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ANALYSIS OF THE SAFETY OF ELECTRIC VEHICLES

ANALIZA BEZPIECZEŃSTWA POJAZDÓW ELEKTRYCZNYCH

Abstract: The rise of electric vehicles (EVs)¹ has ushered in a new era of transportation, bringing with it a host of innovations and challenges. This comprehensive article aims to delve into the intricate landscape of electric vehicle safety, dedicating in-depth analysis to various concerns while spotlighting cutting-edge solutions. Through an exploration of battery safety,² crash standards,³ charging infrastructure,⁴ human factors,⁵ fire safety,⁶ regulations, case studies⁷ and future trends, this article

¹ **Electric Vehicles (EVs):** Refers to vehicles powered by electricity instead of traditional internal combustion engines.

² **Battery Safety:** Pertains to the safety measures and technologies related to lithium-ion batteries used in electric vehicles. This includes thermal management systems and advances in battery safety protocols.

³ **Crash Safety:** Refers to the measures and design considerations to ensure the safety of occupants in the event of a collision involving electric vehicles.

⁴ **Charging Infrastructure:** The network of stations and systems required to charge electric vehicles, including safety measures for these facilities.

⁵ **Human Factors:** The study of how drivers interact with electric vehicles and how their behaviour affects safety.

⁶ **Fire Safety:** Concerns related to preventing and managing fires in electric vehicles, particularly those originating from battery malfunctions.

⁷ **Case Studies:** Examples and analyses of real-world incidents and developments related to electric vehicle safety.

offers a 360-degree view of the safety implications and advancements in the electric vehicle industry.

Zarys treści: Rozwój pojazdów elektrycznych (EV) zapoczątkował nową erę transportu i przyniósł ze sobą szereg innowacji i wyzwań. Ten obszerny artykuł ma na celu zagłębienie się w skomplikowany krajobraz bezpieczeństwa pojazdów elektrycznych. Autor dokonuje dogłębnej analizy różnych obaw i jednocześnie zwraca uwagę na najnowocześniejsze rozwiązania. Bada bezpieczeństwo akumulatorów, normy zderzeniowe, infrastrukturę ładowania, czynniki ludzkie, bezpieczeństwo pożarowe, przepisy, studia przypadków i przyszłe trendy. Dzięki temu artykuł zawiera wieloaspektowy obraz bezpieczeństwa pojazdów elektrycznych.

Keywords: electric vehicle, battery safety, crash safety.

Słowa kluczowe: pojazd elektryczny, bezpieczeństwo akumulatora, bezpieczeństwo w razie wypadku.

Introduction

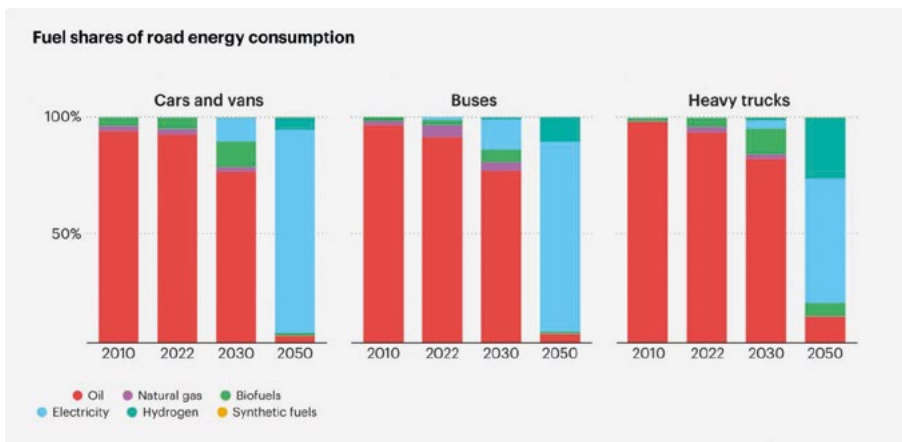
The transportation sector is undergoing a major transformation as electric vehicles (EVs) gain traction. With an increasing emphasis on environmental sustainability⁸ and energy efficiency, governments, industries and consumers are recognizing the potential for cleaner and more efficient mobility. However, amid this exciting shift towards electrification, it is essential to address the safety aspects associated with this technological revolution. This introduction sets the stage for a comprehensive examination of the safety issues and innovative solutions shaping the present and future of electric vehicle safety. As EVs become more integrated into our daily lives understanding these issues and the proactive measures being implemented is crucial. This knowledge is vital for charting a safe and sustainable course in the burgeoning field of electric mobility.

