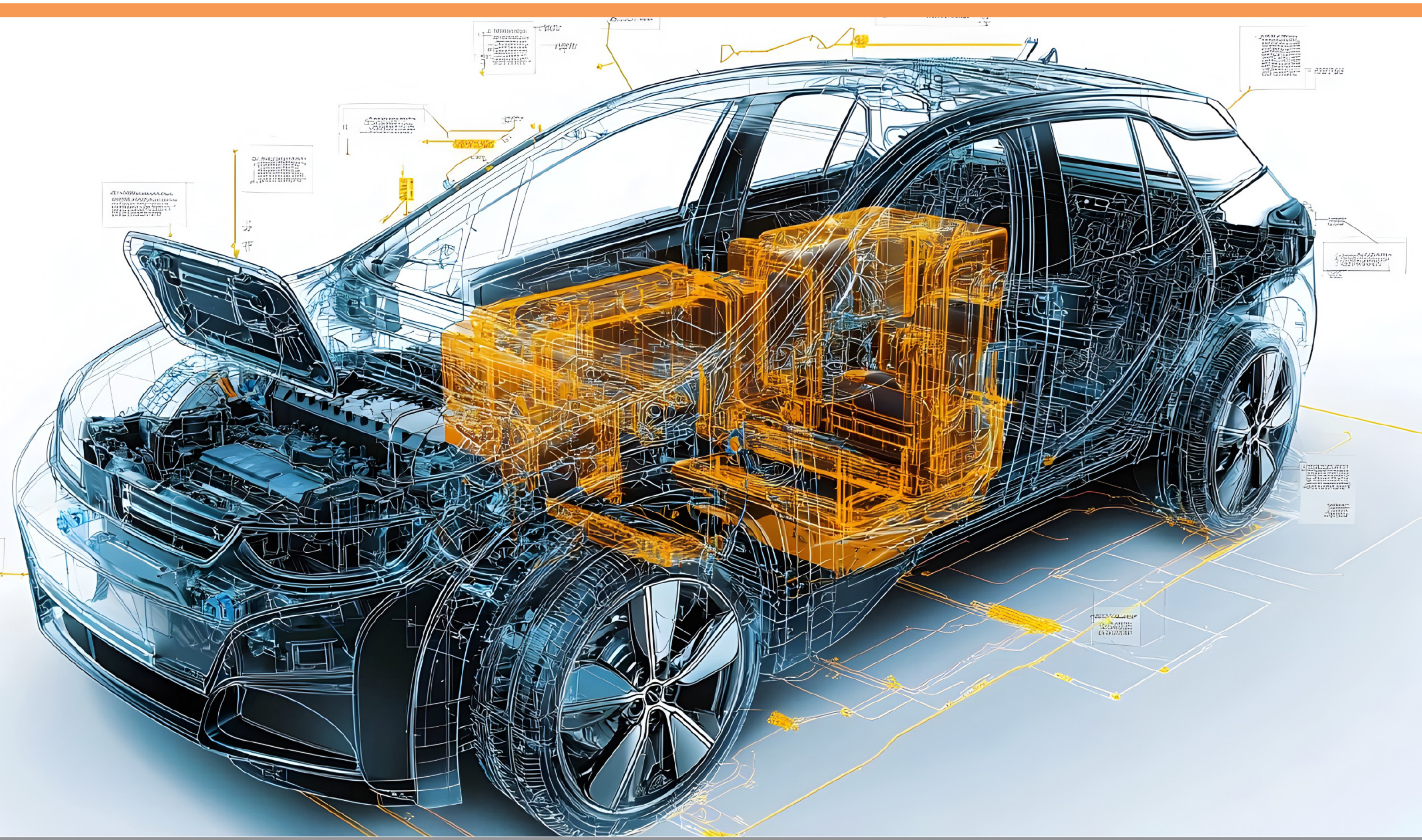
Appendices

A Policy Brief

Improving Safety for Battery Electric Vehicles

Carnegie Mellon Safety21 National University Transportation Center and Scott Institute for Energy Innovation

Corey Harper, Chris Hendrickson and Karen Lightman
with assistance from Sanjeev M. Naiek, Sorawich Aungsuthar and Haoming Yang



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Executive Summary of Policy Recommendations

Battery electric vehicles (BEV) are increasing in sales and use throughout the world. BEV safety requires special efforts such as BEV specific standards and BEV training for first responders for incidents. This policy brief develops policy recommendations to improve BEV safety as summarized in the table below. The goal is to make BEVs significantly safer than the existing vehicle fleet of BEV and conventional internal combustion vehicles.

AREA	RECOMMENDATION	RESPONSIBILITY
FIRE SAFETY-1	Continued monitoring on incidents of BEV fires. Reporting of crashes and fatalities should include vehicle types.	USDOT, Responding Agencies, Insurance
FIRE SAFETY-2	Continued investigations of causes of BEV fires with recommendations for standards improvements.	NTSB, Standards Agencies
FIRE SAFETY-3	Vehicle and battery manufactures should pursue improvements in advanced thermal management systems, flame-retardant materials, and active suppression technologies in mitigating BEV fire risks. Standard setters should encourage best practices in these technologies.	Battery and Vehicle Manufactures; Standards Agencies
FIRE SAFETY-4	Training for BEV technicians and first responders should be introduced and standardized. USDOT and AASHTO should take a lead in standardization efforts. Adequate test tracks for training should be encouraged.	AASHTO, USDOT, Education and Training Entities
VEHICLE WEIGHT-1	Subsidies and tax credits should encourage consumers to purchase smaller and lighter BEVs. Fleet purchases should also consider vehicle weights.	Congress, DOE, State Governments, Fleet Managers
VEHICLE WEIGHT-2	Establishment of widespread fast charging stations can alleviate range anxiety and encourage purchase of smaller vehicles.	Businesses, DOE, Local Governments
DRIVER EDUCATION-1	Driver education programs should be modified to include training on BEV characteristics.	State and Local Governments, Education and Training Entities
PARTIAL AUTOMATION SYSTEMS-1	Requirements for effective partial automation systems on all vehicles, such as the proposed rulemaking for active forward collision avoidance, should continue to be pursued.	NHTSA, Vehicle Manufacturers, Standards Agencies

Introduction

As Battery Electric Vehicles (BEVs) become more commonly used to reduce harmful emissions and enhance transportation efficiency, improving their safety performance becomes increasingly important. Such improvement should be of great interest to policy makers, vehicle manufacturers, emergency responders, owners and society as a whole. This Carnegie Mellon University Safety21/Scott Institute policy brief is intended to suggest means to achieve this goal.

BEVs are slightly safer than conventional vehicles in terms of crash rates (Naiek 2024, CAETS 2024). So far, their insurance claims due to crashes are lower than for conventional vehicles. But they do have special circumstances with regard to fire, noise and crash momentum that merit policy attention. New policies and technology should be aiming to make new BEVs significantly safer than the current generation of motor vehicles.

BEV Fires

BEVs have lower fire incidence than conventional vehicles in terms of fires per vehicle (Naiek 2024), but BEV fires have different characteristics. BEV fires can result from crashes, overheating such as exposure to house fires, and prolonged submersion in saltwater leading to short circuiting. Thermal runaway in lithium-ion batteries may occur with re-ignition of fires possible within batteries. Moreover, BEV fires can release toxic materials from their batteries.

Due to the special characteristics of BEV fires, fighting BEV fires has special considerations. Fire suppression often requires more water and/or foam retardant than for conventional vehicles. Manual cut-off of battery power may be needed (although manufacturers can install automatic cut-offs in battery management systems). Care to avoid toxic gases for first responders is imperative. Environmental clean-up after fires should consider the possibility of hazardous materials in run-off.

Mitigation measures can significantly reduce the dangers of BEV fires. Improved battery and vehicle designs can reduce the incidence of fires, especially with the introduction of effective standards to ensure implementation. For example, flame retardant materials and coatings may be used in battery packs. Continued monitoring of BEV fires can help inform designs and standards. BEV vehicle technicians are needed to ensure that vehicle software and hardware work properly and meet standards. Training for emergency responders should include responding to BEV fires. Safety21 National University Transportation Center members, Community College of Allegheny County and Philadelphia Community College have already developed and implemented such training in technician and first responder courses (Saxton, 2024; Starr 2024). The Pennsylvania Safety Transportation and Research Track, PennStart, is planning a comprehensive venue for first responder training and has already started with Traffic Incident Management training for first responders in the region (RIDC 2024). Manufacturer's instructions and best practices for fire suppression need to be available to first responders.

