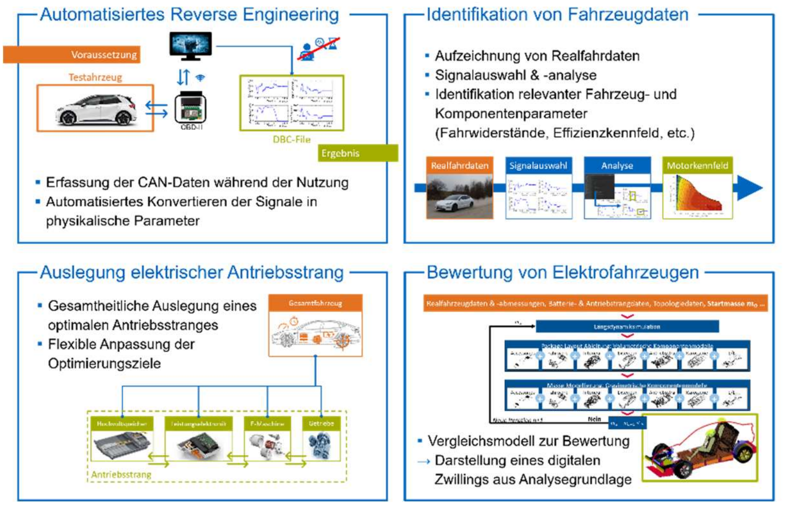
Explorative Analysis of the Potential of Benchmarking for Electric Vehicle Concepts

Explorative Potentialanalyse aktueller Benchmarkuntersuchungen von Elektrofahrzeugen



Wissenschaftliche Arbeit zur Erlangung des Grades
Bachelor of Science (B.Sc.)
am Department Mobility Systems Engineering
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Lehrstuhl für Fahrzeugtechnik
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Aufgabenstellung

Explorative Analysis of the Potential of Benchmarking for Electric Vehicle Concepts

Hier steht ein zum Thema hinführender Text.

In einer konstruktiven (oder theoretischen) Semesterarbeit sollen (...)

Folgende Punkte sind durch Herrn Augusto Lucioni Calabrese zu bearbeiten:

• Literaturrecherche zur Vorbereitung, der Durchführung und Auswertung von Benchmarkuntersuchungen und deren ökonomischen Aufwand

• Themenblock 1: Datenerfassung der internen Kommunikation sowie des automatisierten Reverse Engineerings

• Themenblock 2: Identifikation von Gesamtfahrzeug- und Komponentenparametern naahnd von Realfahrdaten

• Themenblock 3: Bewertung elektrischer Fahrzeugkonzepte anhand von Simulationsmodellen, Analysen und Vergleichstests

• Themenblock 4: Optimierung der gesamtheitlichen Auslegung von elektrischen

Antriebsstrangsystemen und Komponenten

• Kritische Bewertung neuer Ansätze zur Digitalisierung, Automatisierung und Optimierung von herkömmlichen Benchmarkingprozessen

• Umfassende schriftliche Dokumentation und kritische Reflexion der Ergebnisse.

Die Ausarbeitung soll die einzelnen Arbeitsschritte in übersichtlicher Form dokumentieren. Der Kandidat/Die Kandidatin verpflichtet sich, die Bachelorarbeit selbständig durchzuführen und die von ihm verwendeten wissenschaftlichen Hilfsmittel anzugeben.

Die eingereichte Arbeit verbleibt als Prüfungsunterlage im Eigentum des Lehrstuhls.

Ausgabe: 11.04.2023

Abgabe: 08.10.2023

Prof. Dr.-Ing. M. Lienkamp

Betreuer: Nico Rosenberger, M. Sc.

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Herr: **Lucioni Calabrese, Augusto**

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Erklärung

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Garching, den 08.10.2023

Augusto Lucioni Calabrese, B. Sc.

Lehrstuhl für Fahrzeugtechnik
TUM School of Engineering and Design
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Declaration of Consent, Open Source

Hereby I, **Lucioni Calabrese, Augusto**, born on 02.10.2001, make the software I developed during my Bachelor Thesis available to the Institute of Automotive Technology under the terms of the license below.

Garching, 11.04.2023

Augusto Lucioni Calabrese, B. Sc.

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1 Introduction

1.1 Motivation

In an era marked by rapid technological advancements and an ever-growing need for sustainable transportation solutions, the automotive industry stands at a crossroads. The relentless march toward electromobility has ignited a race among car manufacturers to secure their place in the evolving market. Billions are being invested in research and development, driving innovation in electric propulsion systems. Within the hallowed halls of automotive giants, closely guarded secrets are being developed into groundbreaking concepts, poised to shape the future of transportation.

In this dynamic landscape, the practice of benchmark studies plays a pivotal role. Benchmarking is the compass that guides manufacturers through the turbulent waters of competition. It allows us to examine and analyse the strategies and technologies adopted by rivals, gaining valuable insights into the complex world of electromobility. However, as the stakes rise, so do the challenges and costs associated with these benchmark studies. The status quo demands an exorbitant investment of both time and money, limiting the speed at which we can drive innovation forward.

The time has come for us to delve deeper into the heart of this field, to challenge conventional wisdom, and to embark on a transformative journey towards a more efficient, sustainable, and cost-effective future. In this pursuit, our thesis endeavours to shine a bright light on the uncharted territory of digitization, automation, and optimization in electric propulsion system investigations.

Our thesis is a compass that guides us through the intricacies of this vast field, breaking it down into four distinct but interdependent areas of study: data acquisition, parameter identification, evaluation, and optimization. These four pillars form the foundation of our investigation, each contributing to our comprehensive understanding of electric propulsion systems and their potential for improvement.

As we embark on this intellectual voyage, we are acutely aware of the transformative power that digitization and automation bring to the table. The integration of cutting-edge technologies into the heart of electric propulsion systems promises to revolutionize the way we perceive and interact with them. Our mission is to unravel the potential hidden within these advancements, revealing how they can enhance efficiency, reliability, and performance.

Moreover, we recognize that no significant progress can be made without considering the financial aspects of our endeavours. We are committed to conducting a meticulous analysis of the expected costs and gains associated with digitization, automation, and optimization of electric propulsion systems. By doing so, we aim to provide a comprehensive overview of the economic feasibility of our proposed advancements, ensuring that they are not only groundbreaking but also financially viable.

In our relentless pursuit of knowledge and innovation, we understand that the road ahead will be paved with challenges and uncertainties. Yet, it is precisely in these moments of uncertainty that the greatest breakthroughs occur.

1.2 Aim of work

The aim of our project is to undertake a comprehensive examination of current benchmark studies, encompassing various industries and domains. We intend to explore different approaches and scientific publications, procedures from companies and external suppliers, journals, and online presences to identify opportunities for digitization, automation, and optimization. Furthermore, our goal is to analyse the expected costs and gains associated with implementing these services. In essence, our project revolves around enhancing efficiency and cost-effectiveness across various sectors by leveraging insights gained from this extensive analysis.

The first crucial aspect of our project involves examining the current benchmark studies available in the field. This entails reviewing the latest research, reports, and data related to our chosen industry or domain. By doing so, we aim to gain a deep understanding of the existing standards and practices in place. This step serves as the foundation for identifying areas where improvements and innovations can be made.

Our project goes beyond merely reviewing benchmark studies. We recognize that innovation often arises from cross-pollination of ideas across different industries and sources. To that end, we will consider a wide range of approaches and sources, including scientific publications, procedures from companies and external suppliers, journals, and online presences. This multidisciplinary approach allows us to think creatively and identify novel solutions that may have been overlooked.

One of the central objectives of our project is to explore the potential for digitization, automation, and optimization within the chosen domain. In today's rapidly evolving technological landscape, these elements can significantly enhance efficiency and reduce costs. We will carefully assess how emerging technologies can be harnessed to streamline processes, improve decision-making, and ultimately drive productivity.

Efficiency and cost-effectiveness are not only about implementing new technologies but also about understanding the financial implications. Our project will include a thorough analysis of the expected costs and gains associated with the services and solutions we propose. This analysis will provide stakeholders with a clear understanding of the financial feasibility and return on investment for each proposed initiative.

In summary, our project's aim is to improve efficiency and cost-effectiveness by conducting a comprehensive examination of current benchmark studies, considering diverse approaches and sources, exploring the potential for digitization, automation, and optimization, and analyzing the associated costs and gains. Through this holistic approach, we seek to drive innovation and positive change within our chosen industry or domain, ultimately benefiting both businesses and consumers.

1.3 Structure of the thesis

Now, we will delve into the structure of a comprehensive project focused on the optimization of electric powertrains for electric vehicles (EVs). This project is organized into seven main sections, each with specific objectives and sub-sections aimed at achieving a thorough understanding and effective execution of the research.

In the forthcoming discussion, an exploration of electric vehicles will be undertaken, focusing on the definition of essential concepts and an examination of the state of the art in four interconnected areas: data acquisition, parameter identification, optimization of electric powertrains, and evaluation of electric vehicles. Firstly, a foundational comprehension of these concepts will be established. Subsequently, a review of the current state of the art within each domain will be conducted, highlighting the latest advancements, innovative technologies, and research findings that shape the electric mobility landscape. From the precision of data acquisition methods to the intricacies of parameter identification techniques, the optimization of electric powertrains, and the rigorous evaluation of electric vehicle performance, this discussion aims to provide an impartial, comprehensive overview of the cutting-edge developments propelling the electric vehicle industry forward.

In this comprehensive exploration of electric vehicles, a delve into four pivotal facets encompassing the dynamic realm of EV technology will be undertaken. Firstly, a journey into the realm of data acquisition will be initiated, scrutinizing the methods and tools employed to gather critical information about electric vehicles. Subsequently, a dive into the realm of parameter identification will be conducted, unravelling the intricate web of variables that define an EV's performance. The voyage continues with a deep dive into the optimization of electric powertrain systems, exploring how innovation has shaped and continues to refine the heart of these vehicles. Finally, an evaluation of electric vehicles will be undertaken, assessing their overall impact and effectiveness in the automotive landscape. In each of these sections, the methodology will entail a literature review, scrutinizing cutting-edge research and industry developments. Following this, conclusions will be drawn regarding the innovations driving these fields, the costs associated with their implementation, and the promising outlook that awaits the electric vehicle industry.

In the last section, the focus will shift towards the conclusion and outlook of the research project. This segment will provide a comprehensive summary of the findings and their implications, as well as offer insights into potential future directions and areas for further exploration within the research domain. The objective is to distil the core outcomes of the study and present a forward-looking perspective that underscores the significance and potential impact of the research in a broader context.

1.4 Definition of concepts

The "Definition of Concepts" section plays a critical role in setting the stage for our discussion by offering clear and straightforward explanations of essential terms and ideas central to our topic. In this section, our aim is to simplify the language and technical terms that might otherwise make it challenging to understand the subject matter thoroughly. By establishing a common vocabulary and context, we provide a strong foundation that helps readers navigate the complexities of the topic with confidence and seriousness. Whether you're new to this topic and looking for basic explanations or an experienced individual seeking a comprehensive reference, this section ensures that you're well-prepared to engage with the subsequent content on a deeper level.

The Controller Area Network (CAN bus) in an electric vehicle (EV) serves as a vital communication network responsible for overseeing and governing various electrical and electronic components within the EV. Employing a standardized communication protocol widely adopted in automotive and industrial settings, the CAN bus facilitates efficient and reliable information exchange among diverse electronic control units (ECUs) and devices. This communication protocol operates in a serial fashion, boasting attributes of robustness, minimal latency, and high reliability, making it an ideal choice for real-time control and monitoring in automotive contexts. Data transmission within the CAN bus occurs in the form of messages or frames, comprising an identifier, data bytes, and control bits. These messages can be either broadcasted to all nodes on the bus (broadcast messages) or directed to specific recipients (unicast messages), with the identifier serving to prioritize messages and data bytes conveying details about various vehicle parameters. In the context of an electric vehicle, the CAN bus connects a multitude of ECUs and sensors, encompassing the battery management system (BMS), powertrain control module (PCM), motor controller, charging controller, regenerative braking system, and an array of sensors monitoring parameters such as temperature, speed, voltage, and current. The CAN bus facilitates real-time data exchange and command transmission among these components, exemplified by the BMS monitoring battery state of charge (SoC) and state of health (SoH) and communicating this information to the PCM for precise power delivery adjustments to the electric motor. Additionally, the CAN bus plays a pivotal role in enabling communication between safety systems like the anti-lock braking system (ABS) and airbag system, ensuring swift response in emergency scenarios. The system also encompasses fault detection mechanisms to identify errors in data transmission, permitting nodes to request retransmission or undertake appropriate measures to preserve data integrity. Given the criticality of the data shared on the CAN bus, modern EVs incorporate security measures, such as encryption and authentication mechanisms, to safeguard against unauthorized access and potential cyberattacks, fortifying the communication network's protection.

2 State of the Art

This thesis endeavours to delve deeper into the realm of benchmark studies within the context of current research. The work is structured into four key domains: data acquisition, parameter identification, evaluation, and optimization of electric propulsion systems. The multifaceted nature of this research requires a comprehensive exploration of diverse sources, encompassing scientific publications, corporate methodologies, contributions from external suppliers, journal publications, and online resources. Of particular interest are scientific publications that form the cornerstone of this investigation.

Reverse engineering data from internal communication systems in electric vehicles (EVs) is a complex and rapidly evolving field. Researchers and security experts have been exploring ways to access and analyse the data transmitted within EVs for various purposes, including diagnostics, performance optimization, and security assessment.

The Controller Area Network (CAN) bus is a critical component of a vehicle's internal communication system (see figure 1). Reverse engineering the CAN bus allows researchers to access information about various vehicle systems, sensors, and controls. Advanced tools and hardware interfaces can be used to monitor and analyse the CAN bus traffic, deciphering the messages exchanged between different components [1]. For this matter On-Board Diagnostics (OBD-II) devices are commonly used to access vehicle data for diagnostics. These are advanced data loggers that can be used to capture data from internal communication systems, including CAN bus data, and store it for later analysis [2]. Moreover, Electronic Control Units (ECUs) control various functions within an EV, such as the powertrain, battery management, and safety systems. Reverse engineering the firmware of these ECUs can provide insights into how they operate and communicate [3].

Once data is acquired, machine learning and data analytics techniques can be applied to make sense of the information collected. This might involve identifying patterns, anomalies, and correlations in the data to improve performance, diagnose issues, or enhance security [4].

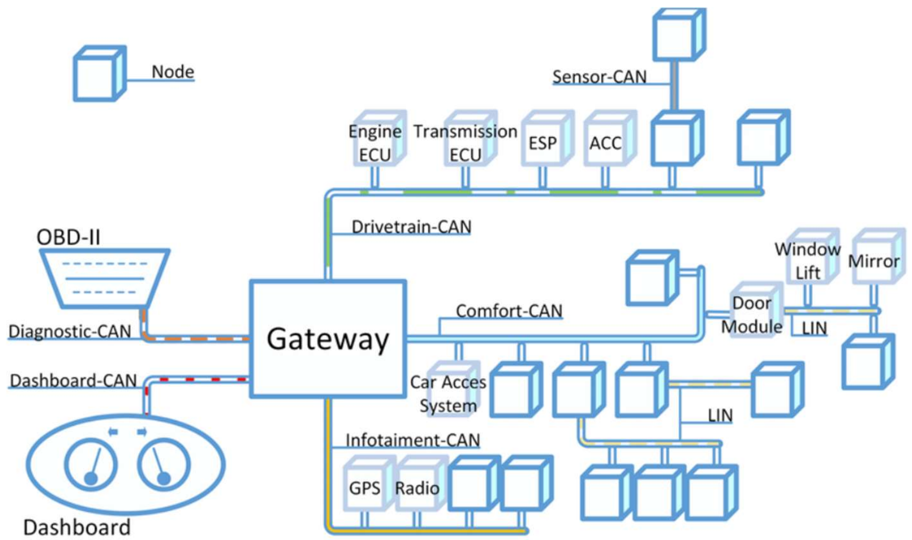

Figure 1: Generic model of a car CAN bus [9]

Currently, the identification of comprehensive vehicle parameters and components from real driving data in electric vehicles (EVs) is an active area of research and development. This process involves extracting detailed information about various aspects of the vehicle's behaviour, performance, and components using data collected during real-world driving scenarios. In the world of car engineering, the drive for efficiency revolves around understanding important aspects like battery state of health, how the engine behaves, the impact of slopes, and how much energy is used.

A key part of this effort is carefully choosing and looking at the right signals from the car. Signals like Battery Management System, Charge Rate and Powe, and the conditions (e.g., temperature) help us understand the battery state of health [5]. The efficiency of the engine is better understood by looking at torque and rotation speed parameters and the energy it uses [6]. Figuring out how road slopes affect things like energy usage relies on acceleration related signals and GPS [7]. Energy usage is complex, including things like the way the car recovers energy when braking and how other systems work. Getting a good picture involves picking signals that show how energy flows in real-time [8] (see figure 2). This complex process, which mixes engineering knowledge with understanding data, reveals important insights that help design and operate cars more efficiently.

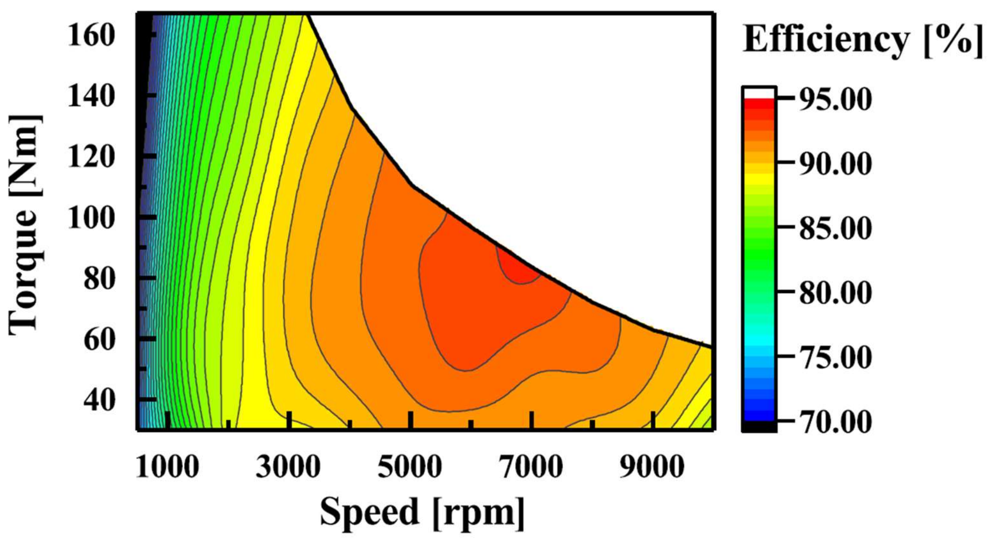

Figure 2: Efficiency map of a tested EV [8]

Current optimization investigations in electric vehicles are revolving on three pivotal aspects: optimal gear shift ratios, powertrain optimization, and energy storage optimization. In the quest for optimal gear shift ratios, researchers employ usually simple simulation tools to avoid excessive calculation and multi-objective optimization processes to determine the most efficient transmission configurations for electric vehicles [10]. Powertrain optimization involves a multifaceted approach, integrating simulations to fine-tune electric motor designs, enhance inverter efficiency, and improve the interplay between different powertrain components. The current focus of the investigation of the powertrain is either to achieve the best gear ratio and torque–speed motor curve in the powertrain of EV [11] or to improve fuel economy and acceleration time

[12]. In the domain of energy storage optimization for electric vehicles, the primary focus revolves around formulating and fine-tuning a cost function that effectively determines the ideal size and configuration of the energy storage system. For that matter, this usually encompasses the development of sophisticated battery models and management systems that employ predictive analytics [13]. These investigations are instrumental in pushing the boundaries of electric vehicle technology, making them more efficient, reliable, and sustainable.

The evaluation of electric vehicles (EVs) is typically conducted through three primary methods: complete comparison among different vehicles, component comparison among different vehicles, and in-depth analysis of one vehicle. In a complete comparison, the most important factors considered include range, energy efficiency, charging, safety features, total cost of ownership, and driving experience [14]. This method provides consumers with a comprehensive view of how various EV models stack up against each other across key performance and ownership aspects. Component comparison, on the other hand, focuses on specific components like batteries and motors or bigger parts of the car like the powertrain. Factors of paramount importance in this approach are usually energy density, power output, charging speed, and lifespan [15]. Lastly, in-depth analysis of a single vehicle entails a meticulous examination of all its features and performance metrics [16]. Each of these evaluation methods contributes to a holistic understanding of the strengths and weaknesses of electric vehicles, helping consumers make informed choices in a rapidly evolving market.

3 Data Acquisition

In this section, we delve into a literature review to explore and analyse the existing research on data acquisition from electric vehicles. By synthesizing the insights and findings from various academic sources, we aim to draw meaningful conclusions and contribute to the ongoing conversation in this area. This literature review serves as the foundation for our subsequent analysis and insights.

3.1 Literature Review

The Parameter Analysis System of CAN Bus for Electric Vehicle Based on LabVIEW

The paper "The Parameter Analysis System of CAN Bus for Electric Vehicle Based on LabVIEW" aims to develop a parameter analysis system based on a LabVIEW platform for the Controller Area Network (CAN) bus of Electric Vehicles (EVs). One of the main problems encountered in EV maintenance is the difficulty of real-time monitoring and analysis of vehicle parameters, which can affect system operation. Therefore, the purpose of the proposed system is to address this issue and provide a platform for real-time parameter analysis and fault diagnosis.

The paper describes the methodology and implementation of the parameter analysis system. The system is based on a modular design that includes hardware and software components. The hardware module is based on the USB-CAN card, which provides bus access and message transmission. The software design is based on LabVIEW programming. A graphical user interface (GUI) was implemented using the front panel capabilities of LabVIEW. The system can display and record all monitored parameters and provide real-time analysis on the EV system.