The global automotive industry is at a pivotal point, moving towards a future characterized by sustainability and environmental consciousness. With growing

⁸ **Sustainability:** The environmental benefits of electric vehicles, including reduced carbon emissions and improved energy efficiency.

awareness of climate change and a collective commitment to reducing carbon emissions, electric vehicles (EVs) have emerged as catalysts for innovation and positive change. As the automotive landscape undergoes significant transformations, understanding the historical context is crucial for unravelling the challenges we⁹ face and appreciating the remarkable milestones achieved. This study provides the foundation for understanding the driving forces behind the global shift to electric mobility, from the creation of the first electric wheelchair in the 19th century to the mass production of advanced electric vehicles today.

Image 1. Fuel shares of road energy consumption



Source: The International Energy Agency, *Global EV Outlook 2023, Trends in Electric Light-Duty Vehicles*, <https://www.iea.org/reports/road-transport>, (accessed 20.01.2023).

Electric car sales reached another record high in 2022, despite challenges such as supply chain disruptions, macroeconomic and geopolitical uncertainties and high commodity and energy prices. This growth occurred against the backdrop of a globally contracting car market, where total car sales in 2022 decreased by 3% compared to 2021. Sales of electric cars, including battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), surpassed 10 million last year, marking a 55% increase from 2021. This figure of 10 million EV sales worldwide surpasses the total number of cars sold across the entire European Union (approximately 9.5 million vehicles) and represents nearly half of the total number of cars sold in China in 2022. In just five years, from 2017 to 2022, EV

⁹ 'We' refers to automotive manufacturers as a collective group of industry specialists. Being part of the automotive industry, the researcher gains insights from different brands and summarizes the overall status of the industry. Knowledge and information gathered based on the work experience and interaction with other specialists.

sales skyrocketed from around 1 million to over 10 million. Previously it took five years, from 2012 to 2017, for EV sales to grow from 100,000 to 1 million, highlighting the exponential growth of EV sales. The share of electric cars in total car sales increased from 9% in 2021 to 14% in 2022, more than ten times their share in 2017.¹⁰

Battery Safety

Electric vehicles derive their revolutionary efficiency and power from the vital core of lithium-ion batteries.¹¹ Delving into the core of battery technology, we unravel the complexities of lithium-ion batteries by scrutinizing their composition, functionality and inherent performance issues.

The key role of thermal management systems¹² in reducing the risks associated with overheating, a major safety concern for electric vehicles, becomes the focus. In addition, recent advances in battery safety protocols highlight the ongoing research and development aimed at improving the resilience of electric vehicle power supplies.

As we tackle the complex challenge of electric vehicle battery safety, a nuanced understanding emerges, laying the foundation for comprehensive strategies and innovative solutions in the relentless pursuit of safer electric mobility.¹³

Battery Technology Overview

At the heart of the electric vehicle revolution is the technological marvel that is the lithium-ion battery. Understanding the intricacies of these energy storage devices is essential to understanding both the strengths and challenges of electric vehicle (EV) technology. Li-ion batteries, with their high energy density and efficiency, have become the backbone of electric vehicles, providing them with unprecedented levels of performance. By unravelling the complexity of lithium-ion batteries, we will gain

¹⁰ The International Energy Agency, *Trends in Electric Light-Duty Vehicles – Global EV Outlook 2023 – Analysis*, <https://www.iea.org/reports/global-ev-outlook-2023/trends-in-electric-light-duty-vehicles>, (accessed 20.01.2023).

¹¹ **Lithium-Ion Batteries:** The primary type of battery used in electric vehicles, known for their high energy density and efficiency.

¹² **Thermal Management Systems:** Systems designed to manage the temperature of EV batteries to prevent overheating and improve safety.

¹³ The International Energy Agency, *Global EV Outlook 2023. Trends in Electric Light-Duty Vehicles*, <https://www.iea.org/reports/road-transport>, (accessed 20.01.2023).

a clearer understanding of their role in powering electric vehicle propulsion systems and the subsequent safety implications. As the automotive landscape embraces electrification, a fundamental understanding of battery technology is imperative to address safety concerns and facilitate continued progress in this key aspect of electric vehicle development.