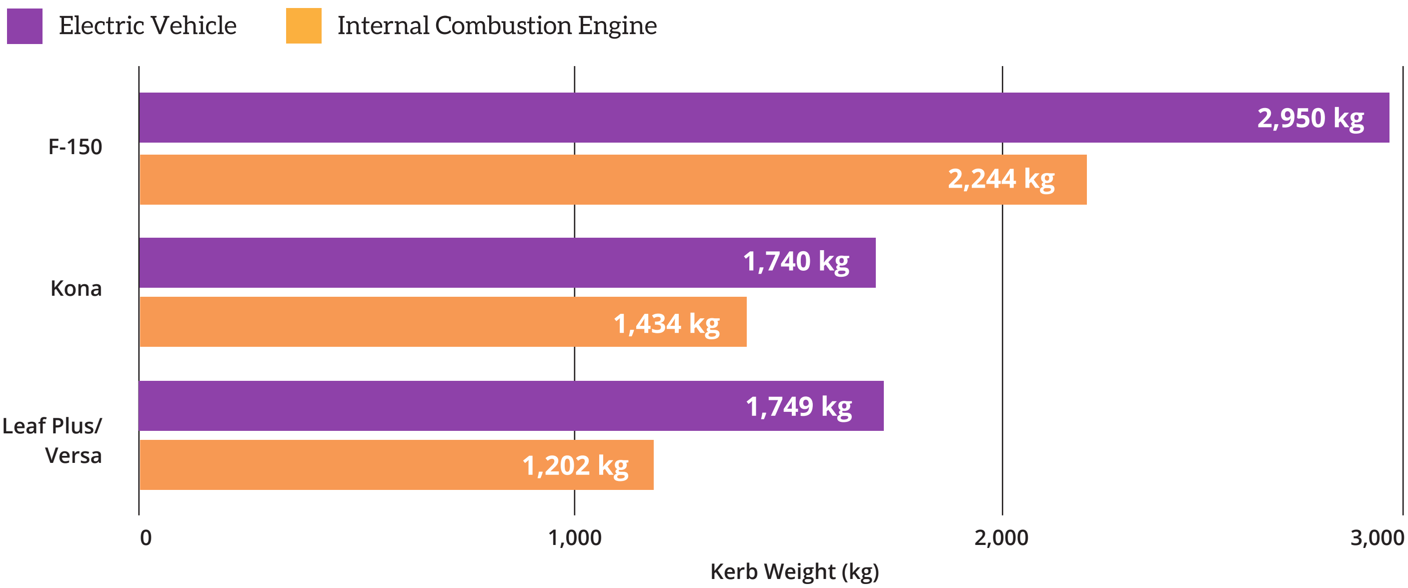
Weight and Safety Effects

BEVs typically weigh more than comparable conventional vehicles due to the weight of batteries. This extra weight may affect stopping distances and increase momentum in crashes. While the extra weight may help protect vehicle occupants in a crash, it has a deleterious effect on other vehicles, bikers or pedestrians involved in a crash. The force involved in a crash is proportional to vehicle weight and speed, and higher momentum forces lead to more severe crashes.

Mitigation policies can reduce the effect of BEV extra weight (Shaffer 2021). Lightweighting vehicles is possible by improving battery energy storage, reducing the mass of batteries in a vehicle, and other design decisions. Vehicle purchase subsidies and vehicle miles traveled taxes can favor lighter and smaller vehicles. Improved availability of fast charging stations reduces incentives for purchasing vehicles with the longest possible driving range.

HEAVIER ELECTRIC FLEET

Bulky batteries and their supports mean electric vehicles weigh more than petroleum predecessors.



Shaffer 2021

Noise and Vehicle Driving Characteristics

BEVs have some different driving characteristics than conventional vehicles (Naiek 2024). Regenerative braking systems (also found in hybrid vehicles) slow vehicles as soon as the accelerator is released. BEVs have faster acceleration than comparable conventional vehicles. So far, these different driving behaviors have not led to major problems. Drivers seem to readily adjust to the different characteristics of BEVs. However, researchers and safety professionals should continue to monitor BEV driver performance. Driving training courses to include BEV and hybrid vehicle performance characteristics.

In the early years of BEV adoption, concerns were raised about the quietness of the vehicles. While this is desirable to reduce noise pollution, it also raises a safety concern that pedestrians and bikers may not hear the approach of BEVs. However, regulatory requirements and design changes have introduced some artificial vehicle noise at slow speeds to eliminate this concern. Of course, tire noise for all vehicles continues to exist.

New technology can also help bikers and pedestrians. Connectivity with smartphone apps could provide warnings for oncoming vehicles. Warning systems with radar sensors for approaching vehicles are already available for bikes.

Role of Automation

A common theme in this review of safety policies for BEVs has been design improvements and new standards. A common theme for technology is the role of vehicle automation in improving safety. As BEVs are relatively new, most of the BEV models in the marketplace have a variety of crash avoidance technologies, including lane departure warnings, excessive speed warnings, and collision warning systems. Partial automation systems are also being introduced with braking automatically applied from radar warnings of collisions. These warning system and partial automation aids have already demonstrated their effectiveness in terms of reducing crash frequency and severity (Khan, 2019; Yang, 2024).

Higher levels of automation are actively being developed, tested and implemented. With good sensors and software, the safety record of highly automated vehicles can exceed human drivers (Di Lillo 2024; Victor 2023). BEVs would benefit from this improvement, along with other vehicles in use.

Possible Policies to Improve BEV Safety

FIRE SAFETY

FS-1

Continued monitoring by USDOT and private entities on incidents of BEV fires. Reporting of crashes and fatalities should include vehicle types.

FS-2

Continued investigations of causes of BEV fires by NTSB with recommendations for standards improvements.

FS-3

Vehicle and battery manufacturers should pursue improvements in advanced thermal management systems, flame-retardant materials, and active suppression technologies in mitigating EV fire risks. Standard setters should encourage best practices in these technologies.

FS-4

Training for BEV technicians and first responders should be introduced and standardized. USDOT and AASHTO should take a lead in standardization efforts. Adequate test tracks for training should be encouraged.

FS-5

Regulatory standards and best practices are needed for environmental protection from emissions resulting from BEV fires and suppression.

VEHICLE WEIGHT

VW-1

Subsidies and tax credits should encourage consumers to purchase smaller and lighter BEVs. Fleet purchases should also consider vehicle weights.

VW-2

Establishment of widespread fast charging stations can alleviate range anxiety and encourage purchase of smaller vehicles.

OTHER

O-1

Driver education programs should be modified to include training on BEV characteristics.

O-2

Requirements for effective partial automation systems on all vehicles, such as the proposed rulemaking for active forward collision avoidance, should continue to be pursued.

Acknowledgements

The contents of this policy brief reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. Financial support from Federal Grant Numbers: 69A3552344811 and 69A3552348316 Safety21 from the U.S. Department of Transportation's University Transportation Centers Program, the Scott Institute for Energy Innovation and Metro21: Smart Cities Institute is gratefully acknowledged.

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Carnegie Mellon University | POLICY INSIGHTS

Improving EV fire safety

There are more than 5 million electric vehicles on America's roads, but emergency responders have little to no training on how to safely respond to Battery Electric Vehicles (EV) crashes and fires.

EV fires have unique characteristics. Without proper training and tracking of EV fires, emergency workers will face potentially life-threatening challenges in responding to EV incidents.

A new policy brief from Carnegie Mellon University outlines steps policymakers can take to improve roadway safety in the age of EVs. The recommendations include:

- Requiring the U.S. Department of Transportation to develop standard EV training for first responders, including the development of test tracks for training.
- Improved National Traffic Safety Board investigation of the causes of EV fires to develop standards improvements.
- Improvements in advanced thermal management systems, flame-retardant materials, and active suppression technologies in mitigating EV fire risks.

Fighting EV fires requires special consideration beyond traditional training. For example, suppressing EV fires often takes more water or foam retardant than conventional vehicles.

- First responders may need to manually cut off battery power to stop a blaze.
- And EV fires can release toxic gases from their batteries. The emergency response should include proper protections for emergency workers and environmental clean up afterward that accounts for hazardous materials in run-off.

Carnegie Mellon's Karen Lightman and Chris Hendrickson can speak to the importance of EV first responder training to improve safety on America's roads.