The results demonstrate that the proposed system can accurately and reliably monitor the operation of EVs, detect any faults, and provide the technician with the necessary information to make repairs. The system has a robust function of recording and analysing the historical data of the EVs, which provides a basis for the optimization and improvement of the EV system efficiency.

In conclusion, the implementation of the parameter analysis system has significantly improved the maintenance of EVs. Despite its positive results, the system has some limitations, such as the inability to identify the root causes of the faults, indicating that more advanced analysis techniques may be necessary. Furthermore, the study did not cover a large sample size, and more extensive experiments and data analyses are needed for further research and development. Nevertheless, the proposed system is a step forward in creating an efficient and effective EV maintenance system.

LibreCAN Automated CAN Message Translator

This paper describes the development of an automated framework for reverse-engineering the Controller Area Network (CAN) messages of a vehicle. The main objective of this research is to translate the messages obtained from a CAN bus into a human-readable format, and this paper presents the two phases of the framework, which include a pre-processing stage and a clustering stage.

In the pre-processing stage, the authors describe the trace collection process, explaining that the trace length plays a crucial role in the precision of the clustering algorithm. A human-study experiment was also conducted to assess the time required to record all events listed in Table 10. For this purpose, an Android app was used, and ten users participated in the experiment. In summary, the pre-processing stage aims at collecting and cleaning the data to prepare it for the clustering stage.

The clustering stage is the most significant part of the framework, as it is responsible for translating the data into a human-readable format. This stage employs a clustering algorithm that groups similar messages into clusters, labels each cluster, and extracts the relevant signals. The extracted signals are then merged into a suitable format, making them readily available for analysis. To assess the framework's validity, it was tested on several datasets, and the results showed that it outperformed most of the existing reverse-engineering techniques.

While this research provides a great step forward in reverse-engineering CAN messages, it has some limitations that need to be addressed. For instance, the study was conducted on a single car model (Vehicle A), and it might not be generalizable to other models. The results also showed that the system is susceptible to false positives, which could lead to security issues. Finally, the paper did not address all the possible attacks that could occur when reverse-engineering CAN messages.

In conclusion, this PDF file provides a comprehensive explanation of a two-phase framework that can automatically translate CAN messages into a human-readable format. The clustering stage is the most significant part of the framework, and it is responsible for translating the data. The system's validity was confirmed by several tests and outperformed most of the existing systems. However, the research has some limitations that need to be addressed in future studies.

Towards Reverse Engineering Controller Area Network Messages Using Machine Learning.

The primary challenge this work addresses is the complex and time-consuming task of reverse engineering Controller Area Network (CAN) messages to understand their functionality within a vehicle. The proprietary nature of CAN implementation details by vehicle manufacturers makes it difficult to decode and correlate CAN messages to specific vehicle operations, hindering innovation and development in the automotive domain.

To tackle this issue, the authors propose the creation of a machine learning classifier that can analyse CAN messages and determine their relationships with other messages and vehicular functions. The software they propose eliminates the need for access to a physical vehicle during reverse engineering. Their algorithm relies on labelled time frames corresponding to specific vehicular functions and detects CAN messages with changing data bits. By combining a supervised learning approach and agglomerative clustering, they aim to reverse engineer CAN message functions and classify unknown ones.

The study demonstrates that the proposed machine learning classifier can effectively determine the function of CAN messages without the need for manual reverse engineering of physical vehicles. The research explores CAN traffic from various vehicles and standards, showcasing its applicability to a wide range of vehicles.

The paper raises several noteworthy concerns and criticisms. Firstly, it lacks information on the accuracy or error margin of the proposed algorithm when applied in real-world scenarios, which is essential for assessing its reliability. Additionally, there is a notable absence of details regarding the setup process for implementing the software and the time required for this setup, limiting our understanding of the practical aspects of deploying this solution. Furthermore, the paper does not mention the processing time required for the algorithm to handle CAN data, crucial for evaluating its efficiency in real-time applications. Lastly, the acknowledgment that the algorithm combines supervised learning with clustering suggests a potential lack of full automation, prompting the need for a more comprehensive explanation of the degree of human intervention and manual labelling involved in the process to clarify the algorithm's practicality and scalability.

Integrated OBD-II and mobile application for electric vehicle (EV) monitoring system.

The paper aims to address the growing interest in using electric vehicles (EVs) by providing a low-cost method for monitoring and controlling specific EV parts. Despite the increasing popularity of EVs, users are often under pressure to understand the status of their car's electrical system. This paper proposes a solution to this problem by collecting CAN data through the OBD-II port, allowing experienced users to monitor and control specific EV parts easily and seamlessly.

The results of this research show that the proposed integrated OBD-II and mobile application for EV monitoring system is effective in collecting CAN data and providing users with real-time information about the status of their EVs. The authors demonstrate that the system can be used to monitor and control specific EV parts, such as batteries, energy management, and electric drive train. The system is also low-cost and easy to use, making it accessible to a wide range of users.

While this research presents a promising solution for monitoring and controlling EV parts, there are some open points and critics to consider. For example, the authors do not provide information about the compatibility of the system with different types of EVs. Additionally, the authors do not discuss the potential security risks associated with collecting and transmitting CAN data through the OBD-II port. Overall, this research provides a valuable contribution to the field of EV monitoring systems and opens up new avenues for future research.

ACTT Automotive CAN Tokenization and Translation.

This paper addresses the problem of decoding Controller Area Network (CAN) data, which is a proprietary and complex system that varies per make, model, year, and trim. This makes it difficult for non-OEM (Original Equipment Manufacturer) entities to augment vehicles and operate blind to CAN message syntax and semantics. The authors propose the first algorithm to simultaneously tokenize and translate CAN data, learning message-to-function mappings by leveraging diagnostic information.

The methodology employed in this paper involves capturing CAN traffic using a Kvaser Leaf Lite V2, which provides CAN-to-USB translation to a Linux OS laptop using SocketCan software. The algorithm assumes that there is a CAN capture from a vehicle during a sufficiently long driving period to exercise most variation in the CAN data. The authors define the notation for representing the 64-bit payloads for an AID over time, and then present their algorithm for tokenization and translation.

The results of this paper show that the algorithm was tested on three vehicles dated 2008, 2015, and 2016 of two different makes, three models, and using both gasoline and hybrid. The authors present results and examples from a 20-minute capture from a 2008 gasoline vehicle in city and highway driving conditions. The particular car used 25 AIDs and responded on 31 DIDs, which were queried at a rate of 20Hz throughout the capture. The authors note that they obtained similar, if less comprehensive results for all vehicles tested.

An open question arises as the authors exclusively showcase results and examples stemming from a 20-minute data capture obtained from a 2008 gasoline vehicle during city and highway driving conditions. It would be intriguing to evaluate the algorithm's performance in electric vehicles and in diverse driving scenarios. Furthermore, although the authors mention having obtained similar, but less complete, results for all the vehicles tested, the algorithm's adaptability to a broader spectrum of vehicles remains uncertain.

I Know Where You Parked Last Summer Automated Reverse Engineering and Privacy Analysis of Modern Cars.

This paper aims to solve the issue of reverse engineering modern car telematics systems that make it difficult to fully understand the data being collected. This task requires a great deal of effort and can only be performed on a case-by-case basis due to the variety of communication protocols, message formats, and interpretations of the data.

To tackle this problem, the authors developed an open-source tool that utilizes machine learning techniques to extrapolate structured interpretations of Controller Area Network (CAN) data. This tool can be used for more platform-independent attacks on cyber-physical systems and provides a better understanding of privacy implications related to car telematics.

The results of this study demonstrate that a passive attacker can easily deduce private data from CAN logs without requiring physical access to a car. Furthermore, the authors reverse engineered the software of a Telematic Control Unit and were able to understand which data was collected, how often, and to whom it was sent. The research reveals that a CAN log without prior knowledge of make or model can provide sufficient information to mount effective attacks.

While this research provides valuable insight into car telematics security and privacy concerns, it also reveals the shortcomings of the technical and regulatory environment of modern cars. The researchers identify that standardization efforts and increased regulatory attention is required to address the privacy implications of car telematics systems. Additionally, the paper highlights the need for companies to disclose the data they are collecting and for users to have more control over their personal data.

CAN-D A Modular FourStep Pipeline for Comprehensively Decoding Controller Area Network Data.

This is a paper about a new approach to decoding CAN communication. The main problem that this paper aims to solve is the lack of accuracy and speed in the current tools used for decoding the network data. This becomes a crucial issue when it comes to debugging the electronic control units (ECUs) in the automobile, which are responsible for controlling various systems like engine, transmission, and others.

This paper proposes a four-step pipeline solution that combines a heuristic algorithm, machine learning, statistical methods, and parsing techniques to extract information from the CAN data. The pipeline includes steps for identifying signal boundaries and clusters, parsing signals, decoding each signal's value, and mapping the signals to meaningful data parameters. The pipeline's efficiency and accuracy are improved by using the J1939 standard and the Transport Protocol implemented with the Python programming language.

The proposed pipeline was tested against other algorithms and showed considerable improvement in the comprehensive decoding of the CAN data. The results of the tests revealed that the proposed pipeline's accuracy was much higher than the currently implemented tools. Moreover, the pipeline's translation of signal values from raw data to meaningful information on each ECU was substantially more precise.

Although the pipeline is a promising solution for decoding CAN data, the size and complexity of the code increases with the addition of multiple ECU subsystems, such as engine control unit (ECU) or anti-lock braking system (ABS ECU). Also, the accuracies of considered algorithms are highly dependent on the training data set and the features or field definitions. Despite these open issues, the proposed four-step pipeline presented in this paper is a major step towards improving the accuracy and efficiency of CAN data decoding.

An Enhanced Method for Reverse Engineering CAN Data Payload.

This paper addresses the issue of automotive cyber-security threats that have become a growing concern in modern computerized vehicles, where various electronic components are installed for improved safety and convenience. As a result, car manufacturers have made confidential the CAN database, which specifies signal information assigned in the CAN data payload, hindering automotive security research significantly because of limited accessible information by researchers.

To overcome this predicament, the authors proposed an enhanced method for reverse engineering CAN data payload that identifies signal boundaries. They employed a bit-flip rate time-series correlation analysis method to obtain the correlation between bit positions and identified signals. They also compared their approach to the existing Reduced Effort Algorithm for Data extraction (READ) method and evaluated the proposed method's effectiveness in terms of the number of identified signals and accuracy in identifying signal boundaries.

The results obtained show the proposed method's outperformance over the existing READ method in identifying signal boundaries effectively, even though the READ algorithm suffers from producing the same result as Open DBC, likely due to different vehicle models and dataset collection methodology. The proposed method's effectiveness can be attributed to its capability to identify a greater number of signals than the READ method through correlations even when the total bit-flip rates of two consecutive bits are similar.

However, the dataset used to evaluate the proposed method is from specific vehicles of Hyundai and Kia motor groups, raising concerns about its generalization to other vehicle models and protocols. Moreover, the proposed method's computational efficiency needs to be enhanced to make it more practical and applicable to larger CAN data payload sets. Nonetheless, the proposed method offers a promising approach for identifying signal boundaries and can be integrated into IDS technologies, improving their detection capabilities.

CANvas: Fast and Inexpensive Automotive Network Mapping.

The paper addresses the problem of identifying and mapping the communication structure of the Controller Area Network (CAN) in cars. The researchers aim to improve the understanding of the complex and often obscured message exchange among automotive Electronic Control Units (ECUs), which is essential for effective automotive security analysis.

The authors introduced an approach based on a lightweight, controlled message injection that provides temporal context for the analysis. They use network tomography techniques to estimate the information that is not explicitly available in the messages. The resulting analysis enables ECUs to be grouped based on their communication patterns and to identify the most critical parts of the network, where vulnerabilities may exist.

The authors evaluated their approach on a range of automotive communication scenarios, with encouraging results. They demonstrate the effectiveness of their method by identifying known vulnerabilities in the communication systems and previously undiscovered vulnerabilities when compared to traditional discovery methods. They also assess the scalability of their approach and show that it supports different injection rates, providing options for efficient discovery and mapping.

While the proposed approach shows promising results, there are some limitations to the methodology. The techniques are effective in identifying the structure of the CAN network, but they only provide a snapshot of the communication patterns, which may limit their ability to detect anomalous behaviour that changes over time. Additionally, the authors point out that their approach has some technical challenges and requires hardware support that may pose practical difficulties in the real world. Finally, the paper's methodology primarily focuses on the automotive domain and may not be applicable to other cyber-physical systems.

Discovering CAN Specification Using On-Board Diagnostics.

This paper aims to address the issue of the obscurity of Controller Area Network (CAN) specifications, which poses a significant challenge to reverse engineering message payloads and conducting in-vehicle security research. The paper proposes a novel CAN reverse-engineering algorithm that autonomously analyses CAN traffic data with onboard diagnostic (OBD-II) query responses to discover the information of CAN implementation associated with major vehicle parameters, with the goal of facilitating security analysis of in-vehicle network data.

The proposed method utilizes the OBDs system and can be applied to all modern vehicles equipped with OBD. The algorithm is evaluated using a real vehicle, and the collected data set contains 40 CAN traffic logs collected by periodically sending OBD queries while driving in a controlled environment. The data set is publicly available to foster further research. CAN data frames have an identifier, also known as CAN ID, and payload. CAN ID is used to indicate which signal data the message contains in the payload. The payload contains actual data values.

The result of the experiment shows that the proposed algorithm is able to extract CAN information that can affect various vehicle functions and allows researchers to understand and interpret CAN traffic data more efficiently. The proposed algorithm is a significant contribution to in-vehicle network security research, as it lowers the barriers to initiating vehicle security studies for researchers lacking vehicle expertise.

While the results of the experiments demonstrate the effectiveness of the proposed algorithm in interpreting and analysing CAN traffic data, further research is still required to evaluate the proposed methodology's robustness on different vehicle models.

Automated Cross-Platform Reverse Engineering of CAN Bus Commands From Mobile Apps.

The paper "Automated Cross-Platform Reverse Engineering of CAN Bus Commands From Mobile Apps" addresses the problem of reverse engineering the communication between mobile apps and a vehicle's CAN bus.

The authors employ a combination of static and dynamic analysis techniques to reverse engineer the messages exchanged between the mobile app and the car. They also use machine learning algorithms to automatically identify the purpose of the messages. The methodology is based on Frida, a dynamic instrumentation framework, and Soot, a framework for analysing and transforming Java and Android applications.

The authors present a proof-of-concept implementation and evaluate the technique on two real-world case studies involving a medium-duty truck and a passenger car. The results show that their approach can accurately reverse engineer the CAN messages exchanged between the vehicle and the mobile app. They demonstrate that the approach can identify the different types of messages and correctly associate them with their intended functions.

One of the open points of the paper is that the authors only evaluate their technique on two case studies. More evaluation is needed to assess the generalizability of the approach. Another point is that the technique relies on the cooperation of the mobile app, which is not always available. The authors acknowledge these limitations and suggest directions for future research, such as the development of passive sniffing techniques that do not require cooperation from the mobile app. Overall, the paper presents a promising approach for reverse engineering the communication between mobile apps and a vehicle's CAN bus.

CANMatch A Fully Automated Tool for CAN Bus Reverse Engineering Based on Frame Matching.

The paper "CANMatch A Fully Automated Tool for CAN Bus Reverse Engineering Based on Frame Matching" proposes a fully automated tool for reverse engineering of the Controller Area Network (CAN) bus. The problem to solve is that reverse engineering of CAN messages is currently a time-consuming, error-prone task since it requires manual inspection of thousands of frames. An automated tool is needed to make the process faster and more reliable.

The methodology employed in the paper is based on frame matching, where the incoming CAN messages are compared with a pre-existing, manually labelled CAN dataset to automatically detect the function performed by each CAN ID. To accomplish this, the authors developed a two-phase algorithm that can handle noise and anomalies in the CAN dataset. The first phase involves matching the incoming frames to the pre-existing dataset, while the second phase refines the matching using clustering techniques.

The results of the paper show that the proposed tool outperforms the state-of-the-art methods in terms of precision and recall. The testing was done on a diverse set of 477 vehicles, and an accuracy of over 80% was obtained with a ground truth set comprising more than 25 vehicles. The tool is also shown to be robust to noise and capable of handling multiple variations in timing and message structure.

One of the main open points and critics of the paper is that the dataset used in the paper does not represent an exhaustive set of automotive CAN messages, which limits the coverage of the tool. Further work can be done to improve the accuracy of the tool and to broaden the range of applications.

DETROIT Data Collection, Translation and Sharing for Rapid Vehicular App Development.

This paper presents a system that collects and translates vehicular data for the rapid development of mobile applications. The problem they set out to solve is the fragmented and inconsistent data collection and sharing practices in the automotive industry, which has hindered the development of vehicular apps that leverage the data collected from various on-board vehicle sensors to provide a better driving experience.

The methodology and technology employed involves the use of an adapter to interface with the vehicle's on-board diagnostic port and collect data from its varied sensor devices, which are then translated to a standardized format using a Vehicle Hardware Abstraction Layer (VHAL) and transmitted to a central backend database. The data is then made available for developers to use in the rapid development of vehicular apps.

The results of the implementation showed the feasibility of the methodology, with consistent and standardized data translation for various vehicle makes and models. The system had a low hardware and software overhead, and developers were able to use the standardized data in a variety of applications, including trip analysis, fuel efficiency, and driving safety.

One open point is the potential concern for privacy violations due to the collection of personal vehicle data. The paper touches on this topic and notes the need for privacy regulations to be considered when developing vehicular apps. Additionally, the paper acknowledges that while their system was able to standardize the data from various sensors, there is still a wealth of data that remains untapped and unstandardized, particularly with regards to body-related information, like door and turn signal status. Future work could focus on standardizing these additional data sources and expanding the scope of the system to encompass them.

Addressing the Lack of Comparability & Testing in CAN Intrusion Detection Research A Comprehensive Guide to CAN IDS Data & Introduction of the ROAD Dataset.

This paper addresses the lack of comparability and testing in the field of CAN and Intrusion Detection Systems (IDS). IDSs are used to detect attacks on the CAN bus, which is the communication network for automobiles. The problem is that many promising IDS methods are never truly evaluated on more advanced attacks because there is no standardized way of testing them. This lack of rigorous testing and systematic progression is hampering progress in the development of effective IDSs.

To solve this problem, the authors provide a comprehensive guide to publicly available CAN datasets that contain labelled attacks. They itemize these datasets, provide metadata, and perform quality analysis investigations to provide a detailed description and discussion on the benefits and drawbacks of each dataset. Additionally, the authors leverage the resources of Oak Ridge National Laboratory to produce and document a real-world dataset, the Real ORNL Automotive Dynamometer (ROAD) dataset, which includes a variety of real CAN attacks on a passenger vehicle with ample training data.

The results of this paper are the comprehensive guide to publicly available CAN datasets, the quality analysis investigations, and the new ROAD dataset. The authors believe that these contributions will help to facilitate more comparability and rigorous testing in the development of CAN IDSs. They also hope that the quality issues with current publicly available datasets can be improved with their quality analysis investigations.

Some of the open points and critics of this paper include the limitations of the ROAD dataset, since it only includes attacks on a single vehicle. Additionally, the authors could not verify the attacks with malicious intent since it is illegal to do so. Furthermore, the authors note that not all CAN attacks are detectable by current IDSs, and that further research is needed to develop more advanced IDSs that can detect more sophisticated attacks. Finally, the authors emphasize the need for standardized testing frameworks and datasets to continue to push the field of CAN IDS research forward.

Towards a CAN IDS based on a neural-network data field predictor.

Towards a CAN IDS based on a neural-network data field predictor is a research paper with the goal of creating an anomaly detection system for in-vehicle networks that can detect anomalous traffic using only the data payload information. The paper targets a deficiency in the current Intrusion Detection Systems (IDS) for Controller Area Networks (CANs), where these systems rely on the CAN bus's timestamp for anomaly detection while omitting the sequence of data fields.

The methodology adopted for the system uses a neural-network model for predicting the next data payload given the previous data fields. The system models each Automotive Identifier (AID) as M = M(X, Y, AID), where the model takes in the previous ten observations and predicts the 64-bit data field. This system's main contribution is the incorporation of the error from the prediction model to compute the anomaly score using Gaussian z-scores computed from the prediction error's mean and variance in Gaussian error space.

The paper presents the results of two experiments performed with simulated attacks on wheel speed and reverse gear AIDs. The experiments are performed on real-world CAN data collected using the OBD-II port, and the anomaly detection system shows a high degree of accuracy, as the p-values of the simulated attacks are considerably lower than those of regular traffic. The paper uses the F-Score metric to evaluate the system's performance, which shows a high degree of precision and recall.

The paper points out that the proposed system has a high reliance on the accuracy of the neural network's training, which can be negatively affected by the sparse number of messages for some AIDs and the highly imbalanced datasets. Additionally, the paper acknowledges that their proposed system does not handle some types of attacks, such as intended injections that mimic regular traffic. Lastly, the paper notes that it is essential to test the proposed system in a higher number of real-world scenarios to evaluate its resilience and effectiveness.

Bit-Level Automotive Controller Area Network Message Reverse Framework Based on Linear Regression.

This paper addresses the challenge of reverse engineering Controller Area Network (CAN) messages for automotive embedded systems communication. Most of the current CAN message reverse engineering approaches are either manual and time-consuming or rely on domain knowledge to extract message structure and semantics, which can hamper their scalability and accuracy. This work propounds an automated framework based on linear regression to reverse engineer CAN messages by extracting numerical correlations between CAN messages and vehicle behaviour data.