Thermal Management Systems

In the dynamic world of electric vehicle batteries, thermal management systems protect against the risks associated with overheating and failure. As electric vehicles push the limits of performance, the demand for batteries is increasing, making effective thermal management mandatory. By preventing overheating, these systems not only improve the safety of the electric vehicle, but also contribute to the longevity and reliability of the battery itself. We explore the mechanisms and technologies used to monitor and regulate temperature, striking a delicate balance between optimal performance and safety. Advances in thermal management systems underscore the industry's commitment to improving the safety of electric vehicles, paving the way for increased reliability and widespread adoption of this revolutionary mode of transportation.

Advancements in Battery Safety

As the electric vehicle landscape continues to evolve, so do advances in battery safety protocols. Manufacturers are at the forefront of addressing battery safety issues, from the use of innovative materials to the introduction of advanced safety features. We examine current research and development initiatives aimed at improving the thermal stability, durability and overall safety of lithium-ion batteries. In addition, integration of smart technologies allow us to monitor battery health in real time and take proactive measures to prevent potential problems. By highlighting these achievements, we recognize the industry's commitment to not only meeting but exceeding safety standards,¹⁴ creating a safe and reliable foundation for the widespread adoption of electric vehicles.

¹⁴ **Safety Standards:** The regulatory requirements and guidelines that electric vehicles must meet to ensure safety.

Crash Safety

Beyond the realm of efficient propulsion lies a critical facet of electric vehicle design – crash safety. The evolution of electric vehicles necessitates a re-imagining of structural design, ensuring the safety of occupants in the event of a collision. We explore the innovative approaches taken by manufacturers to fortify the structural integrity of electric vehicles, employing advanced materials and engineering techniques. From enhanced occupant protection measures¹⁵ to the integration of cutting-edge safety technologies, electric vehicles are rewriting the script on crash safety, setting a new standard for secure and responsible transportation in the electrified era.

Structural Design Innovations

The electrification of transportation necessitates a paradigm shift in structural design to meet the rigorous demands of crash safety. Electric vehicles, with their unique components and power-train systems, demand innovative approaches to structural engineering. Advanced materials such as high-strength alloys and carbon fibre composites are increasingly integrated to enhance both strength and weight distribution. These structural design innovations not only contribute to crash safety but also play a pivotal role in optimizing the overall performance and efficiency of electric vehicles.

One of the major differences between the traditional combustion engine powered vehicle and electric vehicles is upstream of the power-train, which includes the engine and gearbox in front of the vehicle and which might penetrate the vehicles interior in case of a frontal collision. Electric vehicles are significantly safer in this case as the energy gets absorbed by the whole structure of the frame.

By examining these engineering advancements, we gain insights into the dynamic landscape of electric vehicle design, where safety and performance are intricately interwoven for a holistic and secure driving experience.

¹⁵ **Occupant Protection Measures:** Safety features designed to protect passengers in the event of an accident, including airbags and reinforced cabin structures.

Advanced Crash Testing Protocols

Ensuring the crashworthiness of electric vehicles involves subjecting them to rigorous and meticulous crash testing protocols. Advanced crash testing involves simulating a range of collision scenarios to evaluate the structural integrity, impact resistance and overall safety features of electric vehicles. Manufacturers leverage sophisticated testing facilities and simulation technologies to replicate real-world crash scenarios, ensuring that electric vehicles not only meet but surpass conventional safety standards. The integration of advanced crash testing protocols stands as a testament to the commitment of the electric vehicle industry to prioritize occupant safety, providing consumers with vehicles that are not only environmentally friendly but also engineered to withstand and mitigate the impact of collisions.

Occupant Protection Measures

In the pursuit of comprehensive safety, electric vehicle manufacturers prioritize advanced occupant protection measures. Electric vehicles often feature an array of cutting-edge safety systems, including adaptive airbag systems, pre-tensioning seatbelts and reinforced cabin structures designed to dissipate and absorb impact forces. Moreover, we explore the integration of state-of-the-art sensor technologies and artificial intelligence for real-time risk assessment, enabling rapid deployment of safety measures. By prioritizing occupant protection, electric vehicle manufacturers are not only meeting regulatory standards but also setting new benchmarks for passenger safety in the realm of automotive engineering. This commitment underscores the holistic approach taken to ensure that electric vehicles are not only environmentally conscious but also provide a secure and protective driving environment.