- Karen Lightman, executive director of Safety21- US DOT National University Transportation Center for Safety, karenlightman@cmu.edu
- Chris Hendrickson, director of Traffic 21 Institute, cth@cmu.edu

World Electric Vehicle Journal

IMPACT FACTOR 2.6

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Review

Battery Electric Vehicle Safety Issues and Policy: A Review

Sanjeev M. Naiek, Sorawich Aungsuthar, Corey Harper and Chris Hendrickson

MDPI

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World Electric Vehicle Journal

Review

Battery Electric Vehicle Safety Issues and Policy: A Review

Sanjeev M. Naiek , Sorawich Aungsuthar , Corey Harper and Chris Hendrickson *

Department of Civil and Environmental Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA; snaiek@andrew.cmu.edu (S.M.N.); saungsut@andrew.cmu.edu (S.A.); cdharper@andrew.cmu.edu (C.H.)
* Correspondence: cth@cmu.edu

Abstract

Battery electric vehicles (BEVs) are seeing widespread adoption globally due to technological improvements, lower manufacturing costs, and supportive policies aimed at reducing greenhouse gas emissions. Governments have introduced incentives such as purchase subsidies and investments in charging infrastructure, while automakers continue to broaden their electric vehicle portfolios. Although BEVs show high overall safety performance comparable to internal combustion engine vehicles (ICEVs), they also raise distinct safety challenges that merit policy attention. This review synthesizes the current literature on safety concerns associated with BEVs, with particular attention to fire risks, vehicle weight, low-speed noise levels, and unique driving characteristics. Fire safety remains a significant issue, as lithium-ion battery fires, although less frequent than those in ICEVs, tend to be more severe and difficult to manage. Strategies such as improved thermal management, fire enclosures, and standardized response protocols are essential. BEVs are typically heavier than ICEVs, affecting crash outcomes and braking performance. These risks are especially important for interactions with pedestrians and smaller vehicles. Quiet operation at low speeds can also reduce pedestrian awareness, prompting regulations for vehicle sound alerts. Together, these issues highlight the need for policies that address both emerging safety risks and the evolving nature of BEV technology.

Keywords: battery electric vehicles; roadway safety; fire safety; vehicle weight; driver training; first responder training

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1. Introduction

The market for electric vehicles has seen substantial growth over the past decade, spurred by manufacturing and technology improvements, consumer demand and governmental policies. Governments worldwide are implementing various incentives to promote electric vehicle (EV) adoption, such as tax rebates, subsidies, and the development of extensive charging infrastructure. In addition, many countries have set targets for phasing out internal combustion vehicle (ICEV) sales to combat climate change and reduce dependency on fossil fuels. Major automakers are also investing heavily in EV technology, with plans to release a wide range of electric models across different vehicle segments, from compact cars to luxury SUVs (sport utility vehicles) and commercial trucks [1].

However, a future with widespread adoption of electric vehicles faces several challenges along the way. The high capital cost of EVs, although decreasing, remains a barrier for many consumers. The development of a comprehensive and reliable charging infrastructure is critical to address range anxiety. Additionally, factors such as the perceived driving range of EVs and the limited variety of available models continue to hinder customer adoption [2]. While the tailpipe emissions of EVs are zero, the environmental impact of battery production and disposal, as well as the sourcing of raw materials like lithium and cobalt, poses many sustainability concerns.

BEVs also present several safety concerns that need attention. Fire safety is a major issue, particularly with the risks associated with lithium-ion batteries, as evidenced by several high-profile EV fire cases. Noise emissions from EVs are significantly reduced compared to ICEVs, raising pedestrian safety concerns due to their quieter operation. The increased weight of EVs, due to their batteries, affects road infrastructure and vehicle dynamics, potentially influencing crash outcomes. Moreover, the distinct driving characteristics of EVs, such as rapid acceleration, deceleration, and different handling dynamics, require drivers to adapt. Lastly, while EVs have unique safety features, continuing analysis of crash frequency and severity compared to ICEVs is needed.

Despite these challenges, the continued innovation in EV technology and supportive regulatory frameworks suggest EVs will be a major part of the future transportation ecosystem. Safety will continue to be a major concern no matter what the vehicle fleet includes. This review focuses on four key safety concerns associated with battery electric vehicles: fire risk, vehicle weight, quiet operation at low speeds, and distinct driving characteristics. It draws on the current technical literature, real-world case studies, and recent developments to evaluate safety implications and propose relevant policy recommendations. Recent publications from 2023 to 2025 reflect significant advances in fire response strategies, including multi-sensor thermal runaway detection, chemistry-specific suppression techniques, and updated protocols for first responders.

While we focus on BEV safety concerns, we should note that the safety performance of BEVs is comparable to conventional vehicles. According to the HDLI, EVs have consistently shown lower claim frequencies and overall losses in collision and property damage liability coverages compared to their conventional counterparts over the years [3]. EVs show lower claim frequencies across all categories of injury coverage, including Bodily Injury (BI), Personal Injury Protection (PIP), and Medical Payments (MedPay), when compared to conventional vehicles [3]. However less frequent, the severity of the claim for BEVs is higher. Although claim severity trends are decreasing over time [3], these special characteristics of BEVs suggest the need for targeted safety policies for BEVs.

2. Methodology

This paper is a literature review that draws from academic and technical sources relevant to the safety concerns of battery electric vehicles (BEVs). The primary databases used were Google Scholar and ScienceDirect, which were selected for their broad access to peer-reviewed engineering, transportation, and safety literature. A sample of keyword phrases used in the search includes "BEV safety", "electric vehicle fire risk", "thermal runaway", "EV accident statistics", "EV pedestrian safety", and "braking performance of electric vehicles". Boolean operators (e.g., AND, OR) were employed to refine queries and maximize the relevance of retrieved articles.

Efforts were made to prioritize recent publications, especially from the past ten years, though foundational older studies were also included when necessary to provide context on technical mechanisms such as thermal runaway or battery design. Initial inclusion of literature was based on availability, followed by manual screening for topical relevance and quality of information. Peer-reviewed journal articles were prioritized, but high-quality gray literature, including NTSB and NHTSA reports, was incorporated where peer-reviewed coverage was limited. Zotero was used to manage references and organize articles into thematic categories aligned with the paper's structure: fire safety, vehicle weight and crash dynamics, quiet operation, and unique driving characteristics.

3. Fire Safety

3.1. Introduction

While ICEVs have long been associated with fire incidents, the increase in EVs equipped with lithium-ion battery packs presents new challenges to manufacturers, firefighters, and drivers. EVs demonstrate a notably lower fire incidence compared to ICEVs, with only 25 fires per 100,000 EVs sold as compared to 1530 fires per 100,000 ICEVs sold [4,5]. However, less fire incidence does not necessarily suggest increased safety. Although the incidence of fires in BEVs may be lower; only coupling this low incidence with robust fire suppression procedures ensures comprehensive safety. Despite their rarity, the potential severity of BEV fires necessitates the implementation of effective and well-prepared methods for handling and extinguishing such fires to maintain high safety standards.

EVs, specifically their batteries, do not respond to fire in the same way that ICEVs do, and thus require specialized training. Insights from [6] shed light on the complexities of measuring heat release rates (HRRs) in lithium-ion battery (LiB) fires. These HRRs are essential to understand burn characteristics in fire scenarios. In their review, authors of [7] explore various solutions to prevent and suppress thermal runaway events in LiB cells, exploring passive and active solutions, from insulation to novel materials.

3.2. Risks of Lithium-Ion Batteries

Thermal runaway, a phenomenon triggered by overcharging, physical damage, and manufacturing defects, is a significant concern in lithium-ion batteries (LiBs). In essence, if the rate of heat generation in the battery remains uncontrollably greater than heat dissipation, degradation of the battery or, in severe cases, EV fire can occur [7–11]. Exceeding temperatures of 70–100 °C increases the risk of triggering thermal runaway [12]. The combustion of a LiB involves rapid gas release during thermal runaway, which occurs more quickly compared to the gradual combustion process in ICEVs. However, ICEVs reach their absolute peak heat release rate (HRR) faster due to the sudden release of a large amount of chemical energy when the fuel tank ruptures, as observed in the fire test [10]. Further, the quantity of heavy metals found within the combustion gasses was found to be higher in EVs, owing to the combustion of battery metals [10].

How a battery goes into thermal runaway and how the fire spreads depend on many factors. Apart from the battery chemistry, there are factors such as how the cells are arranged, how the thermal management system works, and whether safety features like emergency cooling or sensors are in place. These parts all interact and make battery fires more complicated to understand and manage [13].

Thermal runaway behavior and corresponding response strategies can vary significantly across lithium-ion battery chemistries. Recent studies have shown that NMC (nickel–manganese–cobalt) batteries, while offering higher energy density, tend to release greater quantities of ultrafine particulate matter and toxic metals such as nickel and cobalt during thermal runaway events compared to LFP (lithium iron phosphate) batteries [14,15].

One recent study [14] found that emissions from NMC cells induced more oxidative stress and DNA damage in human airway epithelial cells than those from LFP, demonstrating greater health risks for first responders and nearby individuals. Another study [15] conducted standardized abuse tests showing that NMC cells reached higher maximum temperatures (505–548 °C vs. 278–286 °C for LFP) and generated longer jet flames, necessitating more aggressive fire suppression measures such as high-volume cooling and explosion-proof containment.