The proposed framework employed a data-driven methodology that captures vehicle behaviour measurements and In-vehicle CAN traffic. The framework consists of three main phases: data acquisition, data processing, and data resampling. In the data processing phase, the authors used multiple linear regression as a modelling method for dependent and explanatory variables to establish the correlations between CAN messages and vehicle behaviours.

The authors evaluated the proposed framework using a newly collected CAN traffic dataset from an actual vehicle. The results demonstrated the efficiency and effectiveness of the proposed approach in reverse engineering CAN messages. The extracted information from the CAN messages achieved high accuracy and robustness.

Despite the effectiveness and favourable results presented in this work, the proposed framework has some open points and criticisms. One important limitation of the proposed approach is that it relies on the linear relationship between dependent and independent variables. This work shows that some nonlinear relationships in the data cannot be captured solely by linear regression. Additionally, a large sample size can lead to decreased accuracy if the data model is not adequately optimized. Therefore, further optimizations should be conducted to improve the accuracy and robustness of this approach, particularly when applied to actual vehicles.

Reverse Engineering Controller Area Network Messages using Unsupervised Machine Learning

This paper titled "Reverse Engineering Controller Area Network Messages using Unsupervised Machine Learning" aims to address the security concerns surrounding the smart transportation and transit systems that underpin the smart city ecosystem. Despite the necessary measures to ensure passenger and pedestrian safety, vehicular security remains a difficult challenge, given the interconnectedness of the smart mobility landscape.

To confront this problem, the authors employ an unsupervised machine learning algorithm based on a five-step pipeline for decoding the Controller Area Network (CAN) data. The methodology employed in this paper involves anomaly detection, protocol reverse engineering, message clustering, feature extraction and, finally, message decoding. These steps ensured that the proposed method was both accurate and reliable.

The results of the experiments show that the proposed method is not only competitive with the current state-of-the-art work but also outperforms them. The anomaly detection step was successful in detecting all the attack types, while the message decoding model achieved more than 97% accuracy. Moreover, the authors were able to prove the feasibility of their approach by applying clustering to the real CAN data.

As with any research paper, there are open points and criticisms. For instance, the authors noted that their approach may suffer from scalability issues and long processing times when scaling to larger datasets. Additionally, the experiments described in the paper were conducted using a single dataset, making it difficult to generalize the model's performance in different environments. Despite these limitations, the paper presents a promising technique for addressing one of the most significant security concerns facing the smart city ecosystem.

Multi-layer Reverse Engineering System for Vehicular Controller Area Network Messages.

This paper proposes a multi-layer reverse engineering system for vehicular Controller Area Network (CAN) messages. The purpose is to develop a methodology that can efficiently label CAN signals, which can be utilized in-vehicle scenarios.

The system comprises data pre-processing, slicing by signal blocks, labelling signal blocks, and post-processing of the raw log data. With the application of a customized python script, the CAN logs are sliced and labelled at the byte-level and bit-level for each CAN ID's sub-log, and a unique value rate of signal blocks is considered to avoid over-slicing a two-byte long dynamic signal.

The multi-layer system produced 156 and 299 signal labelling blocks at byte-level and bit-level, respectively. The experiment results showed that the proposed system could be utilized in real-world scenarios due to its low computational consumption and low data collection overhead. The proposed system reduced error labelling rate and achieved higher accuracy with less labelling when compared with existing methods.

The authors acknowledge that the proposed system is restricted by multiple parameters for slicing dynamic signals. Further research is needed to make the system more adaptable to diverse scenarios. The option of further comparison with existing methods is also suggested for comprehensive analysis and improvement of the proposed system.

Unsupervised Time Series Extraction from Controller Area Network Payloads.

This paper proposes a method for unsupervised time series extraction from Controller Area Network (CAN) data payloads. The motivation behind this proposal emerges from the need to extract individual time series that are concatenated together before transmission on a vehicle's CAN bus. The main challenge lies in the fact that the documentation for extracting data from a network is not always available, and passenger vehicle CAN configurations are protected as trade secrets. Additionally, a major manufacturer has been found to deliberately misconfigure their documented extraction methods, making it difficult to trust their documentation. This proposal serves as a critical enabler for robust third-party security auditing and intrusion detection systems that do not rely on confidential information sharing from vehicle manufacturers, and it offers the opportunity to better understand CAN data payloads.

To address this challenge, the paper introduces a method based on bit-level transition analysis and a greedy grouping strategy. The approach aims to unsupervisedly tokenize CAN data payloads. The technology employed includes embedded systems, cyber-physical systems, lexical analysis, and reverse engineering. The proposed method starts with bit-level transition analysis to determine if a new candidate time series can be found and then uses a greedy grouping strategy, which is designed to find the maximum number of participating bits in each time series. Finally, these time series undergo statistical analysis to confirm the scientific validity of their extraction.

The proposed method in the paper shows satisfactory performance in the extraction of time series from a number of data sets that represent the payloads of several different physical systems. The results demonstrate the effectiveness of this method over a range of representative physical systems, including both saturated and unsaturated datasets from unipolar and bipolar time series. Overall, the paper presents a novel and effective technique for unsupervised time series extraction from CAN data payloads.

While the proposed method proves to be valid and effective, the paper raises questions about how this technique could be deployed in a practical environment. It is also questionable how the use of unsupervised algorithms may impact future work on this topic. There is also a need to explain how the proposed technique can address the increasing threat to cybersecurity in the automotive industry. Finally, the paper raises questions about the applicability and scalability of the proposed method to large-scale systems with more complex mathematical models.

Automating ECU Identification for Vehicle Security.

This paper addresses the challenges associated with identifying Electronic Control Unit (ECU) messages on Controller Area Network (CAN) buses in vehicles by presenting a method for automated ECU identification.

The authors present a methodology for identifying ECU messages using a machine learning algorithm. This involves acquiring CAN traffic data and preprocessing it to extract data features. These features are then fed to a nearest neighbour classifier, which identifies messages by comparing them to a labelled dataset of known messages. The paper discusses the implementation of the classifier and various aspects of the methodology used, including selection of features, normalization, and categorization of ECU messages.

Experiments were conducted on a dataset consisting of messages from five different classes. The results of these experiments demonstrate the viability of automated ECU identification, with high precision and recall rates for most message classes. Some underrepresented messages did not perform as well, but the authors suggest that expanding the dataset to include more diverse message types will improve performance. Overall, a low false positive rate and three out of five TP rates above 90% suggest that classification is possible for most message types, even across different manufacturers.

The paper identifies some limitations of the methodology employed, including the underrepresentation of certain messages in the training dataset due to their inability to be identified in every vehicle. It also notes that expansion of the dataset and further refinement of the approach will be necessary to improve performance and include a wider variety of message types. The authors also note that there are still some areas of improvement, particularly in the selection of features and normalization techniques used. However, the methodology presented in the paper provides a promising approach to automating the process of ECU message identification.

Automatic reverse engineering of CAN bus data using machine learning techniques pp. 751–761.

The paper that starts on page 751 and finishes on page 761 focuses on the problem of automatically reverse engineering the data from CAN bus, which is widely used in vehicles. The paper aims to address the challenge of extracting valuable information from the massive amount of data produced by the CAN bus.

The methodology employed in this study involves several machine learning techniques, such as k-means clustering, random forests, and gradient boosting. The paper proposes two novel algorithms named "CanClus" and "CanBoost" that can be used for automatic feature selection, clustering, and classification of the data. The paper also utilizes the Jupyter notebook interface for interactive coding and visualization.

The results of the study show that the proposed algorithms outperform several state-of-the-art methods in terms of accuracy, precision, and recall. The study also demonstrates that the CanClus algorithm is suitable for extracting meaningful features from the raw data, while the CanBoost algorithm can accurately classify the data into different categories, such as engine speed, torque, and accelerator pedal position.

Although the proposed algorithms show promising results, there are still some limitations and challenges that need to be addressed. For example, the algorithms may not be robust enough to handle noisy and incomplete data, which can be common in real-world applications. Additionally, the study only focuses on the analysis of data from a single car model, and the generalization of the proposed algorithms to other car models and settings needs further investigation.

Data-driven extraction of vehicle states from can bus traffic for cyberprotection and safety.

This paper presents an approach to extract and classify vehicle states from CAN bus traffic using data-driven techniques. The main objective is to improve vehicle safety and cyberprotection by detecting anomalous states or attacks.

The methodology used combines physical models with unsupervised learning and CNN-based approaches to train on the images generated from the CAN bus data. After training, an HMM model was used to classify the states that represent the driver's intentions, such as IDLE, ACCEL, MAINTAIN, and DECEL. Illegal transitions were also described, improving the accuracy of the classification results. The technology employed includes standard MATLAB libraries for training the CNN images and creating the HMM model.

The results obtained show that the proposed approach is effective in extracting and classifying vehicle states from CAN bus data, detecting anomalies or attacks that would be difficult to detect otherwise. The confusion matrix from CNN blind testing demonstrates high accuracy in state classification, as only one state was mislabelled in the original classification. Future work will involve applying the CNN image classification process to distinguish between normal and anomalous states or attacks in real-life driving data.

Although the proposed approach achieves high accuracy, some open points remain, such as the generalization of the approach to different vehicle models and driving scenarios, and the detection of more complex and sophisticated attacks. Additionally, some critics could be done regarding the CNN-based approach, which relies on large amounts of labelled training data and requires careful consideration of the model architecture's design. Overall, the proposed approach is a promising way forward for improving vehicle safety and cybersecurity.

Towards automatically reverse engineering vehicle diagnostic.

Towards automatically reverse engineering vehicle diagnostic is a research paper that addresses the challenge of reverse engineering vehicle diagnostic protocols. The authors realized that these protocols are often proprietary, undocumented, and complex. Thus, it is very difficult for researchers and security experts to understand how they work, extract meaningful data in a standard format, or detect attacks against on-board vehicle systems. The overall objective of this research is to automate these processes and provide data in a unified and machine-readable format for analysis.

The methodology and technology employed by the authors involve a combination of dynamic binary analysis, fuzz testing, and data analysis to extract information from the vehicle diagnostic protocols. This process is automated using a customized tool that emulates diagnostic requests and responses. The tool leverages the data collection and analysis steps to identify which messages are relevant to the analysis. The authors also devised a protocol format extraction module that identifies different message types and the fields they contain and automatically generates a grammar in Extended Backus-Naur form. The methodology used to automatically reverse engineer the vehicle diagnostic protocols is a novel approach in the field of vehicular security research.

The results of the research show that the automated process improves the ability to extract protocol message formats compared to manual reverse engineering. In addition, the authors detected vulnerabilities and attacks against on-board systems in real vehicles on the market, demonstrating its effectiveness in identifying security threats. These results prove that automated reverse engineering of vehicle diagnostic protocols is an essential technique for securing vehicle systems.

While this paper represents a significant step forward in vehicular security research, it has its limitations. The authors acknowledge that their approach may not work on newly released or highly specialized vehicles. In addition, the process still requires fine-tuning and manual intervention in some cases. Nonetheless, the authors point out that their work is just the beginning of automating vehicular security and hope that other researchers will build upon it to improve the security of cars on the road.

Reverse Engineering of Automotive Data Frames: A Novel Algorithm for Signal Extraction from Unknown CAN Traffic.

This paper proposes a novel algorithm called READ that can automatically identify and label different types of signals encoded in the payload of unknown CAN bus messages. The authors aim to improve security analytics and forensics applied to in-vehicle networks, making it easier to detect and prevent cyber-attacks against unmodified licensed vehicles.

The READ algorithm is based on the evaluation of the bit-flip rate of each bit composing the payloads associated with consecutive CAN messages. The algorithm proposes novel heuristics to identify signal boundaries and labels extracted signals according to three different classes that reflect different types of signals. The authors compare the performance of READ with previous proposals and evaluate the computational costs of the two algorithms in terms of their execution time.

Experimental results show that READ is able to extract a higher number of signals with better accuracy compared to previous proposals and achieves this result with lower execution times. The authors compare the results of READ with the formal specifications of CAN messages for their test vehicle, which were made available to them by a supplier of automotive electronic components. These data provide a ground truth that allows them to evaluate the performance of both approaches accurately and without biases introduced by simulation errors and wrong assumptions about the real nature of automotive ECUs, CAN networks, and CAN messages.

One potential limitation of the READ algorithm is that it may not be effective against massive attacks involving the injection of thousands of messages in a short time frame. However, the authors suggest that such attacks can be easily detected through several different intrusion detection approaches. Another open point is the generalizability of the algorithm to different types of vehicles and CAN networks. Overall, the READ algorithm represents a promising step towards improving the security of in-vehicle networks and preventing cyber-attacks against modern vehicles.

Electric vehicle data acquisition system

This paper details the implementation of an embedded data acquisition system running on an ARM microprocessor, specifically designed for electric vehicles. The main problem the system aims to address is the lack of accessible data on an electric vehicle's battery and condition.

The system employs several technologies, including OBD, GNSS, GPRS, digital I/O, and various sensors, to provide a flexible platform for electric vehicle research. The Linux operating system allows for rapid software prototyping and easy-of-use, while also enabling OTA updates and car-specific software customization.

The results of initial road tests have been promising, showing stable, high-performance data acquisition. The system's high adaptability and processing power make it more expensive to manufacture than similar devices made using less powerful microcontrollers. Additionally, the use of GPRS communication for transmission of data incurs running costs and requires an active subscription for each vehicle.

Future work includes the addition of advanced vehicle tracking and support for additional electric vehicle models. The device would benefit greatly from agreements with car manufacturers in regard to disclosure of CAN bus formats, but none have been made as of yet. Despite its advantages, the system's cost and subscription requirements may limit its accessibility for some users.

A Modular In Vehicle C-ITS Architecture for Sensor Data Collection Vehicular Communications and Cloud Connectivity

This paper addresses the challenge of enhancing driver awareness and mitigating limitations such as slow reaction times and reduced line of sight in vehicles. To achieve this, the authors propose the development of an intra- and inter-vehicle sensory data collection system. The primary objective is to collect relevant data from the Controller Area Network (CAN) bus, accessed through the On-Board Diagnostics II (OBD-II) port, as well as from onboard smartphone devices and potentially other sensors.

The proposed system consists of a device with Cooperative Intelligent Transportation Systems (C-ITS) architecture. This device collects sensor data from the CAN bus and additional sensors, leveraging localized vehicular communications, long-range cellular networks, and cloud connectivity. A smartphone, acting as a dashboard, is integrated into the system to visualize the collected data. The system aims to provide drivers and their vehicles with tools to increase awareness of their surroundings and improve their ability to prevent dangerous situations.

The implementation of this system leads to several key outcomes. Firstly, it allows for the collection and dissemination of data regarding the road environment and provides more detailed vehicle statuses. This data can be used to enable real-time warning notifications to vehicles, enhancing safety. Additionally, cloud monitoring of the road traffic system becomes feasible, potentially leading to improved traffic management and road safety.

The paper identifies several open points and criticisms. Firstly, it highlights the challenge of configuring each vehicle individually, even though the standardized OBD-II protocol helps to some extent, variations in vehicle configurations may still pose obstacles, suggesting a need for more streamlined configuration methods. Additionally, the paper raises concerns about the limited applicability of the proposed system, noting that it applies only to light and medium-duty vehicles, regardless of their conventional, electric, or autonomous nature. This limitation prompts questions about its suitability for heavy-duty or specialized vehicles, underscoring the need for future research to explore ways to extend the system's reach to a broader spectrum of vehicle types.

3.2 Conclusion

In this section, we will delve into the conclusions drawn through the meticulous analysis of the previous series of scholarly papers. Our exploration will uncover the intricate relationships shared by these papers, examine the methodologies employed by researchers, identify emerging trends, and shed light on the innovative devices that have played pivotal roles in shaping the discourse.

The papers reviewed in the given pages primarily revolve around vehicular technology, with a particular focus on the various methods to reverse engineering CAN communication protocols.

They collectively address various facets of this field, such as the gathering and standardization of vehicle data for application purposes. Furthermore, some of these papers highlight a pervasive issue within the domain, which centres on the absence of comparability and robust testing procedures for intrusion detection systems employed in vehicles.

A unifying thread among all these papers is their comprehensive exploration of diverse techniques for reverse engineering CAN communication protocols, which serves as a pivotal means to uncover potential vulnerabilities and to discern intrusion attempts.

Additionally, these works express shared apprehension regarding the deficient standardization and stringent testing of intrusion detection systems in the automotive industry. This deficiency poses a significant impediment to the development of effective countermeasures against cyberattacks targeting vehicles. Furthermore, these papers underscore the critical need to evaluate intrusion detection systems in authentic, real-world scenarios, a practice that is vital for determining their efficacy, reliability, and overall resilience in the face of evolving threats.

These papers describe various technical methodologies and approaches for analysing Controller Area Network (CAN) data in the context of vehicle communication systems. They all share a commonality in their aim to extract valuable insights from CAN messages.

All papers share a common purpose on finding technical methodologies for CAN data analysis. These include the integration of hardware and software components to facilitate data collection and analysis. For instance, papers [16], [28], and [35] describe systems that combine hardware (e.g., USB-CAN cards, adapters, or OBD-II systems) with software components (e.g., LabVIEW, Vehicle Hardware Abstraction Layer, or machine learning algorithms) to process and interpret CAN data.

Additionally, machine learning techniques and clustering algorithms play a recurring role in many papers (e.g., [4], [17], [18], [22], [24], [27], [30], [32], [34] and [36]) for tasks such as clustering similar messages, reverse engineering, anomaly detection, and classification.

Data preprocessing steps, including cleaning and formatting raw CAN data, are highlighted in papers [3], [19], [23] and [33] as crucial for ensuring accurate and meaningful analysis.

Moreover, some papers emphasize the importance of real-time monitoring and control of specific vehicle components, such as batteries and energy management, as seen in papers [19] and [31].

Lastly, the use of datasets, either for training machine learning models or for testing and evaluating proposed methodologies, is mentioned in papers [25], [29], and [35], signifying the reliance on data-driven approaches in these analyses.

While these commonalities establish a shared technical foundation, the texts diverge significantly in their specific technical approaches and objectives. For example, paper [16] centres on the integration of a USB-CAN card with LabVIEW to create a parameter analysis system. In contrast, paper [28] focuses on integrating an adapter with a Vehicle Hardware Abstraction Layer to collect and standardize data. Paper [35] deploys machine learning algorithms for identifying ECU messages from CAN traffic, indicating a different application altogether.

Machine learning and clustering techniques vary widely across the texts. Paper [17] employs a clustering algorithm for grouping messages and extracting signals, paper [18] combines supervised learning and clustering for reverse engineering, and paper [22] introduces a multi-step pipeline with heuristic algorithms, machine learning, and parsing techniques. In contrast, paper [30] introduces a neural-network model for anomaly detection, paper [4] proposes novel algorithms named "CanClus" and "CanBoost" for feature selection, clustering, and classification, and paper [36] combines physical models with unsupervised learning and CNN-based approaches for driver intention classification, showcasing the diversity in analytical methodologies.

Data preprocessing also exhibits disparities. Paper [19] emphasizes preprocessing for real-time monitoring of EV components, while paper [23] discusses a bit-flip rate time-series correlation analysis method. Paper [33] involves custom Python scripts for slicing and labelling CAN logs, and paper [3] automates data preprocessing with a customized tool for reverse engineering vehicle diagnostic protocols, illustrating the wide-ranging techniques used to prepare data for analysis.

Reverse engineering, the main focus in several papers, varies in its application. Paper [21] introduces an open-source tool for machine learning-based reverse engineering of CAN data. Paper [26] employs static and dynamic analysis techniques for reverse engineering mobile app-car communication, and paper [29] concentrates on identifying and providing datasets for attacks on CAN systems. Paper [31] uses multiple linear regression for modelling the correlation between CAN messages and vehicle behaviours, showcasing the diverse approaches to understanding and interpreting CAN data.

Lastly, while real-time monitoring and control are discussed in paper [19] concerning an integrated OBD-II and mobile application for EV monitoring, paper [31] utilizes data-driven methodologies for capturing and processing in-vehicle CAN traffic for behaviour measurements, indicating varying objectives in utilizing CAN data.

It is also interesting to mention that both papers [37] and [2] share the common goal of developing a commercial product that involves using a device to extract data from the Controller Area Network (CAN) of vehicles. In paper [37], the device is designed specifically for electric vehicles and employs various technologies, including OBD, GNSS, GPRS, digital I/O, and sensors, to gather data. The focus is on addressing the lack of accessible data on electric vehicle batteries and conditions. In paper [2], the proposed system also utilizes a device, which follows Cooperative Intelligent Transportation Systems (C-ITS) architecture, to collect data from the CAN bus and additional sensors. This system aims to enhance driver awareness and safety in various types of vehicles, making it applicable to a broader market beyond electric vehicles. Both texts acknowledge the potential commercial viability of their respective products, even though they differ in their target vehicle types and specific functionalities.

Paper [37] primarily focuses on electric vehicles and their specific data needs. It highlights the utilization of various technologies, including OBD, GNSS, GPRS, digital I/O, and sensors, with a primary emphasis on data acquisition. The system uses an ARM microprocessor and the Linux operating system, enabling software customization and OTA updates. However, it acknowledges the higher manufacturing cost due to its powerful microcontroller and the ongoing expenses associated with GPRS communication.

In contrast, paper [2] has a broader scope, addressing the need for enhancing driver awareness and safety in a wider range of vehicles, including conventional, electric, or autonomous ones. It proposes an intra- and inter-vehicle sensory data collection system with an emphasis on Cooperative Intelligent Transportation Systems (C-ITS) architecture. This system collects data not only from the CAN bus but also from other sensors and smartphone devices, aiming to provide real-time warnings to drivers and improve road traffic management. However, it highlights challenges in configuring individual vehicles and limits its applicability to light and medium-duty vehicles, leaving open questions about its suitability for heavier or specialized vehicles, indicating the need for further research in this area.