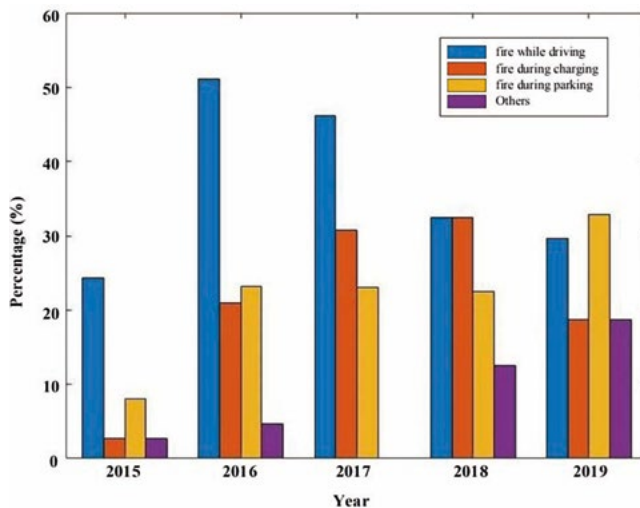
Fire Safety Concerns

As electric vehicles revolutionize the automotive landscape, a critical consideration arises in the form of fire safety. By dissecting the root causes of battery fires, such as thermal runaway events, we gain insights into the preventative measures and safety protocols implemented by manufacturers.

As lithium-ion batteries power electric vehicles, factors such as overcharging, overheating or external damage can trigger chain reactions that may culminate in a battery fire. By understanding the intricacies of these potential risks, manufacturers can implement targeted safety measures and protocols to prevent and manage such incidents, underscoring the commitment to prioritizing the safety of electric vehicle technology.

The statistics in Image 2 shows electric vehicle fires worldwide from 2015 to 2019. It suggests an increasing proportion of electric vehicle fires during the charging process. Multiple electric vehicle fires occur every year around the world, which sometimes cause casualties.

Image 2. Statistics of worldwide electric vehicle fire status from 2015 to 2019



Source: China Electric Power Research Institute, *Review of the Charging Safety and Charging Safety Protection of Electric Vehicles*, ResearchGate, https://www.researchgate.net/publication/355228230_Review_of_the_Charging_Safety_and_Charging_Safety_Protection_of_Electric_Vehicles, (accessed 20 January 2023).

Emergency response and firefighting procedures are paramount in mitigating the risks associated with electric vehicle fires. Additionally, advancements in fire suppression systems designed specifically for electric vehicles are discussed, emphasizing the industry's commitment to ensuring not only efficient energy storage but also robust safety mechanisms. By navigating the intricacies of fire safety concerns, the electric vehicle industry works towards fostering confidence in the safety of this transformative mode of transportation.

The electrification of transportation brings forth a complex tapestry of regulations aimed at ensuring the safety and standardization of electric vehicles on a global scale. Governments and international bodies collaborate to establish

comprehensive safety standards covering diverse aspects, including crash safety, battery technology and overall vehicle performance.

Examining the global regulatory framework sheds light on the shared objectives of nations to create a unified approach to electric vehicle safety. Harmonization efforts are crucial in fostering an environment where manufacturers can design vehicles that meet consistent safety criteria, promoting cross-border acceptance and facilitating the international growth of the electric vehicle market. By navigating through the nuances of these global regulations, we gain a deeper understanding of the concerted efforts to create a secure, standardized, and globally accepted foundation for the electrified future of transportation.¹⁶

Continuous Improvement in Safety Protocols

As electric vehicles proliferate, manufacturers face a myriad of challenges in ensuring compliance with evolving safety standards. Manufacturers navigate the intricacies of diverse safety standards set by different regions, each with its unique specifications and protocols.

The discussion unfolds to explore how the electric vehicle industry addresses compliance challenges through technological advancements, rigorous testing and collaboration with regulatory bodies. Initiatives to streamline compliance processes and foster a proactive approach to safety are crucial in overcoming hurdles presented by rapid technological advancements.

Considering complexity of the technology, government regulators in the EU have decided to establish the Joint Research Centre (JRC) which provides customer-driven scientific and technical support to the conception, development, implementation and monitoring of EU policies, alongside with the US Department of Energy's Argonne National Laboratory, to support automotive manufacturers and technology providers to market the vehicles across the continent.¹⁷

By understanding these compliance challenges and the proactive measures in place, we gain insights into the resilience and adaptability of the electric vehicle industry in navigating the complex terrain of global safety regulations. This ongoing dialogue between regulators and industry stakeholders is instrumental

¹⁶ The International Energy Agency, *Global EV Outlook 2023...*, op. cit.