These findings demonstrate the importance of tailoring fire safety measures, such as enclosures, insulation, and suppression methods, to the specific chemistry of the battery system in use.

Further complicating the matter, oxygen calorimetry, the most common type of calorimetry used to measure HRR, has numerous issues that lead to underestimation, due to self-generated oxygen and combustible gas release from LiBs. One study found that on the cell level, "peak HRR was underestimated by up to 100%" [6]. Studies conducted by EV manufacturers are not publicly available, but likely provide further insight.

In a recent study investigating the fire safety of EVs, researchers conducted a series of full-scale fire experiments to better understand the thermal behaviors [16]. Utilizing an EV model equipped with a capacity of 64 kWh, researchers conducted analysis by testing components such as the LiB pack body after disassembly. Both [16] and [17] found that the materials in the passenger compartment were the most important variable in peak HRR, not LiB composition. Findings revealed that during testing, EV fires exhibited a combustion duration of approximately 70 min. Most notably, "jet fires" emanating from the LiB pack were observed to increase overall fire spread [16]. Jet fires were observed to reach 2.56 m high [17]. Actively managing these risks is vital.

3.3. Case Studies of EV Fires

The National Transportation Safety Bureau (NTSB) conducts public investigations of all certain BEV fires. In a report covering BEV risks to first responders, they include specific incidents across a range of operating conditions [18]. Each incident's investigation is accompanied by a set of actions taken by the first responders and post-fire analysis.

Lake Forest, California, August 2017: A Tesla Model X BEV traveling over 80 mph collided with a parked vehicle in an open garage, resulting in a severe fire. First responders arrived at the scene and quickly extinguished the first fire. However, the vehicle emitted "heavy white smoke" within an hour of extinguishment, and reignition occurred in a "blowtorch manner". Water at a rate of 200 gallons per minute did not sufficiently cool the battery to extinguish the flames. Only after the vehicle was propped up, exposing the battery, was the fire extinguished. The secondary extinguishment required constant application of water at 600 gallons per minute. The final report noted over 20,000 gallons of water were used to combat the fires. The post-fire analysis revealed that the battery cells underwent thermal runaway due to the collision impact, intensifying the fire [18].

Mountain View, California, March 2018: A Tesla Model X BEV, traveling at 71 mph, struck a damaged, nonoperational impact attenuator at the end of a concrete barrier. The vehicle collided with two other cars and caught fire, resulting in the driver's death. Firefighters extinguished the vehicle fire quickly using about 200 gallons of water and foam. Engineers from the BEV's manufacturer were on the site and coordinating with firefighting efforts. Despite initial extinguishing, the battery reignited five days later during transport, requiring an additional 700 gallons of water and foam. In post-fire analysis, the BEV's battery still was capable of delivering dangerous voltage and current, but engineers found little success establishing a computer connection with the BMS for further testing [18].

Fort Lauderdale, Florida, May 2018: A Tesla Model S BEV traveling at 116 mph, veering off a residential road, hit a wall beside a driveway, igniting the LiB, allowing electrical arcing from the exposed LiB. Firefighters used 300 gallons of water and foam to initially extinguish the fire, using Tesla manufacturer fire response guides. During cleanup, the battery reignited twice and was extinguished both times. Once the vehicle is towed, guidelines suggest BEVs be separated from others in the tow yard. When the vehicle was in the tow yard, the battery exhibited signs of smoking and heat, but did not reignite. A later inspection revealed severe crash and fire damage to the LiB enclosure, from melted holes to deformation in the protective casing. Voltage measurements confirmed that "stranded energy" remained persistent in the LiB over a month later [18].

West Hollywood, California, June 2018: A Tesla Model S BEV traveling on an urban road began emitting smoke and burning without any crash or physical abuse. Firefighters extinguished the fire using 300 gallons of water and foam. Despite the initial extinguishment, the vehicle continued to emit smoke, requiring firefighters to remove parts of the vehicle and apply additional water and foam under the hood and behind the wheels. The fire captain, trained in electric vehicles, noted that the vehicle's computer screen remained on after the high-voltage cut loop was severed, due to the 12-volt battery remaining powered. Post-incident inspection revealed that a module in the LiB experienced thermal runaway, causing off-gassing that was improperly vented, leading to a larger fire [18].

Florida, October 2020: A 2019 Chevrolet Bolt BEV was parked and charging in the owner's garage overnight. The homeowner awoke to an explosion, accompanied by a fire. An investigation by the NHTSA, with General Motors (GM) representatives and experts, determined that the fire originated in the battery compartment of the vehicle. The investigation revealed heat and fire damage on the garage floor directly under the vehicle's second-row left-side seat, indicating the battery source of the fire. The initial explosion was due to the release of battery cell pressure, with a domino effect of fires as battery cells came into contact with heat [19].

The investigation and analysis by the NHTSA and NTSB reveal certain patterns of insight into the challenges and protocols for managing similar safety issues. The intensity and complex behavior of BEV fires is a recurring theme.

BEV fires are often driven by thermal runaway within the LiBs, leading to fires that reignite multiple times as new cells are heated up beyond their thermal threshold. Incidents in Lake Forest and Mountain View highlight the difficulty in fully cooling the battery, which results in flare-ups of smoke, heat, or fires, many days after the initial extinguishment. These cases also demonstrate the substantial water volumes needed to control BEV fires. The Lake Forest incident required over 20,000 gallons of water, proving the resource-intensive nature of BEV firefighting compared to traditional ICEVs.

After extinguishment, BEV batteries seem to retain "stranded energy", posing risks of electrical arcing, reignition, and electrocution without proper precaution. This phenomenon was observed in the Fort Lauderdale incident, where the battery arcing caused difficulty in initial extinguishment.

Access to manufacturer-specific firefighting guidelines seemingly significantly improves the effectiveness of fire response. In Mountain View, Fort Lauderdale, and West Hollywood, BEV fire training or BEV manufacturer fire guides were followed. In these examples, when first responders had sufficient resources, the incidents were managed more effectively with less water usage and better control over the situation.

3.4. Mitigation Strategies and Technologies

Advanced thermal management systems and structural enhancements are important in preventing EV fires. The use of flame-retardant materials in mitigating fire risks associated with EV battery packs, combined with active suppression and extinguishing, can prevent fire hazards [7,20,21]. Investigations studied the effectiveness of measures such as cooling mechanisms, incorporating flame-retardant coatings, or materials inside battery packs to withstand combustion and limit the spread of fires in the event of an incident.

Research in this area has identified optimal application methods and extinguishing agent quantities necessary to effectively combat fires within BEV LiBs. Studies make clear the importance of proximity between flame-retardant materials and battery cells to maximize their effectiveness in containing fires and preventing thermal runaway propagation [21]. There is a threshold found, of both time, quantity, and proximity, of suppressant needed for LiB fire prevention and subsequent reignition. However, the specific requirements are unknown. Further study is needed to determine the thresholds for different substances to ensure firefighters have sufficient information to fight fires effectively.

The existing literature studies ideas beyond direct application. The usage of an Electric Vehicle Fire Enclosure (EVFE) showed water-based fire-extinguishing systems effectively capping temperatures at 50 °C, a limit low enough to prevent re-ignition and thermal runaway within cells. Water usage was effective and efficient at 0.628 m^3/kWh to extinguish EVs on fire [22,23]. Foam within an EVFE similarly cooled BEV LiBs, although they require further study into the numerous foam variables that can affect flame retardancy [23].

Innovations in Battery Management Systems (BMSs) are the driver behind active temperature regulation and fire protection within BEV LiBs [24]. Modern BMS technologies monitor, detect, and respond to potential fire hazards by employing sophisticated algorithms and sensor networks. Using sensor fusion of electrical information and temperature sensors within cells, they develop more robust safety monitoring systems. These systems continuously assess battery health, pre-emptively addressing conditions conducive to thermal runaway events, enhancing the overall safety and reliability of BEVs. Used in conjunction with active fire suppression systems within the car, they could lead to significantly safer BEVs.

3.5. First Responder Preparedness

First responders encounter difficulties when tackling large LiB fires in electric vehicles, as evidenced by NTSB investigations. Some literature reveals gaps in first responders' preparedness for EV-related incidents, with over 40% lacking specific EV safety training [9].

The high voltages present at the scene pose serious danger to emergency responders. The action of finding a high voltage disconnect after an EV has crashed can often be dangerous. With BEVs making the transition to 800 Volt systems for better charging speed and more power, LiBs are only likely to become more dangerous to responders without proper training [25].

In incidents examined, the quantity of water used varied significantly, ranging from 300 to over 20,000 gallons. In extreme cases, elevation of the vehicle for direct water application to the battery underside is the only way to achieve fire suppression. Despite manufacturers' advisories regarding needing great quantities of water, emergency response guides are lacking, hindering effective firefighting efforts [18]. Firefighters in several instances resorted to online searches for guidance, resulting in delays. Some manufacturers, such as Renault in France, have collaborated with emergency services to design inlet ports and voltage shutoff switches, streamlining firefighting procedures significantly [18].