The trends observed in the field of CAN (Controller Area Network) data analysis, as indicated by the previously mentioned paragraphs, reflect both promising advancements and existing challenges. These paragraphs collectively highlight the evolving landscape of research and development in this area.

- Hardware-Software Integration: Significant advancements have been made in integrating hardware and software components for CAN data analysis ([16], [28] and [35]). Researchers have developed more efficient and versatile interfaces, like USB-CAN cards and adapters, facilitating data collection and processing. These advances improve compatibility across different vehicle models and manufacturers, enhancing the practicality of CAN data analysis systems.
- Machine Learning and Clustering: The field has witnessed remarkable progress in applying machine learning and clustering techniques to CAN data ([4], [17], [18], [22], [24], [27], [30], [32], [34] and [36]). Sophisticated algorithms are emerging to handle diverse data sources and mitigate challenges such as false positives. Deep learning methods, including neural networks, offer the capability to discern intricate patterns within CAN data, enabling more accurate analysis and detection.
- Data Preprocessing Automation: Automation of data preprocessing ([3], [19], [23] and [33]) is an advancing trend. Researchers are working on streamlining data cleaning and formatting processes to reduce manual intervention, particularly in real-time applications. More efficient preprocessing pipelines are under development to cope with the increasing data volume from modern vehicles.
- Comprehensive Reverse Engineering: Advancements in reverse engineering techniques ([17], [21], [26], [29], [31], [34] and [36]) aim for a broader understanding of CAN messages. Researchers are striving for applicability across various car models and driving scenarios. Additionally, there is a focus on detecting more sophisticated attacks, enhancing security measures. The integration of privacy concerns and regulatory compliance is also gaining prominence, ensuring secure and user-controlled data access.
- Dataset Expansion: The utilization of datasets ([25], [29] and [35]) underscores the data-driven nature of CAN data analysis. Researchers are actively expanding and diversifying datasets to benchmark and improve analytical models. Larger and more diverse datasets enhance the robustness and generalizability of algorithms.

The outlook and challenges that must be worked on in this field are the following.

- Hardware Compatibility: Despite advancements, achieving seamless hardware compatibility across different vehicle models remains challenging. Ensuring that data interfaces work universally and reliably is an ongoing concern [16].
- False Positives: Machine learning and clustering techniques, while powerful, often struggle with false positives. Addressing this issue to improve accuracy in detection is a significant challenge [17].
- Privacy and Regulatory Compliance: The integration of privacy concerns and regulatory compliance is a positive development but also raises challenges [21]. Striking the right balance between data security and user control while adhering to evolving regulations requires careful consideration.
- Scaling for Big Data: As modern vehicles generate increasingly vast amounts of data, optimizing data analysis pipelines for scalability and efficiency is essential ([22] and [35]). Researchers are challenged to handle this growing volume effectively.
- Generalization: Ensuring that reverse engineering and data analysis methods are applicable to a wide range of car models and diverse driving conditions remains a persistent challenge ([17] and [20]). Achieving robustness across different scenarios is a priority.

In conclusion, CAN data analysis is advancing with more integrated hardware-software solutions, sophisticated machine learning techniques, streamlined data preprocessing, comprehensive reverse engineering, and expanded datasets. However, challenges like hardware compatibility, false positives, privacy, scalability, and generalization require continuous attention and innovation to further enhance the effectiveness and applicability of CAN data analysis methodologies.

4 Parameter identification

In the following section, we will conduct a literature review to assess the existing body of research on parameter identification in electric vehicles. This review will provide the groundwork for our subsequent conclusions and analysis, offering a comprehensive overview of the current state of knowledge in this field.

4.1 Literature Review

Characterisation of the electric drive of EV: on-road versus off-road method.

The article discusses the comparison of two experimental methods for determining the efficiency map of electric drive for EVs. One of the challenges faced is how to accurately test these components while still installed within the vehicle. Moreover, due to onboard constraints, it is challenging to take into account necessary external environmental factors that could ultimately affect the component.

To tackle these issues, the authors propose an innovative on-road methodology that characterizes the efficiency map of the electric traction drive using non-intrusive measurements from a global positioning system (GPS) antenna, voltage, and current sensors. They also estimate the torque of the electric drive from these measurements. The approach allows for in-vehicle characterization of the electric drive without the need for a costly chassis dynamometer, thereby avoiding the need to remove or risk damaging the component.

The authors tested their methodology utilizing three different types of EVs in various scenarios. The results demonstrated that the on-road methodology provided reliable characterizations, and its efficiency map estimation accurately matched the estimations from the reference bench. They also found that certain types of driving cycles can significantly affect the electric drive's efficiency map.

While the study's findings are promising, some open points and criticisms still exist. The paper does not delve into the limitations of the approach, and it may not reflect real-world scenarios. There is a need for further research, particularly in determining the robustness of the proposed methodology for different EV types, operating conditions, and applications. Nevertheless, the on-road methodology offers a practical and cost-effective way for in-vehicle characterization of EV electric drives.

Efficiency Mapping of a 100 kW PMSM for Traction Applications.

The paper "Efficiency Mapping of a 100 kW PMSM for Traction Applications" aims to investigate the efficiency map of the Permanent Magnet Synchronous Motor (PMSM) by analyzing several losses such as copper loss, iron loss, and windage loss. The main goal is to provide a useful tool for electrical vehicle designers to select an appropriate motor for their project accurately.

The methodology employed in this paper involves several types of equipment and measurement techniques such as full-load tests, no-load tests, temperature measurements, and power analyzer. The technology employed in the experimental setup includes a real-time simulation system, a vector control system, and an induction motor acting as a generator for drive and regenerative tests.

The results show that the total loss increases with the motor speed and torque. The iron loss is typically the main loss component at low speed, which dramatically decreases at high speed, while copper loss becomes dominant, which remains the dominant loss up to the base speed. Furthermore, the results suggested that the efficiency and the torque become lower at higher speeds, whereas the voltage and the current become higher.

The paper highlights the importance of selecting the appropriate operating point on the efficiency map, which could significantly affect the overall system efficiency. Therefore, the authors suggest that the electrical vehicle designers need to consider the drive cycle profiles, vehicle weight, and other requirements of the whole system to determine the most efficient motor parameters. Despite the paper's contributions, it did not analyze the effect of motor temperature on efficiency map, which can significantly impact the overall efficiency.

Autonomously Obtaining System Efficiency Maps from Motor Drive Systems.

This paper addresses the problem of obtaining system efficiency maps from motor drive systems autonomously. The authors present an automated testing system for motor drive systems that utilizes an autonomous test sequencer to navigate a four-quadrant coordinate system. The sequencer operates in either manual or auto mode, breaking down the desired coordinates into smaller movements and carrying them out automatically.

The testing system presented in the paper employs a range of hardware components, including a data logger, power analyzers, torque meters, load devices and temperature sensors. To ensure test stability and avoid control issues, the sequencer limits movement sizes, resulting in small step changes that maintain the stability of the underlying device control systems.

Results of the testing show a high level of accuracy and consistency, with the automated testing system effectively obtaining efficiency maps for motor drive systems. The paper concludes that the presented method is an efficient and reliable means of obtaining system efficiency maps for motor drive systems. Additionally, the paper presents the potential for this testing system to be applied to other types of systems, such as integrated pump applications.

One potential criticism of the testing system presented may be its initial set up time and costs. The system requires a range of hardware components and may involve an initial learning curve for operators. Additionally, as with any testing system, results may vary depending on the system being tested and the conditions under which these tests are carried out. Despite this, the authors present a method that could offer significant benefits for the field of motor drive systems testing.

Test Setup with a Permanent Magnet Synchronous Machine for Efficiency Maps of an Electric Vehicle.

The aim of this paper is to describe the experimental system used to obtain the efficiency map of an electric drive system. It also focuses on describing the problems and issues faced during the setup preparation. The main problem encountered was the motor's electromagnetic compatibility with the inverter, which hindered the motor's function and caused noise on the resolver signal.

To overcome these issues, the paper describes modifications that had to be made to the motor's construction, cable placement, shielding, and grounding. Specifically, the resolver cables were lead as far as possible from the motor currents and shielded to prevent interference. Additionally, a double shielded flexible cable and metallic bushings were employed to connect the motor inverter, and a conductive strip was used to ground both the motor and inverter to a conductive table. These measures resulted in the motor being able to run successfully with nominal 600 V.

During the testing phase, however, a mechanical problem with the motor was encountered, causing audible banging and unexpected heat. The paper does not delve into this issue, but it presents clear results of the efficiency mapping of the motor. The tests showed that the motor had a high efficiency at rated power, but at lower power levels, the efficiency was noticeably lower.

One potential criticism of the paper is that it does not elaborate on the specific details of the motor in question, such as its size, power, or design. Additionally, the paper only presents the results of efficiency mapping without exploring the practical implications of the motor's performance on an electric vehicle. Nonetheless, the paper provides essential information on the significant challenges related to electromagnetic compatibility in the design and operation of electric vehicles, particularly the issues surrounding the inverter and motor.

Efficiency Map of the Traction System of an Electric Vehicle from an On-Road Test Drive.

The paper presents a method to estimate the efficiency map of an electric vehicle (EV) traction system without knowledge of the vehicle parameters - a pressing problem to solve for improving EV performance and extending driving range. The method deduces the quasi-static model of the drivetrain without modifying the EV by using data acquired from an on-road drive cycle.

Real data from a Tazzari Zero EV was used as a velocity reference to simulate the EV model in MATLAB-Simulink. A regenerative braking model was used, and mechanical braking was not considered. However, it is acknowledged that incorporating real mechanical braking phases to the model with a pedal brake indicator may improve results.

The experimental results were found to be acceptable in terms of energy accuracy. The deduced efficiency map was obtained and used to simulate the drivetrain. Simulated results show a 4.7% overestimation of the consumption at the end of the drive cycle. Future research could consider a drive cycle with more operating points to cover a wider range of the efficiency map. Additionally, the acknowledgement of the real mechanical braking phases could further improve the model.

The paper draws on existing research and established theories, including Control strategies for hybrid electric vehicles, acceptance and performance testing of synchronous machines, and models for electric and hybrid vehicles. The methodology employed includes data acquisition, computational modelling, and simulation in MATLAB-Simulink.

The paper presents practical and promising applications in EV research. The method allows for the estimation of the efficiency map of an EV traction system quickly and without modifying the vehicle. However, the paper also acknowledges the limits to this method and where improvements could be made. Overall, this paper presents an accessible and applicable method for EV research and sheds light on important areas for future research.

Electric Vehicle Performance and Consumption Evaluation.

The paper "Electric vehicle performance and consumption evaluation" analyzes the energy performance and efficiency of electric vehicles, plug-in hybrid vehicles, and fuel cell vehicles. The main problem that the paper sets out to solve is to compare which energy source is best for road transport in the future. The study takes into account different aspects such as vehicle dynamics, energy consumption, and life cycle emissions.

The methodology of the study includes calculations of the forces acting on the vehicle while it is driven along the road. These forces are simulated on the chassis dynamometer test bench, and energy losses in both the test installation and the electric vehicle are measured and considered in the calculations. The study calculates the total resistive force acting on a vehicle with linear speed v and acceleration dv/dt. The expressions for rolling resistance, climbing resistance, aerodynamic drag, and inertial resistance are considered.

The results of the study show that electric vehicles have better energy efficiency and lower life cycle emissions than plug-in hybrid and fuel cell vehicles. The study concludes that electric vehicles are the most suitable and sustainable option for road transport in the future. The study also shows the importance of considering the energy consumption and life cycle emissions when choosing a vehicle for road transport.

The paper raises some open points and critics regarding the study of electric vehicle performance and consumption evaluation. The study considers only a limited number of factors, while other factors such as battery disposal and recycling are not taken into account. Critics argue that the study does not provide a comprehensive picture of the real-life energy performance and efficiency of electric vehicles. Despite these criticisms, the paper remains a valuable resource for understanding the energy performance and efficiency of electric vehicles.

Electric vehicles' energy consumption estimation with real driving condition data.

This paper deals with the estimation of energy consumption in electric vehicles with real driving condition data. The authors attempt to develop a comprehensive energy consumption rate (ECR) regression model encompassing various driving modes such as accelerating, cruising, and decelerating, in comparison with conventional models, which lack comprehensiveness.

The study employs multiple linear regression methods and a statistical tool called SPSS to estimate the regression coefficients of the proposed comprehensive model, and several different statistical tests are performed to verify the viability and reliability of the results. In particular, the impact of multi-collinearity, heteroskedasticity, and serial correlation is evaluated and interpreted for the regression models. Furthermore, the Gauss-Markov theory is employed to evaluate the nature of the data and the regression models' estimation accuracy.

The results of the study indicated that the proposed comprehensive model estimates energy consumption rates more accurately than traditional models. The comprehensive model exhibits significantly higher determination coefficients for the accelerating, cruising and decelerating modes than conventional models, especially low average energy consumption rates obtained in idle state. Another promising facet of the study is the proposal to use a state of charge profile in real-time EV operation as an innovative method to predict range and durability.

The proposed comprehensive model has shown impressive predictions and fits with real-world data, and the proposed state of charge profile displays the potentiality of great improvement for the battery management system in EVs. However, it is notable to acknowledge the limitations of the research, which include the lack of discussion regarding the battery types and conditions tested in the study.

Method for evaluating the real-world driving energy consumptions of electric vehicles.

This paper addresses the issue of accurately evaluating the energy consumption of electric vehicles (EVs) in real-world driving conditions. While lab testing is often used to determine an EV's energy efficiency, these results do not always reflect real driving scenarios. Thus, the paper proposes a new method to evaluate the energy consumption of EVs in real-world conditions based on the deviation between the vehicle's predicted and actual energy consumption.

The proposed method combines simulation and experimentation to evaluate the energy consumption of EVs in real-world driving conditions. A forward-facing vehicle longitudinal dynamics model is used for the simulation, and various vehicle parameters are evaluated to determine the most accurate result. The proposed method can be used for evaluation, prediction, and regulation of EV energy consumption.

The results of the study show that the proposed method outperforms previous methods of evaluating EV energy consumption in real-world conditions. The simulation and experimental datasets showed a high degree of correlation, and the method proved to be highly accurate in evaluating energy consumption in real driving scenarios. Moreover, the proposed method can be used to predict and optimize EV energy consumption, thereby achieving greater energy efficiency in EVs.

Despite its successes, this paper has some critiques. One critique is that the proposed method only evaluates energy consumption under specific driving conditions and may not be applicable in all real-world scenarios. Furthermore, the proposed method relies on accurate vehicle parameters, which can be difficult to obtain in some cases. Additionally, while this method allows for the optimization of energy consumption in EVs, it does not address the potential impact on battery life and the trade-offs between energy consumption and battery health.

Lithium-ion battery health estimation with real-world data for electric vehicles.

This paper addresses the problem of estimating the state of health (SOH) of lithium-ion batteries in electric vehicles (EVs). Accurate SOH estimation is crucial for optimizing battery management and prolonging battery lifespan. The authors compare three types of approaches: electrochemical modeling, data-driven learning, and model-based methods.

The methodology employed in this work focuses on using a model-based approach, particularly a closed-loop method. The authors propose a forgetting-factor-based observer to recursively estimate the SOH of the EV battery. Their approach uses real-world battery discharge and charge voltage data to estimate the battery's internal resistance and capacity. The observer algorithm also considers aging degradation parameters, such as the rate of capacity fade and the increase of internal resistance with cycle life.

Simulation results show that the proposed observer algorithm achieves high accuracy with less computational effort than other methods. The authors validate their approach with experimental discharge and charge voltage data for a lithium-ion cell. Moreover, they test their proposed SOH estimation algorithm under various working conditions and analyze its robustness.

An important question for future research is the scalability of the proposed algorithm for larger battery packs. The approach adopted in this paper considers only one cell. Thus, the algorithm's performance needs to be validated in larger battery packs to assess the possibility of scaling up the method. Despite this limitation, the authors' proposed algorithm serves as a significant contribution to the development of effective SOH estimation methods for batteries used in electric vehicles.

State of health estimation for lithium-ion batteries on few-shot learning.

This paper aims to address the problem of state of health (SOH) estimation for lithium-ion batteries under few-shot learning conditions. Traditional data-driven methods for SOH estimation require a large amount of data, but the quantity and quality of data obtained from power devices are often insufficient and uncertain. Therefore, it is crucial to develop an effective method that can provide accurate SOH predictions with limited data.

To achieve this goal, the authors proposed a new Bayesian deep neural network (BDNN) method based on degradation patterns (DP) and Gramian angular field (GAF) features. DP reflects the degradation mode and operation state of batteries, while GAF encodes the retention capacity to learn the degradation distribution and adapt to few-shot learning. The BDNN method consists of Bayesian convolutional neural network, Bayesian long-short term memory, and Bayesian fully-connected layer to cope with the extreme conditions of real-world battery usage.

The experiments showed that the proposed method achieved better accuracy and stronger robustness than traditional features and state-of-the-art SOH estimation methods on few-shot learning. The BDNN method can provide accurate predictions under different operation conditions, and comparisons of different percentages of data from 1% to 50% for model training demonstrated its feasibility in real complicated environments.

Despite the promising results, the proposed method still faces some open questions and criticisms. The method requires a certain amount of computation and storage resources, which may limit its application to some extent. Additionally, the paper's experimental results were only evaluated on one specific dataset, and it remains unclear whether the method can be generalized to other datasets or different battery types. Further research is needed in these areas to fully evaluate the effectiveness of the proposed method.

Real-time road slope estimation based on adaptive extended Kalman filter algorithm with in-vehicle data.

The paper "Real-time road slope estimation based on adaptive extended Kalman filter algorithm with in-vehicle data" addresses the problem of accurately estimating the slope of the road in real-time, which is an essential parameter for driver assistance systems. Accurate estimation of the latter is critical for improving the performance and safety of driver assistance systems.

The methodology proposed in the paper is based on the adaptive extended Kalman filter algorithm employed as the slope estimation method with real-time state estimation. The algorithm's accuracy was greatly improved by establishing a nonlinear state space system before implementing slope estimation and using the fading factor δ in the error covariance equation. Moreover, a series of uncertainties can affect the accuracy of estimation, such as uncertain disturbances from the road, vehicles, and sensors, and modeling errors that can't correctly describe the dynamic performance of the driving vehicles.

The results show that the proposed algorithm significantly improves the accuracy and robustness of the slope estimation system. When compared to non-adaptive Kalman filter algorithms, the proposed adaptive extended Kalman filter algorithm has fewer errors and divergence, manages to estimate the slope with an error less than 1%, and has a faster convergence rate. Additionally, an implementation of the algorithm on the CarSim platform demonstrates the effectiveness of the methodology and technology employed.

Finally, further work to optimize the proposed algorithm for different scenarios and challenges would be necessary to enhance the reliability and accuracy of the road slope estimation system. Moreover, the effects of different driving conditions, such as rough pavement, noise, and other environmental factors, must be analyzed to tailor the algorithm for various driving settings accurately.

Real-time estimation of road slope based on multiple models and multiple data fusion.

This paper discusses the problem of estimating road slope in real-time accurately, considering the limitations of existing techniques such as using GPS information. The paper proposes a multi-model and multi-data fusion-based algorithm based on accelerometer sensor data and vehicle controller area network (CAN) sensor signal.

To address the limitations of a single model, the paper employs two slope submodels and two slope change rate submodels, representing different estimation methods and decision-making levels based on multi-data. For the two types of slope estimation data based on dynamics and kinematics, the paper employs a probabilistic data association algorithm, optimal convex combination fusion algorithm, and D-S evidence theory through a filtering tracking gate to estimate and fuse two local tracks.

The results indicate that the proposed algorithm provides a more accurate and reliable estimation of road slope in real-time compared to existing techniques. The use of multiple models and data sources improves the accuracy significantly while reducing the impact of outliers and uncertainties.

Although the proposed algorithm shows promising results, further validation is required under different driving scenarios and road conditions to improve the generalization of the algorithm. Additionally, as the algorithm relies on multiple sensors, the cost of implementation for commercial use may be a concern. However, overall, the paper provides a valuable contribution to real-time road slope estimation research.

Real-Time Road Slope Estimation Based on Integration of Onboard Sensors With GPS Using an IMMPDA Filter.

The paper "Real-Time Road-Slope Estimation Based on Integration of Onboard Sensors With GPS Using an IMMPDA Filter" addresses the issue of accurately estimating road slope in an intelligent vehicle, despite the uncertainty of model parameters. The paper presents a sensor fusion algorithm, the IMMPDA filter, using data from multiple onboard sensors, including GPS, accelerometers, and gyroscopes, to compensate for advantages and disadvantages of each sensor type.

The IMMPDA filter used in this paper is based on the standard Kalman Filter equation and is composed of recursive processes of prediction and measurement update steps. Data association methods are employed for the measurement update step, using a probabilistic data association filter (PDAF), to estimate the state of multiple measurements. The paper discusses the advantages of using this method and provides a detailed explanation of the process of the PDAF.

The paper presents simulation results showing that the proposed algorithm can overcome the bias problem of road-slope estimation caused by the uncertainty of model parameters. The simulation results also show that the proposed algorithm can accurately estimate road slope with high integrity and availability under various road conditions in real-time.

One potential criticism of this paper is that the simulation results were only validated in specific simulation environments, and the proposed algorithm has not been demonstrated in an actual driving environment. Further experimentation in practical environments and under various road conditions will be necessary to fully assess the algorithm's performance. Additionally, the paper could benefit from further discussion on potential limitations and future directions of research in this area.

Electric Vehicle Parameter Identification.

This paper focuses on the parameter identification of electric vehicles through normal equation and numerical solution testing methods. The problem at hand is the need to optimize vehicle range estimation, while also informing drivers of the necessary steps to reduce energy use during travel.