¹⁷ K. Hardy, H. Scholz, *Transatlantic Technical Recommendations for Government Funded Implementation of Electric Vehicle Charging Infrastructure*, Publications Office of the European Union, Luxembourg 2023, p. 1.

in shaping a regulatory landscape that not only keeps pace with technological evolution but also sets the stage for safer and more standardized electric mobility.

Implications for the Future of Electric Vehicle Safety

The integration of artificial intelligence, advancements in sensor technologies and the evolution of connectivity all contribute to a paradigm shift in how safety is approached within the electric mobility landscape.

The anticipations extend to a future where vehicles, equipped with sophisticated AI-driven safety systems, become more than modes of transportation: they evolve into intelligent entities capable of learning, adapting, and proactively ensuring the safety of occupants and pedestrians alike. Vehicle-to-everything (V2X) communication, where vehicles exchange critical safety information in real-time, further solidifies the interconnected and secure future of electric mobility.

Moreover, the discussion encompasses the societal implications, foreseeing a landscape where electric vehicles not only reduce environmental impact but also redefine safety standards. The collaborative interplay of technology, regulations and consumer awareness is poised to shape a future where electric vehicles stand as beacons of sustainability and safety in the global transportation paradigm. As we peer into this future, it becomes evident that the ongoing pursuit of innovation is not only transforming how we drive but also redefining what safety means in the era of electric mobility.

Regulatory Landscape¹⁸

With the proliferation of electric vehicles, the development of a robust charging infrastructure is paramount for the seamless integration of this transformative technology. As electric vehicle ownership rises, charging stations become hubs of activity, demanding comprehensive safety measures to protect both users and the charging infrastructure itself.

The discussion extends to the importance of standardized electrical systems governing charging stations, guaranteeing compatibility and safety across

¹⁸ **Regulatory Landscape:** The set of rules and standards governing the safety and operation of electric vehicles globally.

diverse networks. Cybersecurity¹⁹ considerations are also explored, recognizing the vulnerability of interconnected charging systems to potential threats. By examining the safety protocols in place for charging infrastructure we gain insight into how the industry is evolving to meet the demands of a growing electric vehicle market while prioritizing the safety, efficiency and accessibility of charging networks.

The global surge in electric vehicle adoption has catalysed a transformative expansion of charging infrastructure worldwide. The global network of charging stations not only alleviates range anxiety for electric vehicle owners but also fosters the widespread adoption of electric mobility.

Exploring this expansion entails an examination of the challenges faced in scaling up charging infrastructure to meet the escalating demand. Factors such as location selection, power grid capacity and accessibility are critical considerations in optimizing the efficacy of charging networks. The overarching goal is to create a ubiquitous and user-friendly charging infrastructure that bolsters the convenience and appeal of electric vehicles. As we dissect the complexities of this global expansion, we gain insights into how the charging ecosystem is evolving to shape the future of electric vehicle accessibility and utilization on a global scale.²⁰

Compliance Challenges and Solutions

As the electric vehicle charging infrastructure expands globally, adherence to stringent electrical standards becomes paramount in ensuring the safety and reliability of these charging stations. Rigorous compliance with these standards not only guarantees the safety of users and their vehicles during the charging process but also fosters interoperability across diverse charging networks.

In tandem with electrical standards, the discussion extends to the burgeoning importance of cybersecurity in the realm of electric vehicle charging. With charging stations becoming increasingly interconnected and reliant on digital

¹⁹ **Cybersecurity:** Measures to protect the digital systems of electric vehicles and their charging infrastructure from cyber threats.

²⁰ Joint Research Centre of the European Commission, *EV Charging Infrastructure Rollout: EU-US Technical Recommendations Are Out*, https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/ev-charging-infrastructure-rollout-eu-us-technical-recommendations-are-out-2023-05-31_en?prefLang=sv, (accessed 20.01.2023).

technologies, they become susceptible to potential cyber threats. Examining the cybersecurity measures implemented in charging infrastructure provides insights into the protective measures against unauthorized access, data breaches and other cybersecurity challenges. By scrutinizing both electrical standards and cybersecurity considerations, we gain a comprehensive understanding of how the industry is addressing the evolving safety landscape of electric vehicle charging infrastructure.²¹

Case Studies

In the dynamic realm of electric vehicles, safety is intrinsically linked to a comprehensive regulatory landscape that guides the development, production and operation of these innovative vehicles. From crash safety requirements to battery safety protocols, understanding the regulatory landscape is crucial for manufacturers, policymakers and consumers alike.