Interagency collaborations have resulted in structured EV fire response training programs. For instance, the National Fire Protection Association (NFPA), in collaboration with the U.S. Department of Energy, has developed a standardized and modular curriculum designed to equip firefighters, emergency medical services, and law enforcement personnel with the skills necessary to respond effectively to high-voltage vehicle incidents. Similarly, the National Highway Traffic Safety Administration (NHTSA) has released coordinated guidance to support first responders in managing EV crashes and battery fires. In addition to public efforts, industry actors such as General Motors have developed online training modules tailored specifically for EV incidents, further supporting preparedness among first responders [26].

The gasses released via the burning of LiBs are dangerous to humans in the vicinity of the flames [27]. Therefore, ensuring sufficient detection and protection for first responders is imperative. Studying higher-ranged gas detectors or better protective masks may be a fruitful line of future research.

Building on these prior approaches, recent studies from 2023 to 2025 provide deeper insight into chemistry-specific fire behavior and suppression strategies.

The Washington State Patrol's 2025 study [28], commissioned under SSB 5812, details persistent challenges for first responders, such as re-ignition, toxic gas exposure, and thermal persistence. Based on real-world experience with EV fires, it recommends standardized response checklists, decontamination procedures, and consistent use of SCBAs (Self-Contained Breathing Apparatus) and particulate hoods to address these risks effectively.

A multi-layered approach to lithium-ion battery fire protection is proposed in [29], integrating diverse sensing inputs and various state-of-the-art sensing methods. Ensuring inputs such as temperature, voltage, and gas concentration are collected with precision using new fiber-optic or ultrasonic methods can allow data to be fed into intelligent detection frameworks designed to trigger early intervention and containment actions. Chemistry-specific suppression strategies are outlined in [30], including phase-change thermal barriers, flame-retardant additives, dedicated containment structures, and gas-detection systems targeting CO and H_2 for early thermal runaway warnings. System-level fire scenario classifications and general mitigation strategies are addressed in [20], with an emphasis on tailoring responses to specific battery configurations and enclosure behaviors. Together, these works represent the current state of the art in BEV fire safety and demonstrate the need for coordinated, sensor-informed, and chemistry-aware responder protocols.

3.6. Environmental Impact

The environmental impact of water used for extinguishing fire in large-scale battery fires is a significant concern [31]. PFASs were detected in concentrations up to 1400 ng per liter, with flushing of the battery increasing this concentration to 4700 ng per liter. Furthermore, water used for fire suppression of EV LiBs were shown to include higher concentrations of heavy toxic metals as compared with ICEVs.

Regarding the contamination of infrastructure, thermal runaway and fire of LiBs present significant risks [32]. Burning a LiB in an enclosed parking space can allow heavy metal soot to travel far distances. While the soot was found to be electrically non-conductive or corrosive, it still necessitated decontamination. Additionally, the soot contaminated the water to a degree beyond allowed sewage discharge values, due to the heavy metals and lithium burnt. As such, water needs to be carefully monitored to address both environmental and health hazards posed by LiB fires [32]. Oversight that addresses not only battery safety but also secondary contamination from firefighting efforts is an important step to address.

3.7. Regulatory Standards and Best Firefighting Practices

Relevant literature exists that reviews regulatory standards on the broader scale of LiBs, and summarizes the current state of regulation. Such standards play a central role in mitigating the complex risks discussed above, including environmental, thermal, and chemical hazards. International LiB safety standards fall under the auspices of the "International Electrotechnical Commission (IEC), the International Organisation for Standardisation (ISO), Underwriters Laboratories (UL), United Nations (UN) standard, the Society of Automotive Engineers International (SAE), the Institute of Electrical and Electronics Engineers (IEEE)" [33]. The European Union, Japan, Britain, the People's Republic of China, and the United States (FMVSS) each also have internal standards bodies. Numerous regulations cover the transportation, storage, and chemical stability of LiBs, successful to the point that "Industry experts estimate that between one in 10 million–40 million cells fail during normal operation, if proper quality control is in place" [27]. These include requirements from sealing specifications of electrolytes, to Battery Management System redundancies, to numerous performance specifications.

There are also safety tests that are required to be performed on LiBs to certify them as BEV-grade, or "intended for propulsion." These tests mainly cover abuse ranging from "overcharge, force discharge, short-circuit, nail penetration, crushing, vibration, heating, and fire testing" [33]. For each of these tests, each regulatory body has different definitions for their chosen test methods to achieve their standard. Therefore, BEV LiBs built and approved in one market must go through rigorous testing to expand their market domain and export capabilities. An example of the differing standards can be seen in the gas accumulation tests [27]. When aflame, LiBs can release flammable gasses ranging from methane, ethane, hydrogen, to carbon monoxide. Accumulating gasses cause overpressure in cells or pouches, which can explosively burst and lead to unsafe conditions. Standards that ensure these gasses are not accumulated are pervasive and exist in every market. UL 2580:2013 emphasizes preventing the accumulation of flammable gasses by requiring testing methods with gas monitors. Even still, other standards covering the same issue, such as UN/ECE-R100.02:2013, do not specify evaluation methods for this property [27].

Future developments in standardization and regulation should consider harmonizing testing protocols to ensure consistent and thorough evaluation of automotive battery chemical hazards.

The NTSB also has reports published on the scale of standards and voluntary industry action in the realm of suggested procedures post-crash or post-fire. While vehicle manufacturers are required to ensure that high-voltage sources can be readily disabled via automatic shutoff systems, nearly all also incorporate "cut loops." Cut loops are low-voltage, easily accessible wires that, when severed by first responders, can disconnect the high-voltage systems in the car, ensuring safer working conditions [18]. Similarly, SAE requires the usage of the ISO 17840 standard for vehicle manufacturers to create guidelines for first responders to aid their rapid response to vehicular fires [18].

The NTSB compliance tested 28 BEV first responder guides, against The National Fire Protection Association's (NFPA)'s emergency response protocols, ISO standards, and FMVSS standards. However, adherence to the recommended ISO 17840 format was lacking across all guides reviewed. Specific instructions for combating high-voltage battery fires were scarce, with only two manufacturers providing such guidance. Moreover, six guides omit crucial details about battery characteristics, including peak voltage [18].

The regulatory landscape for lithium-ion batteries (LiBs) in battery electric vehicles (BEVs) is robust but fragmented across international standards bodies and national regulations. Variations in testing methods and safety protocols are challenges in ensuring consistent evaluation and certification of BEV LiBs worldwide. Furthermore, discrepancies in emergency response guidelines among manufacturers demonstrate a real need for standardized procedures to enhance safety for first responders dealing with high-voltage battery incidents that are likely to occur if BEVs catch fire. Harmonizing these standards and ensuring stricter adherence to protocols will be crucial to the future of BEV technologies on a global scale.

4. Safety Concerns for BEV Size and Weight

Within the landscape of road safety, a range of factors contribute to accidents and injuries on the roads. According to GJEL Accident Attorneys, the top causes of car crashes in the US include distracted driving, speeding, driving under the influence of drugs or alcohol, and reckless driving behavior, among others [25]. The leading cause of distraction is drivers daydreaming or external stimulators such as texting, calling, or using infotainment equipment. Speeding is another critical factor, accounting for 29% of motor crash fatalities as reported by the IIHS in 2022 [34]. Additionally, 32% of all traffic fatalities are caused by alcohol-impaired driving [35].

While these issues dominate road safety concerns, an additional concern is the weight of vehicles. Although it may seem less immediate, the increasing weight of vehicles, especially due to the growing popularity of larger vehicles such as SUVs and how the car overall is designed to be bigger and heavier [36], can pose additional risks. Because of the significant weight of the batteries, EVs are generally heavier than ICE vehicles. This additional weight causes many safety issues for drivers and pedestrians, particularly regarding stopping distances and crash dynamics [37,38].

EVs typically weigh about 30% more than traditional ICE [38]. This substantial increase in weight is mainly from the battery systems that power EVs. The median weight of EVs stands at approximately 2145 kg, with the mean weight slightly lower at 2133 kg [36]. This is significantly higher compared to the average weight of ICE vehicles, which ranges from about 1500 kg in the UK to 1800 kg in the US, with the US being the region with the heaviest cars [37]. Moreover, Ritchie notes that the distribution of electric car weights is notably skewed towards the heavier side with only 7% of EV models weighing less than the average car in the UK. This highlights a distinct characteristic of greater vehicle mass in the EV sector [37].