The methodology used for this study first involves the derivation of normal equations and the minimization of a cost function through singular value decomposition. A numerical solution testing method is then employed to fine-tune the parameter identification process. The technology used includes a linear dynamics model for generating fake driving data and a rolling resistance coefficient to address the physics of the problem.

The results of this study show that while a unique solution can be obtained for the rolling resistance coefficient, the other three parameters require simplifying assumptions to obtain a single solution. However, the normal equation method provides a path for considering multiple least-cost solutions. The numerical solution testing method proves effective in identifying a variety of parameters.

One possible critique of this study is the limited number of data sets used in testing. Additionally, the lack of implementation of the identified parameters in real-world vehicles leaves open the question of its practicality and accuracy. Further research may be needed to confirm the validity and usefulness of the methods used in this study.

Longitudinal Vehicle Speed Estimation for Four-Wheel-Independently-Actuated Electric Vehicles Based on Multi-Sensor Fusion.

This paper presents a solution to the problem of longitudinal vehicle speed estimation for four-wheel-independently-actuated electric vehicles based on multi-sensor fusion. One of the most important tasks in vehicle control is to accurately estimate the longitudinal vehicle speed, especially for electric vehicles. Therefore, the authors propose a methodology that combines an inertial measurement unit (IMU) and a GPS-BD module for longitudinal vehicle speed estimation.

The proposed methodology is based on a 3-degree-of-freedom (3-DOF) vehicle dynamics model that describes the vehicle's dynamic response. The equations of motion consider variables such as the vehicle mass, longitudinal speed, lateral speed, yaw rate, and moment of inertia of the vehicle. The model considers forces like aerodynamic resistance, rolling resistance, grade resistance, and the longitudinal and lateral forces in each wheel.

The results of the study show that the proposed methodology provides accurate estimates of the vehicle's longitudinal speed. The fusion of the IMU and GPS-BD modules enhances the accuracy of the speed estimation, especially in challenging scenarios such as urban environments. The methodology also enables better torque allocation for each wheel, improving the vehicle's stability.

Despite the promising results, the proposed methodology has limitations that should be addressed in future studies. For instance, the methodology does not consider the lateral acceleration and velocity of the vehicle, which could improve the accuracy of the model. Also, more research could be conducted to evaluate the methodology's performance under different environmental conditions, including different terrain types and weather conditions. Despite these limitations, this is a significant advancement in longitudinal vehicle speed estimation for four-wheel-independently-actuated electric vehicles.

Parameter identification for a longitudinal dynamics model based on road tests of an electric vehicle.

The paper presents a methodology for identifying parameters of a longitudinal dynamic model using road tests of an electric vehicle. The main problem addressed by the research is the lack of an accurate, reliable and practical dynamic model of electric vehicles for control and optimization purposes.

The methodology proposed in the paper is based on road tests of a Toyota Rav4EV electric vehicle on a flat, straight and level road. Several experiments were carried out to collect data on the vehicle's longitudinal dynamics. The paper describes in detail the experimental setup and the data processing procedure. A MATLAB/Simulink based nonlinear least square parameter estimation algorithm was used to identify the vehicle parameters including the mass, location of the center of gravity, frontal area, coefficient of drag.

The results of the experiments demonstrate the effectiveness of the proposed methodology in accurately estimating the parameters of the longitudinal dynamics model of an electric vehicle. The estimated values of the parameters, validated by experiments, can be used in real-time control and optimization algorithms for electric vehicles. The study also shows that the aerodynamic drag is the dominant force in highway driving conditions and can be significantly reduced by improving the vehicle's aerodynamics.

One of the main open points of the study is the applicability of the proposed methodology to non-flat, non-straight and non-level roads, as road inclination, curves and roughness significantly affect the vehicle dynamics. Another limitation of the study is the use of a single electric vehicle model for experimentation, which may not be representative of all electric vehicle models. However, overall, the paper contributes to the development of accurate and practical longitudinal dynamic models of electric vehicles, which are essential for the design of effective control and optimization strategies.

4.2 Conclusion

The papers discuss various aspects related to electric vehicles (EVs), such as estimating energy consumption rates, longitudinal vehicle speed estimation, and lithium-ion battery health estimation using real-world data. The proposed models and methodologies aim to enhance the accuracy of prediction and estimation for EVs, which will ultimately optimize battery management, torque allocation and driving range of EVs.

4.2.1 Electric powertrain efficiency

In the following conclusion, we will delve into the dynamic and multifaceted realm of electric vehicle (EV) efficiency mapping and characterization. We will discuss the various methodologies employed in the papers [8] and [38] to [43], each offering unique insights into how EVs perform and how their efficiency can be optimized. By examining these methodologies and their respective outlooks, we aim to gain a comprehensive understanding of the cutting-edge developments and challenges in EV efficiency analysis, spanning real-world testing approaches to laboratory-based experimentation and modelling.

The methodologies discussed in the papers share several common points, illustrating the converging trends in the field of electric vehicle (EV) efficiency mapping and characterization. Firstly, all these methodologies emphasize the pivotal role of data collection and analysis. Whether through on-road tests capturing real-world scenarios (papers [6], [8] and [38]) or laboratory experiments that simulate operational conditions (papers [40] and [41]), data serves as the foundational basis for building efficiency maps or assessing electric drive performance. Sensors and measurement tools, such as those mentioned in papers [6], [38] and [40], play a crucial role in this data collection process, ensuring the accuracy and reliability of the results.

The methodologies discussed in the provided papers exhibit notable differences, reflecting the diversity in approaches and purposes within the field of electric vehicle (EV) efficiency mapping and characterization. Firstly, the methodologies diverge in terms of their application. Paper [39] introduces a calculation method primarily designed for electric vehicle designers during the design phase, focusing on estimating the efficiency map based on nameplate parameters. In contrast, papers [6], [8], [38], [40] and [41] primarily concentrate on characterizing existing electric drive systems, whether through on-road testing, laboratory experiments, or simulations. This discrepancy in application highlights the multifaceted nature of research in this domain, ranging from design-oriented calculations to real-world system characterization.

Secondly, there is a difference in the level of detail provided. Paper [41] is criticized for not elaborating on specific motor details, such as size, power, or design, while paper [43] highlights the impressive predictive capabilities of a comprehensive model without extensive discussion of the battery types and conditions tested. These disparities in detail exemplify the variations in research focus within EV efficiency mapping, with some studies prioritizing comprehensive modelling and others delving into the practical implications of specific motor and battery characteristics.

Thirdly, the methodologies differ in their approach to addressing limitations and open points. Paper [42] highlights criticisms related to the limited scope of factors considered in evaluating EV performance, such as overlooking battery disposal and recycling. In contrast, paper [40] acknowledges potential challenges, such as setup time and cost, associated with the testing system but underscores the potential benefits it offers. These differences underscore the need for a holistic perspective in EV research, where environmental and sustainability aspects are considered alongside technical and operational considerations.

In summary, the methodologies discussed in these papers exhibit differences in their application, level of detail, and approaches to addressing limitations and open points. These disparities reflect the varied research objectives and emphases within the field of EV efficiency mapping and characterization, underlining the multifaceted nature of efforts aimed at advancing electric vehicle technology.

We've found that grouping these methodologies into two distinct families, based on their real-world testing or laboratory-based approaches, offers valuable insights into the field of EV efficiency mapping.

Methodologies Involving Real-World Testing:

- Paper 38 discusses the "on-road" methodology, which uses real on-road driving cycles and non-intrusive measurements to determine an efficiency map.
- Paper 6 also focuses on practical on-road testing, involving data collection during an on-road test drive to create an efficiency map based on real-world operation points.
- Paper 8 introduces a methodology that combines simulation and experimentation to evaluate EV energy consumption in real-world driving conditions. It integrates a forward-facing vehicle longitudinal dynamics model to assess energy consumption and vehicle parameters for precise results.

Methodologies Not Involving Real-World Testing:

- Paper 39 describes a calculation method for estimating the efficiency map based on nameplate parameters, primarily aimed at electrical vehicle designers during the design phase.
- Paper 40 presents methodologies for obtaining efficiency maps through laboratory-based testing procedures, including both manual and automated methods.
- Paper 41 mentions the use of automated systems and Finite Element Methods (FEM) for obtaining efficiency maps of electric drive systems, without specifying a particular purpose.
- Paper 42 discusses considerations about the limitations of a study and factors not taken into account but doesn't involve real-world testing.
- Paper 43 discusses a comprehensive model and its predictions but does not involve direct real-world testing.

These groupings distinguish between methodologies that rely on real-world testing scenarios and those that are more focused on laboratory experiments, calculations, or modelling, highlighting the different approaches used in the field of electric vehicle efficiency mapping and characterization.

Looking ahead, the methodologies that involve real-world testing, as discussed in papers [6], [8] and [31], are poised for continued growth and refinement in the field of electric vehicle (EV) efficiency mapping and characterization. These methods, which rely on practical on-road data collection and non-intrusive measurements, offer the advantage of capturing EV performance under actual operating conditions, aligning closely with real-world scenarios.

As the trend towards real-world testing gains momentum, researchers can anticipate several key developments. First, there is a need for further exploration of the robustness and applicability of on-road methodologies across various EV types, operating conditions, and applications. Addressing open points and criticisms, as noted in paper [38], will be essential to validate and refine these methods.

Moreover, the accessibility and cost-effectiveness of on-road testing make it an attractive approach for EV research and development. The outlook suggests the ongoing evolution of these methodologies to provide more accurate and comprehensive insights into EV efficiency, possibly through enhanced sensor technology, data analysis techniques, and standardized testing protocols.

Looking ahead, we can appreciate some challenges for the on-road testing methodologies.

The on-road test drive of EVs may encounter numerous uncontrollable factors, including unpredictable climate conditions, varying traffic patterns, driver behaviours, and diverse road topologies. These factors introduce disturbances to the data collected during testing, making it difficult to isolate specific features that should be used for data adjustments. Moreover, making the testing of a large number of EVs in real-world conditions a time-consuming and often inefficient process. While on-road testing remains crucial for understanding real-world performance, its expense and practical limitations pose challenges, particularly when evaluating a sizable fleet of electric vehicles.

Obtaining accurate real-world driving data for assessing energy consumption in EVs is a fundamental challenge. To effectively evaluate an EV's energy efficiency, a wealth of driving information needs to be collected on board. This necessitates the incorporation of additional instruments such as CAN bus data loggers, global positioning systems (GPS), data storage systems, or wireless data synchronization systems. The associated cost and complexity of integrating these systems into the vehicle can be prohibitive. Furthermore, synchronizing charging and driving data to monitor real driving energy consumption on a large scale adds another layer of complexity to the evaluation process. These challenges underscore the need for innovative solutions and methodologies to streamline data collection and analysis in the context of EV real-world testing.

For methodologies that do not rely on real-world testing, such as those discussed in papers [39] to [43], the outlook suggests continued advancement in modelling, simulation, and laboratory-based experimentation. These methods play a crucial role in understanding the fundamental principles of electric drive systems and offer valuable insights during the design phase.

One prominent trend is the increasing sophistication of modelling and simulation tools. Researchers can expect the development of more accurate and predictive models that account for a broader range of factors, including motor characteristics, environmental considerations, and system interactions.

Additionally, the methodologies that involve laboratory testing, as seen in paper [40], may see improvements in automation, measurement equipment, and testing procedures to enhance efficiency map generation and data quality. Addressing criticisms and limitations, such as those highlighted in papers [41] to [43], will be essential to ensure the comprehensiveness and practical relevance of these methods.

In conclusion, the outlook for methodologies in both families reflects the dynamic nature of the EV field. Real-world testing methods are likely to become more robust and widely applicable, while non-real-world methods will continue to evolve, providing valuable insights into electric drive systems, particularly during the design and development phases.

4.2.2 Lithium-ion battery

Paper [5] and paper [44] both address the issue of estimating the state of health (SOH) of lithium-ion batteries, emphasizing the importance of accurate SOH estimation for battery management and longevity. Both papers use real-world data for their analysis and evaluation. They also acknowledge limitations in scalability and the need for future research to validate their methods under different conditions.

However, the main differences between the two papers lie in their approaches and focus. In paper [5], the authors compare three types of approaches (electrochemical modelling, data-driven learning, and model-based methods) but predominantly employ a model-based approach, specifically a closed-loop method, for SOH estimation. They propose a forgetting-factor-based observer that considers factors like internal resistance and capacity, as well as aging degradation parameters. The paper's primary emphasis is on accuracy and computational efficiency.

In contrast, paper [44] focuses on addressing SOH estimation under few-shot learning conditions, recognizing the limited and uncertain data often available from power devices. The authors propose a Bayesian deep neural network (BDNN) method that incorporates degradation patterns and Gramian angular field features. The paper highlights the adaptability and robustness of the BDNN method in real-world battery usage and emphasizes its performance in conditions with limited data. However, it acknowledges concerns about computational and storage resource requirements and the need for further validation on different datasets and battery types.

One prominent trend emerging from these papers is the growing emphasis on data-driven and machine learning approaches in battery health monitoring. Paper [44] underscores the need for more efficient and accurate SOH estimation methods, especially when dealing with limited and uncertain data. The introduction of Bayesian deep neural networks (BDNN) in paper [44] reflects a broader trend in adopting sophisticated machine learning techniques to tackle these challenges.

4.2.3 Slope Estimation

All three papers address the problem of real-time road slope estimation, a critical parameter for driver assistance systems, using various sensor-based algorithms. They emphasize the importance of accurate slope estimation for enhancing the performance and safety of such systems. Additionally, they recognize the presence of uncertainties, disturbances, and modelling errors that can affect the accuracy of slope estimation, highlighting the need for robust algorithms.

While the three methodologies share common objectives in the realm of real-time road slope estimation, they also exhibit notable differences in their approaches and techniques. Firstly, the choice of estimation algorithms differs significantly. The paper [45] primarily relies on an adaptive extended Kalman filter algorithm, emphasizing the importance of adaptability and improved accuracy. In contrast, the paper [7] adopts a multi-model and multi-data fusion approach, diversifying the estimation methods by employing two slope submodels and two slope change rate submodels. The paper [46], instead of introducing a new algorithm, focuses on utilizing the IMMPDA filter, which is based on the standard Kalman Filter equation, for sensor fusion. These distinct algorithmic choices highlight the diversity in methodologies employed to tackle the same road slope estimation challenge.

Secondly, the methodologies differ in their treatment of validation and real-world applicability. The paper [45] presents an implementation of its algorithm on the CarSim platform to demonstrate its effectiveness. However, it also emphasizes the need for further optimization for different scenarios and environmental factors, suggesting room for real-world validation and adaptability. The paper [7], while showing promising results, raises concerns about the potential implementation cost of relying on multiple sensors, indicating a practical challenge to be addressed. In contrast, the paper [46] primarily presents simulation results without real-world validation, and it does not thoroughly discuss potential limitations or future directions for real-world application.

In the dynamic landscape of real-time road slope estimation, several key trends and future outlooks are shaping the field. One prominent trend is the persistent emphasis on multi-sensor fusion, as evident in all three methodologies discussed earlier. Researchers continue to harness the power of various sensors, such as accelerometers, gyroscopes, GPS, and CAN networks, to enhance accuracy and reliability in slope estimation. This approach not only provides a broader data perspective but also equips driver assistance systems with the adaptability required to address changing road conditions and uncertainties. As seen in the second methodology, cost-effectiveness is another critical facet, with the focus shifting towards developing affordable sensor configurations and estimation algorithms suitable for widespread implementation in consumer vehicles. Achieving this balance between accuracy and cost will be pivotal for the widespread adoption of slope estimation technologies in the automotive sector.

4.2.4 Driving dynamics estimation

In the following table, we present a comprehensive comparison of driving dynamics parameters as identified in various studies. This analysis aims to provide a clear overview of the diverse findings within the field of driving dynamics research, shedding light on the key factors.

Paper [47]	**Paper [48]**	**Paper [49]**
Vehicle Mass	Longitudinal vehicle speed	Mass
Rolling resistance coefficient	Longitudinal acceleration	Location of centre of gravity
lumped aerodynamic coefficient	GPS-BD speed	Frontal area
powertrain efficiency	Absolute longitudinal acceleration	Coefficient of drag
	Measurement variance of GPS-BD speed and absolute longitudinal acceleration	
	Life signal for determining whether longitudinal vehicle	

	speed can be used for final sensor fusion	

Table 1: Driving dynamics parameters identified per paper

In the realm of vehicle testing and data acquisition, all three papers share a fundamental common focus: the acquisition and analysis of data to support their respective research objectives. The paper [47] centres its data collection efforts on a physical vehicle, specifically a 2012 Toyota Rav4EV, employing a trio of data sources—Vehicle Measurement System (VMS), Global Positioning System (GPS), and Controller Area Network (CAN). Similarly, the paper [48] maintains its emphasis on data acquisition but leans towards the utilization of virtual sensors, crafting them by amalgamating data from diverse sources, including GPS-BD and IMU, while also enhancing data comprehensiveness through the incorporation of additional sensors like wheel speed, steering angle, yaw rate, and longitudinal acceleration sensors. In contrast, the paper [49] diverges from the other two by opting for a streamlined approach. It relies on data from a limited set of sensors with a lower sampling frequency, a strategy aimed at reducing system costs compared to methods requiring more sophisticated sensor equipment or extensive computational resources.

The methodologies employed in the previously mentioned papers exhibit several key similarities. First and foremost, all three papers rely on mathematical modelling as a fundamental approach in their research. Additionally, a shared focus on practical applications is evident throughout these papers. They all emphasize the real-world relevance of their findings, whether for optimizing vehicle control, enhancing speed estimation accuracy, or improving electric vehicle performance. Furthermore, an overarching commitment to transparency and academic rigor is apparent, as all papers openly acknowledge and discuss the limitations of their methodologies,

However, the primary differences among these papers lie in their distinct methodologies and areas of focus. Paper [47] primarily concentrates on parameter identification through numerical methods, utilizing normal equations and singular value decomposition. It emphasizes the potential for obtaining multiple least-cost solutions but criticizes the limited dataset and the absence of real-world implementation. In contrast, paper [48] centres its methodology on enhancing longitudinal speed estimation, incorporating sensor integration, yet neglects to consider lateral factors. Paper [49], on the other hand, relies on road tests of a specific electric vehicle, using a nonlinear least square algorithm for parameter estimation and emphasizing practical applications for electric vehicle control. However, it questions the methodology's applicability to non-flat and non-straight roads and the representativeness of a single vehicle model in experimentation. These differences highlight the diverse approaches to studying vehicle dynamics and parameters across these papers, each with its own set of strengths and limitations.

The trends and outlook in the field of vehicle dynamics and parameter estimation, as exemplified by the previously listed papers, reflect the continuous evolution and growing importance of vehicle technology in today's automotive landscape. These papers offer a glimpse into several key trends that are likely to shape future research and applications in this domain.

One prominent trend is the increasing reliance on advanced mathematical modelling and computational methods. Paper [47]'s use of normal equations and numerical solution testing, paper [48]'s integration of IMU and GPS-BD modules, and paper [49]'s implementation of nonlinear least square algorithms all underscore the critical role of mathematical models and computational tools in analysing vehicle dynamics. As technology continues to advance, we can expect even more sophisticated modelling techniques to emerge, enabling more accurate and comprehensive studies of vehicle behaviour.

Another notable trend is the growing emphasis on real-world applications and practicality. All three papers highlight the relevance of their methodologies to real-world scenarios, such as optimizing vehicle control, improving speed estimation, or enhancing electric vehicle performance. This trend suggests that future research in this field will continue to prioritize solutions that have practical implications and can be integrated into automotive systems to enhance safety, efficiency, and overall performance.

5 Optimization of electric powertrain

In the forthcoming section, we will embark on a literature review to examine the existing research pertaining to the optimization of electric powertrains. This review will serve as the basis for our subsequent analysis and conclusions, providing a comprehensive overview of the current state of knowledge within this domain.

5.1 Literature Review

Optimization of Powertrain in EV.

This paper deals with the optimization of powertrain in electric vehicles (EV). The paper explores the methods to optimize powertrain in the EVs for improved performance and energy efficiency.

The paper employs the Nelder-Mead method to optimize the gear ratio and torque-speed motor curve in the powertrain of EV. Two powertrain models are presented in the paper, which are suitable for the preliminary design of the drive system. The paper also describes the block diagram of the powertrain model ver. 1 and ver. 2 and three energy storages.

The research results suggest that the proposed models can achieve improved performance and energy efficiency, which is comparable to the cars with internal combustion engines. Further, the paper provides the performance indices for preliminary drive design. The results of optimization are presented through tables and graphs.

The paper is a significant experience in the domain of electric vehicles and powertrain system design. The proposed model and the Nelder-Mead method can be used for preliminary design purposes. However, more research can be carried on dynamic powertrain optimization, specific energy storages, and energy management strategies. The paper provides a promising approach to optimize powertrain systems in electric vehicles.

A Novel Dual-Motor Two-Speed Direct Drive Battery Electric Vehicle Drivetrain.

The paper proposes a novel dual-motor, two-speed direct-drive battery electric vehicle (BEV) powertrain that aims to improve motor efficiency while maintaining cost-effectiveness. The problem addressed is the lack of balance between motor efficiency improvement and additional cost in existing research on one motor and one speed BEV powertrain. This research aims to provide guidelines for energy-efficiency oriented motor specifications design, optimal control strategy design, and technique for realizing the multi-speed function without a mechanical shifting actuator.

The proposed methodology is based on replacing the popular one motor and one-speed BEV powertrain with two smaller motors with the same output power. The determination of the motor torque-speed profile provides guidelines for motor specifications design, while the alternative motor propelling control strategy is optimized to improve efficiency and smooth torque transfer. The multi-speed function is achieved by switching driving motors with permanently engaged gear pairs, rather than utilizing a mechanical shifting actuator. This design helps to achieve the two-fold objective of reducing energy consumption and maintaining cost-effectiveness.