The discussion delves into the collaborative efforts between governments and industry bodies to establish and enforce these standards. Harmonizing safety regulations on a global scale ensures consistency in safety protocols and fosters cross-border acceptance of electric vehicles. By navigating the regulatory landscape, we gain insights into how safety standards are crafted, implemented and revised to address the dynamic nature of electric vehicle technologies. This understanding forms the bedrock for a secure and standardized approach to electric vehicle safety, promoting confidence among consumers and facilitating the sustainable growth of the electric vehicle industry.

Future Trends and Innovations²²

As electric vehicles become an integral part of our transportation landscape, the horizon is ripe with promise for future trends and innovations that will further enhance safety. Anticipated trends include the integration of artificial intelligence

²¹ K. Hardy, H. Scholz, *Transatlantic Technical Recommendations...*, op. cit., p. 1.

²² For more information about the future trends in the EV market, refer to The International Energy Agency, *Global EV Outlook 2023...*, op. cit. and McKinsey & Company, *Spotlight on Mobility Trends 2023*, <https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/spotlight-on-mobility-trends>, (accessed 20.01.2023).

(AI) to augment safety features, predictive maintenance²³ systems to enhance reliability and advancements in materials engineering for lighter yet stronger vehicle structures. The discussion extends to the role of connectivity and vehicle-to-everything (V2X)²⁴ communication, empowering vehicles to share critical safety information in real-time.

The future of electric vehicle safety is intricately linked to the integration of emerging technologies²⁵ poised to redefine automotive standards. Advancements in sensor technologies, including LiDAR and advanced camera systems, promise to elevate the precision and accuracy of safety features. These sensors contribute to enhanced collision avoidance, pedestrian detection and overall situational awareness, augmenting the safety ecosystem of electric vehicles.

By navigating through these emerging technologies we gain insights into the industry's commitment to pushing the boundaries of innovation. The intersection of AI, advanced sensors and safety systems not only propels electric vehicles into a new era of security but also positions them at the forefront of technological evolution in the broader automotive landscape.

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²³ **Predictive Maintenance Systems:** Systems that use data and AI to predict and address potential vehicle issues before they become serious problems.

²⁴ **Vehicle-to-Everything (V2X) Communication:** Technology that allows vehicles to communicate with each other and with infrastructure to improve safety and efficiency.

²⁵ **Emerging Technologies:** New advancements such as AI and advanced sensor technologies that enhance the safety and functionality of electric vehicles.

Joint Research Centre of the European Commission, *EV Charging Infrastructure Rollout: EU-US Technical Recommendations Are Out*, https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/ev-charging-infrastructure-rollout-eu-us-technical-recommendations-are-out-2023-05-31_en?prefLang=sv, (accessed 20.01.2023).

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Summary

In the dynamic realm of electric vehicle safety, this comprehensive exploration unveils the multifaceted dimensions that underpin the evolution of this transformative industry. From the intricacies of battery safety to the intricately designed crash standards, the challenges posed by charging infrastructure and the nuanced interplay of human factors, this journey has illuminated the crucial facets that define the safety landscape of electric vehicles.

As we conclude this in-depth examination, it becomes evident that safety is not just a regulatory requirement but a guiding principle that propels the industry forward. The global surge in electric vehicle adoption necessitates a harmonized approach, where technology, regulations and user awareness converge to create a secure and standardized foundation. Challenges abound, from cybersecurity threats to compliance complexities, yet within these challenges lie opportunities for innovation, collaboration and a redefined understanding of safety in the context of electric mobility.

Looking ahead, the future holds the promise of groundbreaking technologies, interconnected safety systems and a landscape where electric vehicles not only reduce environmental impact but also set new benchmarks for occupant and pedestrian protection. The ongoing dialogue between manufacturers, regulators and consumers will continue to shape the trajectory of electric vehicle safety, paving the way for a secure, sustainable and transformative electric future.

As electric vehicles transcend the boundaries of innovation, safety remains the compass that guides this transformative journey. It is a journey propelled not only by technological advancements but by a collective commitment to forging a future where mobility is not just efficient and eco-friendly but, above all, inherently secure for all who travel the electrified roads ahead.