The additional weight of EVs affects their stopping distances. Heavier vehicles require more time and distance to come to a stop, which can be concerning in emergency braking situations and impact braking efficiency [39,40]. Under identical conditions of reaction time, energy, heat, and friction, and at the same velocity, an EV, which is on average 30% heavier than an ICE vehicle, typically requires an additional 30% in braking power to stop at the same distance [41]. This extra effort on stopping distance and braking systems poses risks not only to the vehicle occupants but also to others on the road. If the braking power in the vehicle does not compensate for this extra effort, the longer stopping distances required by heavier EVs could lead to an increase in accidents involving pedestrians and cyclists, particularly in urban settings where these incidents have been rising in recent years [42].

The dynamics of crashes involving heavier vehicles can lead to more severe consequences, especially when these vehicles collide with lighter ones. The mass ratio theory, which explains that the heavier vehicle imposes more force upon the lighter vehicle during a collision, concluded that this increases the severity of impact. From the fatality risk equation calculated with mass ratio $R = (M_2/M_1)^{3.73}$ as concluded by Evans and Frick in 1993 for a frontal crash, and assuming only the weight difference where M_2 is the mass of the heavier vehicle and M_1 is the mass of the lighter vehicle, we can calculate that if an EV is on average 30% heavier than an ICE vehicle, the driver fatality risk in the lighter car is 2.67 times what it is in the heavier car. This calculation underscores that while heavier cars may provide more protection for their own occupants, they simultaneously increase the risk for those in lighter vehicles that engage in the crash [43–46]. This relationship is relative and highlights the incompatibility of mass effects in road accidents.

Apart from affecting the occupants of lighter vehicles, the increased mass can also compromise the safety of pedestrians and bicyclists. While the weight differential between any type of passenger vehicle and a pedestrian or bicyclist is already substantial, the additional weight of an EV battery, although it may make little difference, does exacerbate the severity of any crash involving these road users [42].

5. Safety Concerns Due to Quiet Operation

EVs lack a combustion engine and the associated processes that produce driving power by burning fuel, creating mechanical movements in parts, and the sounds of the exhaust.

Consequently, EVs are generally quieter than ICE vehicles. Although this might seem like a positive feature, as engineers have been trying to reduce the noise of combustion engine cars, this lack of sound can reduce the alertness of other road users, particularly pedestrians, and may pose safety issues. A simulation study has found that EVs have a 25% higher likelihood of near-crash incidents involving pedestrians compared to ICEVs [47]. Similarly to pedestrians, cyclists face increased risks of crashes at low speeds and experience greater difficulty detecting acoustic cues, as they travel at higher speeds and encounter aerodynamic noise [48].

Although when moving at speeds above 12 miles per hour, noise generated from tyres and the road starts to be comparable to combustion engine vehicles [49]; at lower speeds, the absence of a combustion engine means that they operate in a nearly silent condition. A study on risk situations related to the quietness of EVs [50] was carried out in working situations. These risky scenarios have the potential to occur in areas with slow-moving traffic, especially during pedestrian crossings or in areas with mixed traffic use. While the study highlights that the perceived danger from EVs' reduced noise is not alarming, participants expressed concerns about the likelihood of accidents due to the difficulty in detecting these vehicles approaching by hearing.

To mitigate and lower the risks associated with these issues, regulatory and design considerations have been implemented. EVs operating at speeds between 0 and 30 mph are required to produce sounds ranging from 47 to 67 dB for the preferred alternative [51]. Automakers are utilizing acoustic vehicle alert systems (AVASs) to comply with this requirement. The AVAS system emits exterior sounds that substitute the detectable sounds of ICE vehicles to alert both cars and pedestrians [49]. Common regulatory frameworks, such as the United Nations Regulation No. 138 and the Federal Motor Vehicle Safety Standards No. 141, are in place across different regions globally. These regulations not only set rules on the volume or sound pressure but also require that this volume should increase with the vehicle's speed. Additionally, the pitch of the sounds must dynamically change to a higher pitch as speed increases to convey the vehicle's speed through sound. The AVAS system frequency must also be designed to ensure that the sound meets the minimum volume requirements in any environment, regardless of the volume level [52,53].

However, there is evidence suggesting that AVAS can improve pedestrian and cyclist detection and help prevent incidents, but its effectiveness depends heavily on the design of the sound alert. The performance of AVAS is highly context-dependent and varies with factors such as sound type and ambient noise levels [54]. Additionally, some studies [55] have raised concerns about the potential annoyance caused by AVAS sounds, which may impact public acceptance and urban noise levels.

6. Safety Concerns Due to Special Driving Characteristics

The mechanical characteristics of how EVs operate, from their electric power storage to driving power, are unique and rival the accustomed driving behaviors that drivers have been used to with traditional combustion engines. These characteristics lead to alterations in driving behavior and therefore raise safety concerns. This review explores how the distinct features of EVs, such as instant torque comparable to sports cars and regenerative braking, influence driving behavior and raise concerns in road safety.

Electric motors can deliver maximum torque from zero RPM, allowing EVs to accelerate more rapidly than ICEVs. This instant torque leads to a noticeably different acceleration rate right from a dead stop, making EVs feel quicker and more responsive during initial acceleration [41,56]. For example, the Tesla Model 3 is reported to reach 60 mph from a complete stop in just 2.9 s with rollout subtracted [57], comparable to top performance sports cars like the McLaren 2021 Speedtail [58]. However, despite their faster acceleration at lower speeds, EVs often experience a reduction in torque at higher speeds, which results in lower top speeds compared to their traditional ICEs [41].

Another feature that distinguishes the driving experience of EVs is regenerative braking. This system allows the electric motor to slow the vehicle when the driver steps off the accelerator pedal, simultaneously recharging the battery. Regenerative braking functions by reversing the electric motor's direction, transforming it into a generator that harnesses the kinetic energy of the moving car to recharge the battery. This mechanism leads to one-pedal driving characteristics, where lifting off the accelerator can bring the car to a complete stop [41].

While this system enhances energy efficiency and reduces wear on traditional braking components [56], it can be initially challenging for drivers. Adapting to the features of regenerative braking and one-pedal driving takes time, which might pose safety concerns as drivers become accustomed to the new dynamics.

The debate on whether the power capabilities of EVs enhance safety or raise concerns remains ongoing. On one side of the argument, the rapid acceleration capabilities of EVs enhance safety as the quick acceleration allows drivers to overtake more safely by minimizing the time spent in the opposing lane. This rapid acceleration is advantageous for lane changes and overtaking on two-lane roads, presenting a valuable safety measure [59]. On the other hand, safety concerns are associated with the instant torque of EVs, especially in urban environments. Urban area safety has been emphasized due to incentives for EV users, such as free parking, and the driving characteristics of EVs, which are primarily used for commuting [60]. The immediate power response from a slight tap on the accelerator can reduce the margin for error previously available on traditional ICEs, potentially leading to accidents. Pedal application errors, which contribute to up to 16,000 crashes annually involving drivers of all ages, can become even more hazardous in EVs. The immediate response can result in severe risks to road safety and endanger pedestrians [61].

Although direct studies on this topic are scarce, insights from a 2016 study by the Insurance Institute for Highway Safety (IIHS) provide some context. The study found that for every additional 3 units of horsepower per 100 pounds of vehicle weight, there was a 38 percent higher chance of the vehicle surpassing the speed limit by over 10 mph, as well as a 2.2 percent rise in the mean vehicle speed [62]. This implies that drivers of high-powered vehicles, like EVs, are more likely to significantly exceed speed limits, correlating with higher crash rates.

Although studies in this area remain limited, evidence suggests that over time, drivers adjust to the unique dynamics of EVs. There are observations that initial strong acceleration and deceleration in EVs tend to become milder over the course of adaptation learning [63,64]. After about five months, drivers exhibit calmer driving behaviors and maintain these even after the initial period of aggressive acceleration and deceleration [64]. This adjustment confirms that driving an EV does not affect the average speed which is driven as generally drivers maintain their driving style on these characteristics [64]. This adjustment is partly due to features like regenerative braking, which is widely accepted by users and leads to optimized driving behavior, significantly enhancing driving efficiency. Moreover, this suggests that while EVs initially present a learning curve that might pose safety concerns, the adaptation process typically leads to safer and more efficient driving patterns.

7. Conclusions and Policy Suggestions

Safety concerns for quiet operation and fire safety have already been addressed by regulation and design changes as discussed above. However, additional attention is suggested for fire safety and vehicle weight.

7.1. Fire Safety

Fire safety in the context of electric vehicles (EVs) is a critical concern due to the unique risks posed by lithium-ion batteries (LiBs). Though there are developments in safer battery chemistries, such as sodium-ion batteries that can be stored at 0 Volts, they have lower energy densities and worse peak performance than LiBs [65].