The results show that the proposed powertrain has achieved significant improvement in energy efficiency than the original 'one motor one speed' BEV powertrain. The incorporation of the dual-motor and two-speed technology leads to an improvement in torque control accuracy and an increase in energy regeneration. Moreover, the proposed powertrain's optimization strategy offers better efficiency and smoother torque transferring.

One of the open points in the research is the impact of motor and gearbox manufacturing cost on the overall cost-effectiveness of the proposed powertrain. Another criticism is that the methodology does not consider external factors, such as road and traffic conditions, that may influence the powertrain's performance. Despite these limitations, the proposed dual-motor and two-speed direct-drive powertrain concept is a vital contribution to the BEV industry's technological advancement.

Multiobjective and Multiphysics Design Optimization of a Switched Reluctance Motor for Electric Vehicle Applications.

This paper deals with the multiobjective and multiphysics design optimization of a switched reluctance motor (SRM) for electric vehicle applications. The paper outlines the problem of designing an efficient electric motor that satisfies multiple objectives such as high torque production, low vibration, and low noise. The authors highlight the need for simultaneous optimization techniques to meet these requirements while minimizing design complexity, material usage, and manufacturing cost.

The methodology employed in this paper is a sequential subspace optimization method (SSOM), which divides the parameters into highly significant, significant, and non-significant subspaces based on compressive sensitivity analysis. The optimization process contains two iterations, and each iteration further contains sequential optimization of the subspaces. The authors employ Sobol' method to obtain the Pareto optimal solutions for each iteration, and the optimization process terminates when the convergence criterion is met. Finite element analysis and 3D topology optimization are used to perform multiobjective and multiphysics design optimization.

The results of the optimization process show the effectiveness of the methodology and technology employed. The SSOM approach reduces the computational burden of the optimization process and yields Pareto optimal solutions that significantly improve the overall performance of the motor. The optimized motor design not only meets the multiple objectives of high torque production, low vibration, and low noise but also minimizes the design's complexity, material usage, and manufacturing cost. Additionally, the results presented in this paper provide insights into the optimization process, and the authors suggest that the proposed methodology can be applied to other electromechanical systems.

One of the limitations of this paper is that the testing of the optimized motor is not presented, and no comparison is made to existing state-of-the-art designs. Additionally, the methodology may be limited in its application to complex systems with numerous control parameters. Nevertheless, the sequential subspace optimization method and Sobol' method have been proven effective in addressing the multiobjective and multiphysics design optimization problem of the SRM motor for electric vehicle applications.

Electric Vehicle Design Optimization: Integration of a High-Fidelity Interior-Permanent-Magnet Motor Model.

This paper presents an optimization methodology for the design of electric vehicles (EVs) that integrates a high-fidelity interior permanent magnet (IPM) motor model. The objective is to find the optimal combination of design variables that minimize charge depletion and acceleration time. The problem is formulated as a multi-objective optimization problem that is solved using the multi-objective genetic algorithm (MOGA) method. The optimization process is based on reducing the motor's weight, so the design variables are motor armature coil turns, stack length, operation DC voltage, and final drive ratio. The methodology is tested on three test cycles: FTP75, US06, and NEDC.

The methodology employs several technologies, including the electromagnetic finite-element analysis that models the physical behavior of the motor, the separable nonlinear optimization method, and the design of experiments (DOE). In addition, statistical models and surrogate modeling are used to capture the relationships between the design variables and the desired EV attributes. In the context of surrogate modeling, two types of models are used: the response surface model (RSM) and the kriging model.

The proposed methodology is demonstrated to be effective by generating Pareto-optimal solutions that balance charge depletion and acceleration time. In the NEDC test cycle, for example, the methodology yields hundreds of Pareto-optimal solutions from just a few hundred samples. The paper shows that incorporating a high-fidelity IPM motor model in an optimization methodology significantly improves the methodology's accuracy, and reliability, leading to better results and insights.

One of the paper's limitations is that the methodology may not be directly applicable to other types of motors without adjustments. Moreover, the methodology's accuracy may decline as the design variables' dimensions increase. As such, future research would involve incorporating more models of EV sub-systems to create an even more sophisticated optimization approach that can further enhance EV performance.

Analysis of electric vehicle powertrain simulators for fuel consumption calculations.

This paper focuses on analyzing several electric vehicle (EV) powertrain simulators commonly used to calculate fuel consumption. The goal is to identify simulators suitable for transportation analysis software.

To achieve this, the authors reviewed a significant body of literature and identified several software tools available for EV simulators. Most of these simulators use a backward-facing modeling approach where the power for the vehicle's tractive force is calculated and input to a series of powertrain component models. However, simplified backward-facing models assume no power limits, resulting in requested vehicle speed always being achieved. Forward-facing models, commonly used in Autonomie, tend to be used if the driving style needs to be included in the vehicle simulator.

The results of the analysis identified several suitable EV powertrain simulators for transportation analysis software. These include Autonomie, Advanced Powertrain Research Facility (APRF), and Future Automotive Systems Technology Simulator (FASTsim). Although the simulators selected provide accurate fuel consumption analysis, they have their limitations. Real-world driving conditions and driver behavior could affect their accuracy, as the simulators assume ideal driving conditions.

In summary, this paper offers a comprehensive analysis of common EV powertrain simulators suitable for fuel consumption calculations. It identifies the ideal simulators for transportation analysis software, including Autonomie, APRF, and FASTsim. Nevertheless, practitioners should note that simulators' assumptions might limit their accuracy under real-world driving conditions and driver behavior. Recommendations for future research in this area are also provided.

High Performance Electric Vehicle Powertrain Modeling, Simulation and Validation.

The paper discusses the development of a software-based approach for high-performance electric vehicle modeling, simulation, and validation. EV powertrain integration presents challenges due to the interdependence of vehicle subsystems. The paper aims to develop a methodology to model and simulate EV powertrain components using software tools and models.

The methodology involves integrating different EV subsystem models, including the motor, inverter, gearbox, differential, and battery, into a single high-fidelity EV model using MATLAB/Simulink. The approach aims to improve control and energy management strategies and powertrain component optimization. To validate the model, the paper compares it with real-world data from vehicle performance tests to measure the mode's energy efficiency, speed, and distance traveled.

The study found close correlation between the energy efficiency results of the model and the real-world vehicle with negligible error values. The study also highlighted limitations of the model's ability to capture dynamic and transient behavior. The equation-based model provided a valuable understanding of how the modeled vehicle would perform under certain driving conditions from an energy efficiency standpoint, but the modeling approach is not appropriate for detailed analysis of vehicle dynamics and control strategies.

In future research, a physical modeling approach could be explored to enable more accurate predictions of real-world performance. The study also suggests exploration of more advanced motor model and motor controller schemes, which should result in more detailed and accurate transient and dynamic responses compared to real-world vehicles. Further research is necessary to improve high-performance EV models and enable higher levels of fidelity in predicting real-world vehicle performance.

Integrated modeling and analysis of dynamics for electric vehicle powertrains.

This paper aims to develop integrated analytic and simulation models that accurately describe the dynamics of electric vehicle powertrains. The authors highlight the need for detailed and accurate analytic models that provide a better correlation between electric input signals and mechanical final output variables, which was not covered in existing research.

To achieve their goal, the authors used theoretical derivations to obtain closed-form expressions for theoretical models that describe evident relationships between electrical quantities and vehicle dynamics such as velocity, acceleration, and forces of the EV. They also constructed a Matlab/Simulink model for an entire EV powertrain to validate the developed mathematical analysis models.

The results confirm that the results from the two models are consistent for a standard vehicle speed profile, and various influences on vehicle dynamics, including velocity, acceleration, and forces of the EV, of electrical quantities were presented and analyzed in detail.

One of the main contributions of this paper is its scientific innovation in developing a generic EV model that combines detailed and accurate analytic models with the correlation between the electric input signals and the mechanical final output variables. However, some limitations of the methodology employed, such as the use of a single driving cycle for validation, should be addressed in future research. Nonetheless, this study provides valuable insights into the development of integrated analytic and simulation models that can be used for the design of more efficient and reliable electric vehicle powertrains.

Design and Analysis of an Electric Hydraulic Hybrid Powertrain in Electric Vehicles.

The paper "Design and Analysis of an Electric-Hydraulic Hybrid Powertrain in Electric Vehicles" addresses the issue of energy management in electric vehicles (EVs). The purpose is to evaluate a novel electric-hydraulic hybrid (EH2) drivetrain that combines efficient hydraulic regenerative braking with fixed-displacement hydraulic propulsion, resulting in improved fuel efficiency and energy recovery in urban driving cycles.

The methodology employed for this research includes mathematical modeling of the EH2 powertrain system and the selection of appropriate hydraulic component parameters. The EH2 performance was evaluated through the developed simulation model, which was validated through experimental results. The EH2 powertrain was evaluated under the New York City Taxi and Limousine Commission (TLC) Drive Cycle and the U.S. Environmental Protection Agency (EPA) Highway Fuel Economy Driving Schedule.

The results of the study suggest that the EH2 drivetrain significantly reduces the energy requirements of the system, resulting in an increase of up to 45% in fuel economy. The fuel savings of the hybrid electric-hydraulic powertrain are shown to exceed those of the conventional mechanical drivetrain at city driving conditions, representing an appealing vehicle platform for city vehicle applications.

The paper notes that despite the EH2 powertrain's fuel efficiency and energy recovery, it is still far from perfect. One limitation is the added complexity of the hydraulic components in the system, which could be problematic for maintenance and repair. Hydraulic fuel leaks can also pose environmental hazards, and more research is needed to study the environmental impact of hydraulic fluids. Furthermore, the price of hydraulic accumulators needs to be reduced to make the EH2 powertrain a more cost-effective solution in the market.

Electric vehicle drive trains from the specification sheet to the drive-train concept.

The paper "Electric Vehicle Drive Trains: From the Specification Sheet to the Drive-Train Concept" aims to propose a methodology for the selection of electric vehicle drivetrains based on specific evaluation criteria. The goal is to identify the best fitting drive train concepts from the technical and economic standpoint.

The methodology involves the identification of evaluation criteria with their underlying evaluation functions, which allows the solutions to be compared. The identified criteria for the evaluation process are costs, installation space requirements, modularity & scalability, weight, driving dynamic performance, and safety. These criteria are then used to rate the solutions and identify the most strategically fitting drive train concept(s). The paper employs empirical values, literature, and design tools for electric machines and drive shafts to estimate the various factors.

The results obtained through this methodology indicate that the selection of the drive-train concepts depends on the vehicle concept's suitable operating scenarios. The evaluation also concludes that the safety criterion is the most significant and should be analyzed right from the beginning. The results also highlight the importance of modularity & scalability in power for a drive train concept.

Despite the comprehensive evaluation process, the determination of costs remains a difficult point due to the lack of market information on BEVs' costs and components available. Additionally, there remain open points of further research as the methodology depends on subjective weighing of criteria in the different use scenarios.

Mathematical Modeling and Simulation of an Electric Vehicle.

This paper, titled "Mathematical Modeling and Simulation of an Electric Vehicle," presents a study on the mathematical modeling and simulation of an electric vehicle (EV) to find the best energy control strategy and exact component size while minimizing energy use. The work utilized a basic model with a simple controller to maintain the identical input-output power of the battery and to compensate for the voltage error.

The modeling and simulation of an electric vehicle are crucial for automotive designers as prototyping and testing are expensive, complex operations. Therefore, this study employed visualization programming to quickly modify parameters, architectures, and graphically examine the output data. Past researchers have also put great effort into modeling EVs; specifically, the study shows the effectiveness of using a switched reluctance motor (SRM) in the electric propulsion unit and drive evaluation.

The results of this study showed that the performance of the EV depends on the performance of the controller in removing error from the system. The P-I controller used maintained an identical input-output power of battery and compensated for voltage error with negligible steady-state error. However, the design noted that further augmentation is required to establish a good EV model, which will form the foundation for further research and development.

The paper acknowledges that the P-I controller used in the study is not sufficient for real-world applications, and further augmentation is necessary. Additionally, while the study presents a promising result, it is unclear how the basic model would perform under demanding road scenarios with varying conditions.

Integrated Design of a CVT-equipped Electric Powertrain via Analytical Target Cascading.

This paper addresses the integrated design problem of a Continuously Variable Transmission (CVT)-equipped Electric Powertrain via Analytical Target Cascading (ATC). The main challenge lies in the strong interdependencies between plant and control design parameters, objectives, and constraints that affect performance and efficiency of the powertrain. To overcome this issue, the authors propose an ATC-based co-design framework to deconstruct the problem into smaller subproblems that can be solved iteratively while accounting for the dependency between subsystems.

The proposed framework employs a Forward Euler method to discretize the continuous-time formulation of the co-design problem. It then optimizes the design parameters, such as EM and CVT design parameters, using a quadratic penalty function to minimize the discrepancy between shared variables. The upper-level subproblem minimizes the requested energy and EM loss, while the lower-level subproblem aims to minimize the CVT mass and leakage losses. The results of the problem are shared variables that converge into the same value, ensuring maximum powertrain efficiency.

The authors present case studies demonstrating the effectiveness of the proposed methodology compared to other state-of-the-art techniques. The example showcases the optimization results for a passenger electric vehicle with a powertrain optimized for maximum efficiency over a drive cycle. The results demonstrate that the proposed design approach finds the optimal solution for the integrated powertrain design problem, improving its overall efficiency and performance.

While the proposed framework optimizes the powertrain design, it has some limitations in terms of solving the co-design problem. The ATC-based approach is computationally expensive and requires considerable effort to implement, making it less accessible for non-experts. Furthermore, the framework heavily depends on the chosen optimization algorithm and the selected optimization weights, which can cause discrepancies between shared variables. Overall, this paper presents an effective and innovative co-design approach for the design of CVT-equipped electric powertrains, although further research is needed to improve its practical applications.

Optimal Design and Control of a Two-Speed Planetary Gear Automatic Transmission for Electric Vehicle.

This paper addresses the problem of optimizing the design and control of a two-speed planetary gear automatic transmission system for electric vehicles. The objective is to minimize electric energy consumption during the whole drive cycle while considering the frequent shift cost. In order to achieve this, a combined genetic algorithm and dynamic programming method is employed. The fitness functions used are the acceleration time from 0 to 100 km/h and the 100 km electric energy consumption.

The methodology used in the paper starts with the design of the powertrain system for a small electric vehicle, followed by the calculation of the objective functions and the optimization process. The electric energy consumption model was used to evaluate the energy efficiency of the system while considering the driving cycles. Then, the algorithm was implemented in MATLAB to optimize the gearshift strategy of the planetary gear automatic transmission, utilizing dynamic optimization techniques to achieve minimum energy consumption.

The results obtained in this study demonstrate that the proposed system has higher energy efficiency compared to a conventional system. The optimized control algorithm improved the motor's energy efficiency by optimizing gearshift patterns, resulting in reduced energy consumption. The simulation results also showed that the proposed system achieved a higher acceleration performance and a smoother driving experience in comparison to a traditional single-speed EV.

As the paper proposed a new optimization method for the design and control of a two-speed planetary gear automatic transmission system, future work can aim to explore the possibilities of using different optimization techniques for further performance improvements. Moreover, it mainly focuses on the electric energy consumption of the system without evaluating the cost of the system. Therefore, the performance of the proposed system under different driving conditions needs further investigation to determine its overall commercial viability.

Gear ratio optimization and shift control of 2-speed I-AMT in electric vehicle.

The paper discusses the optimization of gear ratio and shift control of 2-speed I-AMT in electric vehicles. The main problem addressed is the improvement of the energy consumption economy over the entire drive cycle. The authors employ numerical dynamic programming to minimize a cost function, the sum of the energy consumption economy.

The methodology is based on the mechanical system equation to calculate the longitudinal motion dynamics of the vehicle and the efficiency of electric motor. Besides, the battery internal current and the battery open circuit voltage are discussed. DP is used as a multi-stage decision-making process. In time step K, the state variable is SOCk, the control variable is ig;k, and the change value of battery state of charge is ΔSOCk. Inequality constraints are also imposed to ensure the safe and smooth operation of motor and battery.

The results show that by employing numerical dynamic programming, one can achieve optimal gear shift patterns for electric vehicles, which improve the energy consumption economy. The optimization process can cope with various driving scenarios, including mild terrains, moderate and severe driving conditions. The paper also presents a comparison between I-AMT and fixed-ratio transmissions, which highlights the benefits of the former over the latter.

Overall, the methodology employed provides a framework for further research and development in the optimization of gear shift patterns in electric vehicles. As a limitation, the authors acknowledge that the proposed method does not consider the torque converter and the electric motor separately, which could affect the accuracy of the optimization results.

Multi-objective gear ratio and shifting pattern optimization of multi-speed transmissions for electric vehicles considering variable transmission efficiency.

This paper tackles the problem of optimizing the gear ratio and shifting pattern for electric vehicles with multi-speed transmission systems, taking into account the varying transmission efficiency and the trade-off between energy efficiency and dynamic performance. The optimization process is framed as a multi-objective problem, which calls for a surrogate-based approach to reduce computation effort.

The proposed methodology involves building a surrogate model that approximates the objective function according to design variable values, and an effective sampling method to achieve high predictive accuracy at low computational costs. The gear ratio set and shifting point set are chosen as the design variables, and modified shifting patterns are considered to improve drivability. The optimization is constrained by the feasible region of gear ratios, which considers the selection of motor torque distribution.

The results show that the proposed optimization method can successfully improve the energy efficiency and dynamic performance of electric vehicles with multi-speed transmission systems. Compared with single-objective optimization, the multi-objective optimization process provides a set of solutions that meet different design requirements. The effectiveness of the surrogate model and the accuracy of the efficient sampling method are also demonstrated.

Possible limitations of the study include the simplification of some assumptions and the lack of experimental validation. Furthermore, the proposed methodology might need further adjustments for practical implementation, such as considering the additional weight and cost of a multi-speed transmission system.

Gear Ratio Optimization along with a Novel Gearshift Scheduling Strategy for a Two-Speed Transmission System in Electric Vehicle.

This paper presents a study on gear ratio optimization as well as a novel gearshift scheduling strategy for a two-speed transmission system in an electric vehicle. The main problem addressed in this research is improving the performance and efficiency of multi-speed transmissions in electric vehicles through optimization of gear ratios as well as gearshift schedule. This study aims to demonstrate that integrating both greatly improves vehicle dynamics and economic performance.

The methodology used in this study involves modeling the powertrain components of an electric vehicle within MATLAB/Simulink software environment. A detailed description of the electrical motor and battery blocks, as well as the transmission unit of the vehicle, are provided. A combined optimization process of the gear ratio and shift schedule is done, and the algorithms used for optimization are discussed.

The study's results showed that the implementation of this optimization strategy resulted in significant improvements in both the dynamic and economic performance of the vehicle, including its acceleration, torque capacity, and energy efficiency. Additionally, the results demonstrated that the proposed method of optimization yields better results in comparison to local optimization methods. They highlight that this method can provide accurate simulations to predict the performance of the electric vehicle transmission system.

While the study noted significant improvements, the findings show competitiveness against the use of a simple one-speed transmission system only in this specific case. However, it was recognized that more studies and experiments are required to evaluate the feasibility of such a system for different vehicle performances and applications, considering driving conditions such as hills, high-speed, and various payload conditions. This shortcoming in the exploration leaves an open field for future studies.

Modelling, Simulations, and Optimisation of Electric Vehicles for Analysis of Transmission Ratio Selection.

This paper presents a study on modelling, simulation, and optimization of electric vehicles to analyze transmission ratio selection. The problem addressed in the paper is how to find the best transmission ratio settings for electric vehicles to achieve optimal performance, energy efficiency, and battery life. The paper proposes a new model that includes the dynamics of several components, such as the electric motor, battery, and transmission system, to simulate the electric vehicle's behavior.

The methodology employed in the paper combines different techniques, including physical modelling, simulation, and optimization. The electric vehicle's components' parameters are characterized using experimental data, and a system-level simulation model is developed. The model is then used to perform sensitivity analysis, identify design parameters crucial to the electric vehicle's performance, and perform optimization, such as finding the best transmission ratio settings.

The paper presents several results that demonstrate the effectiveness of the proposed model. The sensitivity analysis shows that the battery's weight and efficiency significantly affect the vehicle's performance and energy efficiency. The optimization results show that the transmission ratio settings significantly affect the vehicle's acceleration and energy efficiency. The findings suggest that a good selection of the transmission ratio settings can improve the electric vehicle's performance and extend its battery life.

The paper's authors acknowledge several limitations of the proposed model, such as neglecting some losses and simplifying some modelling assumptions. Moreover, they note that the model's accuracy depends on the quality of the experimental data used to characterize the electric vehicle's components. They recommend future work to improve the model's accuracy and expand its capability to consider more complicated scenarios, such as the impact of driving conditions and external factors.

Integrated design optimization of the transmission system and vehicle control for electric vehicles.

This paper proposes a methodology for the integrated design optimization of the transmission system and vehicle control for electric vehicles (EVs), which aims to minimize energy consumption while maintaining optimal vehicle performance. The problem addressed is the optimization of the control problem for an EV with a fixed-gear (FGT) and a continuously variable transmission (CVT), by considering the push belt variator type (Vroemen, 2001) of CVT.

To solve this problem, the paper first discusses the power train loss model and the vehicle dynamics model. Then, the optimal control problem is formulated and solved by using the Pontryagin Maximum Principle (PMP) method, which allows for the integration of design variables such as the gear ratio, motor torque, and gear shift strategy, among others. Additionally, the paper introduces a method for controlling the motor torque and gear ratios based on the driver's speed to improve the vehicle's efficiency further. Finally, simulations are performed to verify the effectiveness of the proposed methodology.