Unlike traditional ICEVs, EVs require specialized training for manufacturers, firefighters, and drivers to effectively manage fire incidents due to the unique risks associated with LiBs. Thermal runaway in LiBs, often triggered by overcharging or physical damage, can lead to rapid gas release and toxic emissions, posing significant challenges for firefighting operations. Although EVs statistically demonstrate a lower fire incidence compared to ICEVs [10], their fires involve distinct hazards that necessitate tailored safety protocols.

Studies emphasize the importance of advanced thermal management systems, flame-retardant materials, and active suppression technologies in mitigating EV fire risks. Innovations such as Electric Vehicle Fire Enclosures (EVFEs) and Battery Management Systems (BMSs) play crucial roles in containing fires and enhancing overall vehicle safety. However, first responders face challenges in handling large LiB fires, with gaps in training and varying water usage during firefighting efforts.

Environmental concerns also arise from the use of fire-extinguishing water, which can contain toxic substances such as PFAS and heavy metals from burnt batteries.

7.2. Policy Recommendations for Fire Safety

To address the challenges identified in this review and to ensure occupant safety while mitigating potential environmental hazards, the following policy recommendations are proposed:

- FS-1: Establish continued monitoring of BEV fire incidents by the U.S. Department of Transportation (USDOT) and private entities. Reporting should include vehicle types to ensure the data can be useful in further analysis specifying incidents.
  FS-1 Note: Standardized electronic reporting protocols for fire departments and insurers should include structured fields for battery chemistry, fire behavior, and environmental conditions. These efforts could be supported by public–private data exchanges that use telematics and BMS diagnostics to passively or actively transmit real-time fault and thermal data from fleet and municipal EVs, enabling scalable, low-burden nationwide monitoring.
- FS-2: Conduct comprehensive investigations of BEV fire causes by the National Transportation Safety Board (NTSB), with subsequent recommendations for improving safety standards.
- FS-3: Encourage manufacturers to prioritize advancements in thermal management systems, flame-retardant materials, and active suppression technologies. Standard-setting stakeholders should promote the adoption of best practices to bring these technologies to market.
- FS-4: Develop and standardize training programs for BEV technicians and first responders, led by USDOT and the American Association of State Highway and Transportation Officials (AASHTO). These programs should include access to adequate test tracks for hands-on training.
- FS-5: Implement regulatory standards to address the environmental impact of emissions and fire suppression water used during BEV fire incidents, ensuring sustainable practices are identified for implementation.

7.3. Weight and Vehicle Design

To mitigate the risks associated with the increased weight of EVs, several strategies can be adopted, drawing from examples of today's technology that are already in place for EV cars.

Light weighting BEVs reduced the momentum in any collisions and also improves overall efficiency. Improvements in battery performance and vehicle structural optimization are possible approaches. Matching battery size with range requirements for vehicles can also help.

Advancements in driver assistance technologies (ADAS) present a significant opportunity to enhance road safety. Technologies like collision mitigation braking systems, which are now installed in flagship EV models, automatically apply the brakes when a potential collision is detected, thereby reducing the severity of or possibly avoiding the crash. According to the NHTSA (2018), driver assistance technologies not only contribute to the safety of the vehicle's occupants but also protect other drivers and pedestrians. These systems are designed to compensate for human error, a factor that contributed to 94% of motor vehicle accidents [66].

The effectiveness of various ADAS features is well-documented. Systems such as Forward Collision Warning, Lane Departure Warning, and Automatic Emergency Braking significantly reduce the likelihood of accidents. For instance, studies have shown that the implementation of ADAS could reduce accident frequency by 23.8% in the United Kingdom [67]. Additionally, technologies like Adaptive Cruise Control (CACC) and Lane Keeping Assistance (LKA) have been shown to reduce speed variability and lane deviation, respectively, which are associated with safer driving outcomes [68]. These interventions illustrate the critical role of advanced technologies in addressing the new challenges posed by the evolving vehicle landscape, including the increased weight of electric vehicles.

Setting standards for braking efficiency and crashworthiness can help ensure that the increased weight of EVs does not lead to increased road safety risks. Regular updates to vehicle safety regulations to consider the specific challenges posed by EVs' weight are also crucial. As EVs are engineered to be lighter, or as other vehicles increase in weight to match the dynamics and compatibility, it is essential that these regulatory standards evolve to address the changing landscape, ensuring that all vehicles maintain high safety standards and compatible dynamics regardless of their weight.

7.4. Policy Recommendations for Vehicle Weight

To address the challenges identified in this review and to promote safety and efficiency, the following policy recommendations are proposed:

- VW-1: Subsidies and tax credits should be used as incentive tools for consumers to purchase smaller and lighter BEVs. Similarly, fleet purchase decisions should consider vehicle weight.

7.5. General Policy Recommendations

In addition to fire safety and vehicle weight considerations, other potential general policy recommendations address broader concerns and leverage effective strategies evidenced in this review. These policies aim to ensure safer integration of BEVs into the transportation landscape while addressing their unique safety challenges. Apart from technical aspects, the human and social dimension of EV safety plays a vital role in acceptance and adoption of EVs. Understanding public concerns through social perception research and integrating these insights into policy design, along with proactively communicating risks through transparent updates, can help build public confidence in EV safety.

Achieving a broader global reach for these recommendations will require coordinated governance efforts to ensure adoption beyond a few countries, especially in regions with less stringent regulations. International collaboration among governments, industry stakeholders, and standard-setting organizations will be necessary to align and gradually consolidate safety standards and promote equitable implementation.

- O-1: Updates to driver education and training programs should be made to include BEV characteristics.
- O-2: Requirements for minimum effective partial automation systems on all vehicles, such as active forward collision avoidance, should be enforced, ensuring that every BEV is equipped with adequate safety mitigation systems to address their unique safety challenges.
- O-3: Although this review paper and the stakeholders mentioned focus on the U.S., to ensure that these policy recommendations and measures achieve global reach, platforms such as the World Forum for Harmonization of Vehicle Regulations (WP.29) under the United Nations Economic Commission for Europe (UNECE) could come into play. WP.29 brings together governments, industry representatives, and other stakeholders to create and adopt safety regulations on a global scale.
- O-4: Integration of BEV variables into existing transport safety databases and crash reporting systems should be supported, ensuring consistency with broader road safety monitoring frameworks to enable comparative analysis across modes.

8. Future Work

This review has identified several critical safety challenges associated with battery electric vehicles (BEVs) and proposed policy recommendations to mitigate these risks. However, additional research is necessary to address unresolved questions and emerging concerns.

First, while significant progress has been made in understanding and managing lithium-ion battery fires, further investigation into fire suppression methodologies is essential. Specifically, research should focus on optimizing extinguishing techniques to minimize environmental contamination while enhancing efficacy. Comparative analyses of alternative suppression agents, such as inert gases or encapsulating foams, could yield valuable insights into more sustainable and effective fire response strategies.

Second, as BEVs continue to increase in weight due to advancements in battery capacity and range, the implications for vehicle crash dynamics, road infrastructure, and pedestrian safety require deeper examination. Future studies should assess the efficacy of lightweight composite materials and advanced structural designs in mitigating the adverse effects of vehicle mass. Additionally, standardized crash compatibility assessments between BEVs and lighter vehicles should be established to inform future safety regulations.

Finally, the distinct driving characteristics of BEVs, including regenerative braking and instantaneous torque delivery, necessitate longitudinal studies on driver adaptation and behavioral changes. Understanding how drivers adjust over time and what factors facilitate this adjustment will be critical in refining training protocols and regulatory frameworks. Integrating insights from behavioral science with vehicle automation research could further enhance BEV safety and efficiency. In addition, future research could explore policy design gaps and assess the prioritization and feasibility of proposed interventions to support more targeted and implementable safety measures.

Addressing these research gaps will contribute to a more comprehensive safety framework for BEVs, ensuring their continued integration into a sustainable and resilient transportation ecosystem.