The results show that the proposed methodology can achieve better performance in terms of energy consumption and drive comfort compared to traditional control methods. The PMP-based method can efficiently optimize the motor torque and gear ratios, thereby reducing energy consumption. Additionally, the proposed strategy for controlling the motor torque and gear ratios can maintain a comfortable driving experience while conserving energy. Moreover, the study also analyzed the impact of different optimization objectives on system performance, providing insights into the trade-off between energy consumption and drive comfort.

One of the main limitations of this study is that it does not consider the impact of the battery state of charge on vehicle performance. This could be an interesting area for future research. Furthermore, the proposed methodology could be further improved by considering more complex control structures such as predictive control or model predictive control.

Optimization of Sizing and Battery Cycle Life in Battery/Ultracapacitor Hybrid Energy Storage Systems for Electric Vehicle Applications.

The paper "Optimization of Sizing and Battery Cycle Life in Battery Ultracapacitor Hybrid Energy Storage Systems for Electric Vehicle Applications" focuses on developing an optimal HESS (Hybrid Energy Storage System) design. The primary aim of the research work is to minimize the total weight and cost of HESS while safeguarding the battery by preventing overstress and ensuring an extended cycle life.

To achieve these goals, the authors adopted a multi-objective optimization approach that seeks to derive an optimal design through an interplay of various factors. The battery cell number is constrained between 150 to 175, while the UC cell number is constrained between 60 and 160, and the reference power is tested within the range of 15 to 30 kW. The authors employed a trade-off analysis to quantify the trading relation between HESS sizing, battery cycle life, and weight. They also employed a sample-based optimization algorithm called DIRECT algorithm to solve the multi-objective optimization problem.

The optimization results show that the weight of HESS is more sensitive to the battery cell number and UC cell number than the reference power, while battery cycle life has a stronger dependence on UC cell number, which can significantly reduce battery capacity loss. The authors identify that a larger value of weight factor γ leads to lower battery capacity loss and a larger HESS size. The sample-based optimization algorithm proves to be useful in solving this multi-objective optimization problem and overcoming the issue of the objective function's noisy nature.

The paper's novel contribution is in proposing a multi-objective optimization approach to optimize HESS's design while ensuring the battery cycle life's extension and protecting it from overstress. However, the authors admitted that simulation assumptions may deviate from the actual operating conditions of an EV. Moreover, they only considered the design factors while ignoring manufacturing and maintenance costs. Finally, the research work is still limited to a simulated approach and may require experimentation with real electric vehicles to validate the results.

Optimal sizing of hybrid high-energy/high-power battery energy storage systems to improve battery cycle life and charging power in electric vehicle applications.

This paper addresses the optimal sizing of hybrid high-energy (HE) and high-power (HP) battery energy storage systems in the context of electric vehicle applications, with the objective of improving battery cycle life and charging power. The main contribution of this study lies in the optimal sizing of the system while considering cycle life and fast charging goals separately from classical vehicle requirements such as weight, speed, driving range, acceleration, and load capacity. This paper proposes a model-based design framework in which different models are considered to translate the Electric Vehicle (EV) driving cycle to the battery duty cycle in a top-down fashion. The proposed framework offers a comprehensive approach for designing the hybridization architecture (positions of the HE and HP batteries and the DC-DC converter with respect to the DC-link).

The proposed methodology employs a well-established evolutionary approach based on the genetic algorithm to solve the multi-objective optimization problem. The HE cells with NMC chemistry and HP cells with LTO chemistry are selected as inputs to the optimal sizing problem, and a detailed analysis is outlined that allows suitable voltage profiles for the HE and HP batteries to be decided.

The optimization results show that the proposed approach offers a comprehensive model-based design framework that accounts for the different driving factors while ensuring the longevity of the batteries, fast-charging speed, and improved performance. The data suggests that optimal sizing of the hybrid battery can offer a significant improvement in the battery cycle life, reducing the costs associated with battery replacement and maintenance.

As with all studies, there are limitations to the proposed approach. The authors note that a further study could examine the impact of different power electronics configurations on the performance of the hybrid battery. Additionally, the study is limited to a small-size electric car and may not be directly applicable to other vehicle types. Overall, however, the paper presents a significant contribution to the optimization framework for designing hybrid battery solutions that offer improved performance, longevity, and fast charging, which is critical to the EV market.

Optimization for a hybrid energy storage system in electric vehicles using dynamic programing approach.

This paper deals with the optimization of a hybrid energy storage system (HESS) in electric vehicles (EVs) using a dynamic programming (DP) approach. The main problem being addressed is how to design a HESS, which can properly balance the load distribution between batteries and supercapacitors (SCs), while simultaneously considering the energy-saving effect of regenerative braking and real driving cycles.

The authors conducted experiments using a battery and SC module to obtain the necessary data for the modeling of the components. Then, the DP algorithm was used to optimize the control strategy of the HESS. The technology employed in the study is relatively advanced and provides a sophisticated approach for analyzing and optimizing the performance of a HESS.

The results of this study indicate that the proposed HESS can significantly reduce the fuel consumption (up to 11.5%), thereby enhancing the fuel economy of the vehicle. In addition, the results also show that this approach can provide a more stable SOC distribution during the cycle, prolong the cycle life of the battery, and improve the performance of the vehicle.

Despite the promising results, there are some issues that need to be addressed. One of the main concerns is the computational complexity of the DP algorithm, which may hinder its implementation in commercial EVs. Another issue is that the proposed HESS has yet to be tested in real-world conditions, thus it remains to be seen whether the proposed system can withstand harsh driving conditions and provide a consistently high level of performance and reliability.

Sound Quality Investigation and Improvement of an Electric Powertrain for Electric Vehicles.

This paper investigates the sound quality improvement of an electric powertrain for electric vehicles. Electric vehicles have become increasingly popular due to their low emissions and improved energy efficiency. However, they suffer from poor sound quality, which affects the driving experience. The challenge is to improve the electric powertrain's sound quality, which is the focus of this study.

For subjective data collection, the jury test was carried out; Kendall's coefficient has been presented to show consistency among the subjects. Objective data were also analyzed using psychoacoustic parameters. The research team adopted the third-octave band spectrum analysis to investigate the acoustic characteristic comparison of internal combustion engines and electric vehicles.

The study's findings indicate that low-speed and low-load noises are preferable in electric vehicles, while high-speed and high-load noises are not. The acoustic energy distribution of the two types of vehicles was found to be different, as the ICE's acoustic energy primarily concentrated between 160 and 400Hz, compared to the electric vehicle's third octave bands between 1 and 3 kHz. In contrast, the ICE's sound evaluations were generally more consistent, while the electric vehicle's subjective evaluation varied with frequencies.

This paper offers an in-depth investigation of sound quality evaluation for electric powertrains. However, it is limited to only one model of electric vehicle and does not explore improvements in sound quality in future EV models with different structural designs. This study primarily relied on psychoacoustic parameters and subjective methods for sound quality evaluation and could benefit from using objective methods for future studies.

5.2 Conclusion

In this section, the culmination of the comprehensive analysis of research papers regarding the optimization of electric vehicles is presented. The papers have been grouped into four distinct categories: Motor optimization, Transmission optimization, Energy storage optimization, and Sound optimization. The objective here is to elucidate the commonalities and correlations found among these research works, along with a scrutiny of the methodologies employed by various authors and the identification of emerging trends shaping the future of electric vehicle optimization.

5.2.1 Motor optimization

The optimization methodologies for electric powertrains discussed in the texts share common themes and principles, but they also exhibit distinct differences in their approaches and objectives.

Mathematical optimization is a fundamental element in many of these methodologies. For instance, paper [10] employs the Nelder-Mead method to optimize gear ratios and motor curves, while paper [59] uses a quadratic penalty function for co-design optimization. This commonality underscores the significance of mathematical rigor in achieving optimal electric powertrain performance.

Simulation and modelling are recurring tools in these methodologies. Papers [53], [54], [55] and [58] emphasize the importance of using simulation tools like MATLAB/Simulink and electromagnetic finite-element analysis for modelling powertrain components and validating proposed designs. These modelling approaches are crucial for gaining insights into powertrain behaviour and performance.

Despite these commonalities, the objectives and contexts of these methodologies differ significantly. For instance, paper [50] focuses on optimizing motor torque-speed profiles and control strategies to enhance efficiency, utilizing a two-motor system. In contrast, paper [51] employs a sequential subspace optimization method with Sobol' analysis for multi-objective design optimization, considering sensitivity analysis and Pareto optimal solutions. The variation in optimization goals, from motor efficiency to multi-objective optimization, highlights the diverse applications of these methodologies in electric powertrain design.

Tools and software utilization also vary. Paper [53] discusses the use of various software tools for EV simulators, while paper 8 utilizes simulation and experimental validation for hydraulic EH2 powertrain system optimization. The choice of tools is often driven by the specific needs and characteristics of the powertrain being optimized.

Furthermore, the level of complexity and detail in the models and simulations differs among these methodologies. Paper [54] integrates multiple electric powertrain subsystems, providing a high-fidelity model for comprehensive control and energy management optimization. In contrast, paper [55] employs mathematical analysis models to establish relationships between electrical quantities and vehicle dynamics, likely focusing on simplifying complex interactions.

Mathematical modelling of electric vehicles (EVs) presents a multifaceted challenge, primarily stemming from the inherent complexities of the EV system. One of the foremost hurdles is dealing with ambiguity, uncertainty, unknowns, and unknowable factors within the system. The intricate interplay of numerous variables such as battery chemistry, charging infrastructure, driver behaviour, and environmental conditions can introduce a high degree of uncertainty into the mathematical models. Addressing this challenge necessitates the development of robust algorithms and methodologies capable of handling the ambiguity and unpredictability inherent in real-world EV operation.

Model complexity is another formidable challenge in the realm of EV modelling. Integrating all the essential components and subsystems into a comprehensive model result in a complex mathematical framework that demands significant computational resources for solution. From the intricate electrical and thermal dynamics of the battery to the nuanced interactions between the vehicle's powertrain and external factors like road conditions, achieving a comprehensive and accurate model can be a computational undertaking. Researchers must strike a balance between model fidelity and computational feasibility to make these models practical for real-time applications, optimization, and policy decision-making. Overcoming these challenges is essential to harness the full potential of mathematical modelling in shaping the future of electric mobility.

The trends and outlook of the methodologies discussed in the previous papers reflect both their potential and areas where further research and development are needed in the field of electric powertrain optimization.

Firstly, it's evident that researchers are actively exploring various optimization techniques for electric powertrains. The use of mathematical optimization methods, as seen in papers [10] and [59], is gaining prominence. This trend suggests that future developments may involve more sophisticated optimization algorithms and strategies to achieve even higher levels of powertrain efficiency.

Secondly, a recurring theme is the need for validation and practical application. Multiple papers emphasize the importance of validating proposed designs through real-world testing and data, indicating a shift towards a more practical and application-focused approach. This trend aligns with the increasing demand for reliable and field-tested powertrain solutions in the electric vehicle industry.

However, several limitations and challenges are also apparent. Many methodologies, such as those in papers [50], [51], [52], [53], [56] and [58], acknowledge limitations related to cost considerations, real-world conditions, and the applicability of their approaches to different scenarios. These shortcomings highlight the need for more comprehensive and adaptable optimization strategies that can account for various external factors and manufacturing constraints.

In summary, the field of electric powertrain optimization is in a state of active exploration, characterized by a diversity of techniques and a growing emphasis on validation and practical application. However, acknowledged limitations underscore the need for more comprehensive and adaptable strategies to address real-world complexities and manufacturing constraints.

5.2.2 Transmission optimization

The methodologies employed across these six papers ([9], [60] to [64]) exhibit several common elements that underscore the foundational principles of optimizing transmission systems in electric vehicles. First and foremost, mathematical modelling plays an integral role in each approach, with all papers utilizing mathematical models, often implemented using simulation tools like MATLAB/Simulink, to represent critical components of electric vehicles, including electric motors, batteries, and transmission systems ([60] to [64]). These models serve as the cornerstone for subsequent analysis and optimization efforts, enabling a comprehensive understanding of vehicle behaviour. Secondly, a strong emphasis on simulation and computational analysis is evident throughout these methodologies ([60] to [64]). Researchers leverage these mathematical models within simulation environments, such as MATLAB/Simulink, to simulate various driving scenarios and conditions, allowing for the evaluation of energy efficiency, performance, and other pertinent factors. These simulations provide a controlled environment for testing and optimizing transmission configurations.

Furthermore, the commonality of optimization algorithms is striking, with each paper employing specialized techniques to uncover optimal solutions for electric vehicle transmission systems ([9], [60], [61] and [64]). The methodologies encompass a wide spectrum of optimization strategies, such as genetic algorithms, dynamic programming, surrogate-based modelling, and the Pontryagin Maximum Principle (PMP) method, often implemented using computational tools and libraries available within MATLAB ([9], [60], [61] and [64]). Additionally, the definition of objective functions emerges as another shared feature, with all methodologies incorporating objective functions that quantify and optimize aspects of vehicle performance and energy consumption ([9], [60] to [64]). These functions serve as the guiding metrics to evaluate and enhance electric vehicle transmission systems, whether targeting energy efficiency, dynamic performance, or both. Altogether, these commonalities in mathematical modelling, simulation using tools like MATLAB/Simulink, optimization algorithms encompassing genetic algorithms, dynamic programming, surrogate-based modelling, and the Pontryagin Maximum Principle (PMP) method, and objective functions underpin the robust methodologies employed to optimize transmission systems in electric vehicles across the examined research papers.

One of the striking differences among these methodologies is the variation in optimization techniques and constraints imposed in these methodologies. While optimization algorithms are central to all papers ([9], [60], [61] and [64]), the choice of algorithm differs significantly, ranging from genetic algorithms to dynamic programming to the Pontryagin Maximum Principle (PMP) method. Additionally, the methodologies demonstrate differences in constraint handling ([9], [61] and [64]). For instance, Paper [61] imposes constraints related to motor and battery operation to ensure safe and smooth functioning. In Paper [9], constraints revolve around gear ratios and motor torque distribution, ensuring that performance considerations align with electric vehicle specifications. Paper [64] introduces an intricate control mechanism for motor torque and gear ratios based on the driver's speed, further enhancing vehicle efficiency. These variations in optimization techniques and constraint management illustrate the adaptability of methodologies to cater to the specific needs and challenges of electric vehicle transmission system optimization.

The trends and outlook in the field of optimizing transmission systems in electric vehicles are shaped by the findings and limitations highlighted in the referenced papers. These insights point to several areas of potential future research and development.

First, the optimization of transmission systems remains a fertile ground for innovation. Paper [60] introduces a novel optimization method for a two-speed planetary gear automatic transmission system, but it suggests the exploration of different optimization techniques for further performance enhancements. The evolution of optimization algorithms and modelling approaches will likely play a crucial role in achieving even greater gains in energy efficiency and vehicle performance.

Second, the commercial viability of optimized systems is a key concern. While many papers focus on energy consumption improvements, as noted in Paper [60], there is a growing recognition that the cost-effectiveness and practicality of these systems under diverse driving conditions need further investigation. This suggests that future research should not only strive for technical excellence but also consider the economic and real-world applicability of optimized transmission systems.

Third, addressing the limitations identified in the referenced papers is essential for advancing the field. Whether it's the need to account for torque converters and electric motors separately (as mentioned in paper [61]) or improving the accuracy of models by considering factors like battery state of charge (as in paper [64]), addressing these limitations will lead to more robust and comprehensive optimization methodologies.

Fourth, real-world validation and experimentation are critical. Many papers acknowledge the need for experimental validation and note that the model's accuracy relies on the quality of experimental data (as in paper [63]). Future research should prioritize conducting experiments in varied conditions to validate the effectiveness of optimized transmission systems.

In summary, the trends and outlook for optimizing transmission systems in electric vehicles involve a continued pursuit of enhanced performance through advanced optimization techniques, a focus on commercial viability, addressing identified limitations, and rigorous experimentation and validation.

5.2.3 Energy storage optimization

The methodologies presented in these three research papers ([12], [65] and [66]) on energy storage optimization in electric vehicles share common aspects as well as notable differences. All three papers aim to optimize hybrid energy storage systems (HESS) in electric vehicles to enhance battery cycle life, minimize weight, and improve overall performance. They consider multi-objective optimization problems, wherein trade-offs are assessed among various factors, including battery cell number, ultracapacitor (UC) cell number, and reference power.

In the first paper [65], the authors employ a multi-objective optimization approach with constraints on battery and UC cell numbers and reference power. They emphasize the relationship between HESS sizing, battery cycle life, and weight through trade-off analysis. The DIRECT algorithm is used for solving the optimization problem effectively.

The second paper [12] introduces a model-based design framework that separates cycle life and fast charging goals from traditional vehicle requirements. It uses a genetic algorithm to solve the multi-objective optimization problem, considering high-energy (HE) and high-power (HP) battery cells with different chemistries. This approach aims to improve battery longevity, fast-charging speed, and overall performance.

The third paper [66] utilizes dynamic programming (DP) to optimize the control strategy of a HESS. It balances load distribution between batteries and supercapacitors (SCs) and accounts for the energy-saving effect of regenerative braking and real driving cycles. The technology employed is relatively advanced, with experiments conducted to model the components.

While all three methodologies focus on optimizing HESS for electric vehicles, the first two papers use mathematical optimization techniques, such as trade-off analysis and genetic algorithms, to determine optimal sizing and configurations. In contrast, the third paper employs dynamic programming and advanced control strategies to achieve load balancing and energy-saving goals. These differences highlight the diverse approaches researchers take to address similar challenges in energy storage optimization for electric vehicles.

The methodologies used in the three papers on energy storage optimization for electric vehicles reveal these trends in the field:

- Multi-Objective Optimization: Two of the papers ([12] and [65]) employ multi-objective optimization techniques to find optimal solutions for energy storage system design. This trend indicates that researchers are increasingly recognizing the need to balance multiple conflicting objectives, such as battery cycle life, weight, and cost, when designing energy storage systems for electric vehicles. Multi-objective optimization allows for a more holistic approach to system design.
- Real-World Testing and Validation: In all three papers ([12], [65] and [66]), there is a recognition of the need for real-world testing and validation. This trend underscores the importance of not relying solely on simulation-based results but also conducting experiments and tests in actual electric vehicles to confirm the effectiveness of the proposed methodologies. It reflects the practicality of real-world applicability in the development of energy storage systems.

5.2.4 Sound optimization

In summary, this paper [67] delves into the crucial issue of sound quality improvement in electric powertrains for electric vehicles. Despite its significance, it's noteworthy that there are relatively few publications in this specific domain, possibly indicating limited interest within the research community.

6 Evaluation of electric vehicle concepts

In the next section, we will conduct a literature review to investigate the existing research on the evaluation processes of different electric vehicle concepts. This review will form the basis for our subsequent analysis and conclusions, offering a comprehensive overview of the current state of knowledge in this field.

6.1 Literature Review

Lithium-ion batteries – Current state of the art and anticipated developments.

This paper aims to address the current state of the art and future developments in lithium-ion batteries. The primary problem to solve is how to achieve safer, more energy-dense, and longer-lasting batteries that are sustainable concerning their materials, manufacturing processes, and end-of-life disposal.

To tackle this problem, the paper takes a comprehensive view of the battery components, materials, and processes that are already commercially relevant or anticipated to be thus in the very near future. The methodology includes critical review and analysis of multiple scientific and technical sources in the field that relate to advances in negative and positive electrodes, electrolytes, electrode coatings, and recycling technologies, among others. The technology employed ranges from DFT calculations to artificial intelligence.

The results show that lithium-ion batteries continue to improve in performance, energy density, and cost, led mostly by advances in silicon-based anodes, lithium transition-metal oxides, and electrolytes, among others. There is also an increasing trend towards electrode coatings that enhance battery stability and longevity. However, the authors note that even an efficient 100% recycling rate for these batteries would only cover a small portion of the raw materials needed to satisfy global demands. Thus, there is a need to explore new materials, components, and processes continually, such as those investigated in ongoing research efforts and emerging technologies.

In conclusion, the paper provides valuable insights into the state of the art and expected advances in lithium-ion batteries that will shape the future of energy storage and electric mobility. However, the authors note that the review is not exhaustive, and there might be other materials, processes, and technologies yet to be discovered or developed. The paper encourages researchers to remain open-minded and innovative, leveraging emerging technologies and novel approaches in the ongoing quest for better, safer, and more sustainable energy storage solutions.

DC-DC Converter Topologies for Electric Vehicles, Plug-in Hybrid Electric Vehicles and Fast Charging Stations: State of the Art and Future Trends.

This paper aims to provide an overview of different DC-DC converter topologies for electric vehicles (EVs), plug-in hybrid electric vehicles (PHEVs), and fast charging stations (FCHARs). The main problem it addresses is the demand for small-sized, reliable, parametrized, lightweight, controllable, scalable, and efficient converters for vehicular applications. In addition, it discusses the significance of charging time and the number of available charging stations for EV and PHEV customers.

The authors of the paper used a literature review method to survey the state of the art and future trends in DC-DC converter topologies, modelling, and control design for EVs, PHEVs, and FCHARs. They employed different methodologies, such as the interleaving technique of boost converters, full-bridge boost converters, Zero-Voltage Switching (ZVS) and Zero-Current Switching (ZCS) source converters, and multiphase, multiport, or multidevice boost converter topologies, to identify viable converter topologies that could improve the performance of electric sources and demand for low ripples with tight tolerance.