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Improving US Roadway Safety and Safety Research

Chris Hendrickson, Ph.D., NAE, Dist.M.ASCE

Hamerschlag University Professor, Dept. of Engineering Emeritus, Carnegie Mellon Univ., 5000 Forbes Ave., Pittsburgh, PA 15213 (corresponding author). ORCID: https://orcid.org/0000-0002-9812-3580. Email: cth@cmu.edu

Laurence R. Rilett, Ph.D., P.E., F.ASCE

Director, Dept. of Civil and Environmental Engineering, Auburn Univ. Transportation Research Institute, 238 Harbert Center, 205 W Magnolia Ave., Auburn, AL 36849; Ginn Distinguished Professor, Dept. of Civil and Environmental Engineering, Auburn Univ., Auburn, AL 36849-5330. ORCID: https://orcid.org/0000-0002-6925-5306. Email: lrr0023@auburn.edu

Kumares Sinha, Ph.D., P.E., NAE, Hon.M.ASCE

Edgar B. and Hedwig M. Olson Distinguished Professor, Lyles School of Civil Engineering, Purdue Univ., West Lafayette, IN 47907. Email: sinha@purdue.edu

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Introduction

Roadway safety continues to be a major problem in the US and worldwide. While US roadway fatalities have declined since 1975 (both in total and per vehicle mile of travel), fatalities have increased since 2010 (Fig. 1). This increase has occurred despite numerous public and private efforts to improve safety. There are many potential causes for the rise in fatalities and serious injuries, including increases in distracted driving, impaired driving, and reckless driving and increasing vehicle sizes and weights. Vulnerable roadway users (including bicyclists and pedestrians) and work zones have had significant increases in the numbers of fatalities and serious injuries. In contrast to the US experience, some other high-income countries have experienced roadway fatality and serious injury rates significantly lower than those in the US (NASEM 2024a). Improving roadway safety is an important challenge to the transportation engineering community.

In this short editorial, we suggest some pathways to improve roadway safety, focusing on actions and research that can lead to contributions to the *ASCE Journal of Transportation Engineering Part A* and subsequently impact practice. The journal editors are always receptive to papers that may have a positive impact on transportation engineering practice (Hendrickson and Rilett 2019).

Safety Culture

Transportation engineering in the early and mid-twentieth century focused upon a variety of technical challenges (Sinha 2021). Roadway investment and standards had to accommodate the rapid growth of motor vehicle use. The motor vehicles themselves had numerous improvements in power, reliability, and driving convenience. Transportation engineers not only focused upon roadway vehicle capacity and congestion but also considered safety. However, in the late twentieth century and now in the twenty-first century, a variety of other concerns such as environmental impacts and safety have become critical (NASEM 2024b). As shown in Fig. 1, this new focus on safety has led to improvements. Nevertheless, our experience since 2010 suggests more research is needed.

Developing a safety culture has been demonstrated in a variety of technical domains as a key element to address safety challenges. Transportation engineers need to focus on safety during their working careers in order to really have an impact on safety. Investment decisions should prioritize safety implications. Drivers need to be trained and continually aware of safety risks. It is not the case that safety can be delegated to a few professionals.

The Safe Streets and Roads for All (SS4A) USDOT grant program and associated Safety Action Plans are a good example of a programmatic approach to encourage a safety culture (USDOT 2024b). Community engagement with public officials, community groups, and citizens is integral to the programs. Planning, construction, maintenance, and operation of transportation infrastructure all can emphasize roadway safety through these programs.

A safety culture has implications for teaching and training in transportation engineering. Old materials that focused upon topics

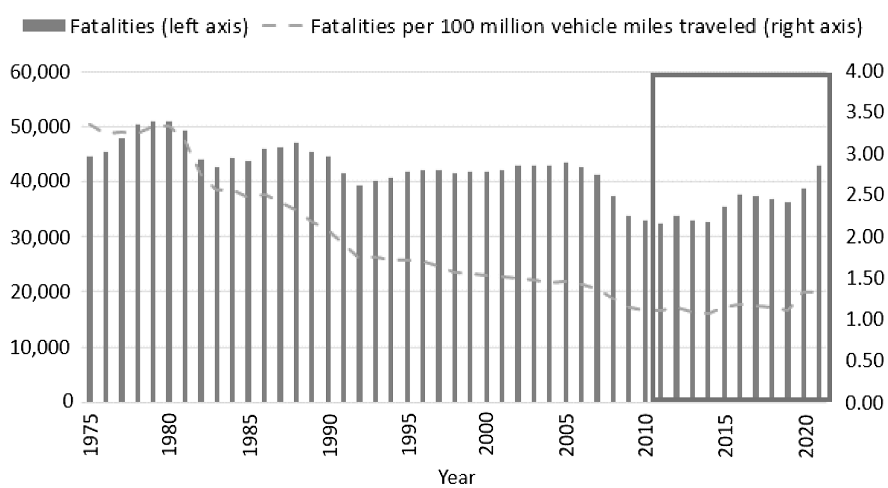

Fig. 1. US roadway fatalities, 1975–2022. (Reprinted from USDOT 2024a.)

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such as traffic flow or geometric design need to be replaced with multimodal approaches (including public transport and active transport), an emphasis on critical issues including safety, and data-driven decision-making.

Several European countries provide examples of embracing a safety culture. Traffic operations and investments are oriented toward safe bicycle and pedestrian movements. Exclusive bike lanes and widespread sidewalks are common. Vehicle movements are restricted in congested areas, speed limits are often lower, and vehicle size and weight are smaller than in the US. Impaired or reckless driving have significant penalties, and enforcement is common. Technology such as speeding cameras is in widespread use. The result is fatality and crash rates well below the US experience.

Role of Emerging Technologies

In 95% of crashes, the human (driver) is a major or contributory factor. Crashes may continue to increase unless the role of driver in driving tasks is eliminated or minimized.

Emerging technologies of connected and autonomous transportation provide a promising solution. In achieving automation, the difficulty arises from the task of controlling human behavior or actions. Humans are subject to risk compensation as we change our driving behavior in response to perceived risk levels. Thus, while fully automated vehicles may remain our long-term goal, various lower levels of autonomy can be achieved to correct or prevent driver mistakes, avoid collisions, aid in case of driver impairments, or apply speed inhibitors. Connectivity pertains to communication and information sharing between vehicles, infrastructures such as work zones, and other entities such as pedestrians and bicyclists, allowing enhanced enforcement of traffic regulations. Connectivity can also help in traffic stabilization and thus reduce recurrent congestion and secondary crashes.

A challenge for transportation researchers is to assess these new technologies. Validation and verification of safety improvements is needed, often with the use of surrogate safety measures rather than waiting for actual crash statistics. Design improvement analysis is also needed. An example of this type of analysis is Zhao and Rilett (2022), and we hope to see similar papers in the journal.

Electric Vehicles and Safety

Battery electric vehicles (BEV) are becoming more common in the global vehicle fleet both for light-duty vehicles and for trucks (International Council of Academies of Engineering and Technological Sciences 2024). Their adoption is motivated both by concern to reduce greenhouse gas emissions causing climate change and the reduction in life cycle vehicle costs for BEV relative to conventional internal combustion engine vehicles (ICEV). BEV have special characteristics that will require changes to transportation practices and more research.

BEV are typically heavier than comparable ICEV, increasing potential impacts on vulnerable roadway users such as bicyclists and pedestrians. As a result, roadside barrier design and stopping distance provisions need upgrading, both due to BEV and the general increase in size and weight for ICEV. Design of braking for heavier BEV is critical, although the regenerative braking of BEV provides help in this regard. Smaller batteries and light weighting can be encouraged by public policies such as ensuring sufficient battery charging infrastructure availability.

BEV also have particular fire hazards compared to ICEV. Thermal runaway may occur in batteries, resulting in reignition occasionally. Exposure to salt water may create short circuits and fires. Emergency respondents need special training to handle BEV fires after crashes, such as means for disconnecting batteries. Improved vehicle and battery designs can reduce fire risks, such as battery management systems with automatic disconnects and fire-resistant coatings.

Research Needs

The 2024 National Academies of Sciences, Engineering, and Medicine (NASEM) study of road safety (NASEM 2024a) recommended a collaborative and transparent process to set research priorities in addition to a rigorous program of safety measure evaluation. Good guidance for safety improvements is certainly needed, and we encourage readers of the *Journal* to consider such thorough evaluations. They can be more valuable than incremental contributions to modeling practice.

New technologies coming into widespread use provide opportunities for research. What is the effect on safety of developments such as automation and connectivity? What are the implications for other surface modes, such as bicycles, scooters, and railways? How should roadway operations and design change to improve safety, or at least not decrease safety, in response to the new technologies? How can infrastructure readiness for connected and automated transportation be measured? What surrogate measures of safety can be used to measure the efficacy of these new technologies? How can new sources of data be best used to avoid or mitigate crashes? Under which roadway/environment conditions should humans take over control from the automated vehicle to protect passenger safety? What is the right balance of human/automation input, and for a given level of autonomy? New research can address these safety-related questions.

Enforcement of traffic regulations is an interesting example of new technology opportunities. These new technologies include in-vehicle sensing and monitoring of driver behavior such as distraction and impairment. Regarding infrastructure, video can be used to sense and monitor speeding, red-light running, and wrong-way driving. The best mix and use of these new technologies with traditional enforcement through police actions presents new research opportunities.

Promotion of a safety culture within the transportation engineering community can be an ongoing responsibility. Again, research can help inform methods to develop and apply a safety culture. We welcome articles on best practices for technology transfer and investments.

Data Availability Statement

Data for Fig. 1 and elsewhere are available from the cited sources. No other data were used in this editorial.

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