The authors presented a comprehensive table that shows a broad comparison between different DC-DC converter topologies for both EVs and FCHARs. They also revealed future trends of research in detail, which involved advanced modelling, new converter topologies, and novel control concepts for high voltage gain and high-power application. Moreover, the paper demonstrated how technologies, such as isolated and non-isolated multi-phase interleaved converters, can minimize input current ripples and output voltage ripples while improving the overall efficiency, integrated thermal distribution, and reliability of the system.

One of the open points of this paper is the sensitivity and stability problems faced with some of the DC-DC converter topologies due to the duty cycle at load changes, and scalability problems as multiple numbers of components are used. Furthermore, the paper highlights the necessity of reducing charging time and increasing the number of available charging stations to enhance the purchase rate of EVs and PHEVs. Overall, this paper provides valuable insights into the latest research on DC-DC converter topologies and the positive impact it can have on the automotive industry.

An Overview of Electric Machine Trends in Modern Electric Vehicles.

This paper provides an overview of the trends of electric machines in modern electric vehicles. One of the main problems the paper aims to solve is the lack of technical literature on the design of electric machines used in electric vehicles. Therefore, the paper employs various sources, such as researchers, third-party sources, commercial entities, individual auto enthusiasts, and laboratory tests to provide insight into the design and construction features of modern electric vehicles.

The methodology of the paper is to gather information on electric vehicle machines and propulsion systems. The paper presents different reviews on technologies such as electric motors, battery, and power electronics, before summarizing various reports from independent sources such as the Oak Ridge National laboratory. The paper also reviews multiple teardowns of electric vehicles, where they were taken apart for more insight into their design.

The results of this paper indicate that electric vehicle technology has significantly improved in recent years, mostly originating from advances in electric machines, battery technologies, and propulsion systems. However, the paper also revealed that there is limited technical literature available from manufacturers on the design of electric machines used in electric vehicles. This means a lack of research on specific designs of electric motors has led to insufficient information on the performance.

The paper does have a few open points and criticisms. Firstly, the findings can only be understood in terms of the scope of the sources mentioned. This rationale suggests that if the scope were to be expanded, it might allow more detailed conclusions about the design of electric machines used in electric vehicles. Secondly, it can be difficult to compare specific designs when limited research data is available to draw conclusions. Additionally, the scope of the paper is only limited to electric motors, and hence research regarding other electric vehicle components should also be considered in understanding the overall trends in electric vehicles.

Performance analysis framework for structural battery composites in electric vehicles.

This PDF file presents a Performance Analysis Framework for Structural Battery Composites in Electric Vehicles. The problem is that there is a need for high-performance and low-mass energy storage solutions for electric vehicles, which can potentially be solved by integrating the battery into the vehicle structure. However, there is a need to analyse and optimize the design to ensure safe and reliable operation.

The methodology is centred on the development of a performance analysis framework based on an interdisciplinary modelling approach that combines mechanical, electrical and thermal modelling. Classical Laminate Theory (CLT) is employed to estimate the in-plane elastic properties of the composite laminate. Additionally, electrochemical modelling is used to simulate the performance of the structural battery cell.

The results of the study show that a structural battery composite (SBC) can potentially be a suitable energy storage solution for electric vehicles. The simulation results indicate that design optimizations can result in a significant weight reduction, increased power and energy density, and efficient use of space. Furthermore, the SBC offers increased mechanical performance compared to conventional batteries.

Despite the promising results, there are still open points and criticisms to be addressed. One limitation of the study is the reliance on modelling and simulation, which may not fully capture real-world conditions. Additionally, there is a need to investigate the long-term durability and reliability of the SBC under various operating conditions. Other areas of possible improvement include the optimization of the composite material architecture, and the integration of safety mechanisms and thermal management into the design.

A review and research on fuel cell electric vehicles: Topologies, power electronic converters, energy management methods, technical challenges, marketing and future aspects.

This paper provides a comprehensive study on fuel cell electric vehicles (FCEVs) with a focus on their topologies, power electronic converters, energy management methods, technical challenges, marketing, and future aspects. Fossil fuels are widely used in the transportation sector, and they have negative effects such as air pollution, noise, and global warming. Therefore, FCEVs are seen as an alternative to traditional vehicles and a solution to these negative impacts. However, there is a lack of detailed studies for researchers in this field, and this paper aims to fill that gap.

The authors employed a literature review methodology to examine numerous studies in detail and provide a comprehensive scientific publication on the current status and future expectations of FCEVs. The paper is organized and classified into several sections, beginning with an introduction to the subject matter and an overview of FC types and electric motors. It then covers the topologies and control/management of FCEVs, including the technical challenges faced during the implementation of these technologies. In the final section, the paper reports the current status and potential future aspects of FCEVs, including marketing and target data.

The study indicates that FCs in the vehicle industry have gained significant attention over the last few decades due to their simple utilization, silent operation, high efficiency, and modular structure. The technological advancements suggest that FCEVs will increase rapidly in the future and may become a revolution. Several commercial vehicles and research projects are underway to ensure that FCEVs have sufficient performance advances for their daily transportation needs. However, the paper also highlights some of the technical challenges and limitations faced in the implementation of these technologies.

In conclusion, this paper presents a thorough research and review report on FCEVs with a focus on their topologies, power electronic converters, energy management methods, technical challenges, marketing, and future aspects. It provides researchers and engineers in this field with a comprehensive publication that sheds light on the current status and potential future advancements of FCEVs. Nevertheless, some limitations still need to be addressed, such as the low durability of FC stacks and the high cost of technology implementation.

Benchmarking of electric and hybrid vehicle electric machines, power electronics, and batteries.

This paper aims to present the metrics and benchmarks used to evaluate the performance of various systems in the realm of electric motors, power electronics, and energy storage for electric and hybrid vehicles. The objective of this study is to identify the current state-of-the-art technologies used in the industry, as well as any future goals and trends. The authors highlight the need for continued research to develop new technologies in order to enable large-scale market penetration of electric and hybrid vehicles.

To achieve the objectives of this paper, the authors start by describing the evolution of electric vehicle technologies, specifically electric motors, power electronics, and energy storage. The paper also presents the current trends in technology, along with performance requirements set for the future. The metrics and benchmarking of the technologies are used to describe the current and potential future states of the technologies.

The authors present an in-depth review of the state-of-the-art technologies in electric motors, power electronics, and energy storage for automotive applications. The results showcase the improvements in these technologies, which have enabled the production of current electric and hybrid vehicles. The paper also reveals potential future trends that suggest the market for electric and hybrid vehicles is poised for continued growth.

Although this paper provides a comprehensive review of the current state-of-the-art technologies and potential future trends in the automotive industry, there are some open points. For instance, the paper does not provide a detailed analysis of the cost structure of these technologies. The study also does not address how the current infrastructure will adapt to the increased penetration of electric and hybrid vehicles. These issues could potentially hinder the further market penetration of these cars.

In conclusion, this paper provides readers with a thorough analysis of the current state-of-the-art electric motor, power electronics, and energy storage technologies used in the automotive industry. While there are ongoing research and development of new technologies, this study suggests that the market for electric and hybrid vehicles will continue to grow and revolutionize the industry in the future. Nonetheless, additional research is needed to address potential cost and infrastructure issues.

Status of Pure Electric Vehicle Power Train Technology and Future Prospects.

The paper evaluates powertrains of pure electric vehicles (PEVs) through analysing the technology barriers of BEVs and the feasible solutions developed in previous reviews. The evaluations are carried out by analysing different aspects of the powertrain system and subsystem, including energy source, charging system, drive train architecture, propulsion unit, design optimization, and future development of pure electric mobility.

The data from different vehicle parameters undergoes different differential equations from vehicle dynamics to size the power train system, as per defined performance requirements. The paper explores the different drive train systems of BEVs and presents the technical issues connected with the powertrain system and subsystem of BEVs. The paper employs different simulation tools to optimize the design and development of pure electric vehicles and hence, evaluates the powertrain system using different simulation models and analysis techniques.

Overall, this paper evaluates powertrains by exploring different drive train systems, technical issues associated with them as well as the different simulation tools employed to optimize the design and development of pure electric vehicles.

One of the open points is the development of charging infrastructure and the range of electric vehicles. The paper discusses different battery technologies and energy sources that can power pure electric vehicles. Overall, this paper offers technical insights into the advances in powertrain technology of PEVs, but more research is needed to solve the challenges of transitioning to electric vehicles fully.

Beyond the State of the Art of Electric Vehicles: A Fact-Based Paper of the Current and Prospective Electric Vehicle Technologies.

This paper aims to provide insights into the latest knowledge and developments of electric vehicles (EVs) and the new promising and novel EV technologies based on scientific facts and figures. The paper addresses potential design and modelling tools, such as digital twin with connected Internet-of-Things (IoT), and potential technological challenges and research gaps in all EV aspects from hard-core battery material sciences, power electronics and powertrain engineering up to environmental assessments and market considerations.

The research paper evaluates electric vehicles based on their life cycle assessment (LCA) by analysing their environmental impact from the production phase until the end of life. The authors utilize a single score level comparison of various EV technologies, including battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell electric vehicles (FCEVs), in terms of energy consumption, carbon emissions, and environmental impacts. The evaluation not only analyses the material and engineering aspects of EVs, but also considers the mobility system perspective and market variability of technologies.

The results of the environmental assessment show that both the BEV and PHEV have the lowest environmental impact in the current Belgian system. In many mid-point categories, the performance of BEVs is better compared to conventional petrol and diesel vehicles, except in the human toxicity category. The high impact on human toxicity is mainly because of the large contribution from the manufacturing of extra components like battery, motor, electronics, etc. Nonetheless, when comparing the well-to-wheel (WTW) phase, which is appropriate for the Belgian boundary (and urban context), the BEV has better scores among all the vehicles in the analysed impact categories. Furthermore, the paper addresses various novel technologies and advancements in batteries, energy management systems, autonomous features, and charging infrastructure.

While this paper offers valuable insights into the most recent knowledge and advancements of EVs, and potential technologies to be developed, it still leaves room for further research. The authors acknowledged that further investigation is necessary to tackle the technological challenges in the development of EVs beyond 2030 and the market and regulatory aspects related to EVs in various countries. Furthermore, more research is also needed to address the issues related to the integration of EVs into the electricity grid network.

State of the Art and Trends in Electric and Hybrid Electric Vehicles.

The paper titled "State of the Art and Trends in Electric and Hybrid Electric Vehicles" aims to provide an overview of the challenges, breakthroughs, and future technologies in the field of Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs). The aim of this research is to optimize the design of energy-efficient powertrains that can help conserve fossil fuel and reduce pollution for a sustainable environment and transportation.

The paper employs a comprehensive methodology that addresses all the factors related to the optimization of the powertrains including hardware optimization like power electronic converters, energy storage systems, powertrain architecture, and transmission type, and software optimization like battery management, fuel consumption, driver performance demand emissions, and management strategy. In addition, the paper also discusses the major challenges and future technologies for EV/HEV.

The outcomes of detailed studies are presented in tabular form to compare the strengths and weaknesses of various methods. The paper analyses current research and suggests its scope for future research in EV/HEV. The presented findings can serve as a reference for those working in this field.

While the paper provides a comprehensive overview of the challenges and breakthroughs in the field of EVs and HEVs and suggests future research directions, there are still some open points and criticisms. The paper mainly focuses on the technical aspects of the optimization of powertrains and less on the socio-economic and policy dimensions that greatly influence the adoption and diffusion of EV/HEV technologies. Therefore, a multidisciplinary approach is needed to address the socio-economic and policy dimensions and their impact on the adoption and diffusion of EV/HEV technologies.

Performance Analysis of Current BEVs Based on a Comprehensive Review of Specifications.

This paper provides a comprehensive performance analysis of over 40 globally available battery-electric vehicles (BEVs) based on a review of manufacturer specifications and dimensional data. The analysis includes vehicles sold in USA, Europe, Japan, and China from 2014-2015. As the motive to increase vehicle electrification is to reduce environmental burdens, this paper aims to support the academic community with vehicle performance data to help focus future BEV research.

The analysis methodology describes the calculation of efficiency, acceleration, gradeability, battery and drivetrain characteristics. The paper also discusses possible improvements such as a shared component strategy for electric motor designs and avoidance of material that is toxic, rare, and difficult to recycle. The paper shows a trend towards life cycle assessment studies on vehicles continues to increase, even though these material choices may cause a degradation of some performance components compared to today's solutions.

The results show large variations between BEVs, even among those sold within the same year and market area. Among the findings, vehicle weight has a noticeable impact on efficiency, and the paper highlights that lightweight structures, as well as the reduction of power demand for vehicle auxiliary systems, are a perspective for future work. The paper also highlights the variations in governing regulations and testing procedures around the world, which may lead to different performance results.

The authors note that improvement of battery technology is also still required, and that a big leap toward new successful chemistries seems a bit remote. Hence, they do not predict how much research will be put into finding new chemistries in the future. The paper recognizes the importance of the environmental impact from a life-cycle perspective and suggests that this topic should be a future research target.

Electric Drive Technology Trends, Challenges, and Opportunities for Future Electric Vehicles.

This paper discusses the current and emerging trends in electric drivetrain technology for electric vehicles (EVs) and hybrid EVs in order to improve their fuel efficiency, range, and charging capabilities. The authors identify the need for higher power and more efficient electric traction drive systems that lead to better fuel economy for a given battery charge.

To address this need, the paper discusses the technical targets for light-duty EVs for 2025 as established by the U.S. Department of Energy (DOE) in collaboration with the automotive industry. The authors then cover the emerging materials and technologies for power electronics and electric motors, highlighting the challenges and opportunities for more aggressive designs to meet the need for next-generation EVs.

The paper also presents commercially available solutions in terms of materials, electric machine and inverter designs, maximum speed, component cooling, power density, and performance. Some innovative drive and motor designs that have the potential to meet the DOE 2025 targets are also discussed.

In conclusion, the authors argue that the transition to electric road transport technologies requires electric traction drive systems to offer improved performance and capabilities. They suggest that electric drivetrain technology will continue to evolve, with opportunities for future research on materials, design, and performance to reduce cost and increase efficiency.

A Comprehensive Study of Key Electric Vehicle (EV) Components, Technologies, Challenges, Impacts, and Future Direction of Development.

This paper aims to review the current state of electric vehicles (EVs) technology and investigate future development potentials in this sector. EVs can offer significant benefits compared to conventional internal combustion engine (ICE) vehicles, including lowering greenhouse gas emissions and noise reduction. However, there are still challenges for EVs to overcome before becoming a total replacement for ICE vehicles.

The researchers used a comprehensive review methodology to gather data on EV configurations, battery energy sources, motors, charging technologies, optimization techniques, impacts, trends, and possible directions of future developments. The study provides a detailed description of the current state of EVs technology, their energy management systems, control algorithms, and the environmental and economic impacts of their widespread use. The results show that the existing power system would face significant instabilities with a high enough EV penetration. Still, better management and coordination could turn EVs into a major contributor to the success of the smart grid concept.

The study indicates that there are possibilities for a significant reduction in greenhouse gas emissions with the extensive use of EVs. However, there are also technical and economic limitations that need to be resolved before widespread adoption. Current challenges include battery autonomy, the availability of charging stations, and the high cost of electrification infrastructures. To overcome these obstacles, considerable investment in research and development is required.

In conclusion, the paper provides an overall picture of the current EV technology, its limitations, and future deployment potentials. Future research should focus on enhancing range, reducing costs, increasing charging efficiency and availability, establishing energy storage and management systems, and developing sustainable manufacturing practices for EVs.

Vehicle Energy Dataset (VED), A Large-Scale Dataset for Vehicle Energy Consumption Research.

This paper introduces a new large-scale dataset, named Vehicle Energy Dataset (VED), designed to provide a comprehensive understanding of vehicle energy consumption and to facilitate research in sustainable transportation. The goal of the research is to provide accurate estimations of fuel and energy consumptions of a variety of vehicles under various driving conditions.

The authors collected data for VED from various sources, including individual drivers and research institutions. The data is cleaned, pre-processed, and analysed using several algorithms to estimate fuel consumption rate, roads and routes travelled by vehicles, speed, acceleration, and other variables. The de-identification procedure is developed to ensure driver privacy without sacrificing the spatiotemporal resolution of the data.

The experiment results demonstrate that the estimated fuel consumption rate and energy consumption of plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs) are highly reliable. The methods used by the researchers achieved high accuracy compared to the traditional dynamometer testing ground truth data. Additionally, the dataset and the algorithms provide significant improvements in accurately estimating fuel and energy consumption rates of vehicles.

One of the main limitations of the VED presented in this paper is the lack of variety in vehicle models, which may cause bias towards specific brands and models. The researchers acknowledge that driver behaviour is significant in fuel consumption estimations. Therefore, future work could focus on incorporating and analysing human factors such as driver behaviour, weather and traffic conditions into vehicle energy consumption models. However, this paper introduces a valuable dataset and algorithms for estimating energy consumption rates in various driving conditions, contributing to the quest for sustainable transportation.

Light electric vehicle powertrain analysis.

This paper presents an analysis of the powertrain of a light electric vehicle (LEV). The authors aim to describe the technical solutions, exploitation properties, advantages, and disadvantages of the Mia Electric vehicle. They perform a roller dyno test and testing under actual driving conditions to gather data and carry out a powertrain analysis.

To analyse the powertrain, the authors use an electric motor, a battery, a charger, a motor controller, and a microcontroller. They also consider the construction of the car and the safety of vehicle occupants and traffic participants. The authors acknowledge the importance of machine vision and remote vehicle detection systems, as well as autonomous driving systems. They present the different components of the LEV in-depth and analyse their efficiency, highlighting possible ideas for improvement.

The data collected from the tests on a roller dyno and under driving conditions provide the authors with insight into the performance of the powertrain. They present a thorough analysis of the powertrain and offer conclusions on its performance and efficiency. The authors conclude that with the introduction of modern electric powertrains, a new chapter has begun for automotive technology.

Although the analysis of the LEV powertrain is extensive, the authors do not discuss the economic, social, or environmental implications of using EVs. They also do not compare the Mia Electric vehicle with other types of electric vehicles. Therefore, future research could explore the potential impact of using EVs on both individual and societal levels more broadly. Overall, the analysed powertrain of the LEV provides an excellent basis for further study and application.

Quantifying the state of the art of electric powertrains in battery electric vehicles: Range, efficiency, and lifetime from component to system level of the Volkswagen ID.3.

This paper titled "Quantifying the state of the art of electric powertrains in battery electric vehicles: range, efficiency, and lifetime from component to system level of the Volkswagen ID3" seeks to investigate the performance of the Volkswagen ID3 Electric Vehicle (EV) in terms of range, efficiency, and lifetime of both component and system levels. The research aims to bring clarity to the measurement of EV performance and how different tests methods can be used to draw user-relevant conclusions to improve EV technology.

The researchers used several tests like coast-down, vehicle dynamometer, and automated throttle and brake control to evaluate the dynamic performance of the EV in both public and laboratory settings. The vehicle onboard data was accessed by using a diagnostic session control request over the OBD-II standardized interface, which allowed the researchers to record the vehicle's data through unified diagnostic services (UDS). For further assessment of the battery cells, three brand new modules were acquired from a teardown vehicle and disassembled for experimental cell testing.

The study results showed that the range of the Volkswagen ID3 EV fell within the expected values compared to its competitors while its efficiency was reasonable. The findings provided a detailed analysis of the battery pack, including measurements of internal resistance and thermal behavior across different temperature and SOC values, giving insights into the lifetime of the battery pack. However, the paper identified open points and criticisms, including the uncertainty of future developments in EV technology's efficiency, durability, and performance relative to consumer expectations.

In conclusion, this paper has provided a detailed analysis of the performance of the Volkswagen ID3 EV, focusing on its range, efficiency, and lifetime from the component to system level.

Car magazines.

As the demand for EVs continues to grow, automotive enthusiasts and consumers alike are keen to understand the intricacies of these electric marvels, from their overall performance to the nuances of their individual components. Car magazines, renowned for their expertise in evaluating and dissecting automotive innovations, play a pivotal role in providing comprehensive insights into EVs. In this section, we delve into the methodologies employed by car magazines to rigorously assess electric vehicles and their various components, shedding light on the critical factors that shape the perceptions and decisions of both automotive enthusiasts and prospective EV buyers. The following information has been extracted from Car and Driver [13], Motortrend [82] and L'Automobile [83].

In terms of how they evaluate electric vehicles, magazines conduct a meticulous assessment that combines both objective and subjective criteria. They evaluate performance metrics such as acceleration, range, charging time, and energy efficiency. Additionally, they consider technical specifications like battery capacity and the availability of charging infrastructure.

When comparing different electric vehicles, magazines take into account several critical parameters. These include range, which indicates the distance an EV can travel on a full charge, and charging time, measuring the duration required for a full battery charge. Performance metrics like acceleration, top speed, and driving dynamics are also assessed. Furthermore, magazines evaluate efficiency, typically measured in miles per kilowatt-hour (kWh), to understand how efficiently the vehicle uses electricity. Battery capacity, measured in kilowatt-hours (kWh), is also considered, along with the availability and convenience of charging infrastructure. Price, including incentives and overall cost of ownership, is factored in. Interior space, including passenger room and cargo capacity, is assessed, as well as the quality of interior materials. The evaluation also includes an assessment of technology and features, encompassing infotainment systems, safety features, and connectivity options. Additionally, reliability is taken into account, assessing the vehicle's dependability and the manufacturer's reputation.

To gather data on electric vehicle performance, magazines conduct various tests. These tests include instrumented testing, where objective measurements like acceleration times, braking distances, and energy consumption are recorded. Real-world testing is also conducted to assess real-world range in different driving conditions and actual charging times. Furthermore, magazines conduct user experience evaluations, offering subjective assessments of the driving experience, ride comfort, and the usability of tech interfaces.

Beyond overall evaluations, magazines go a step further by comparing specific components of different electric vehicles. These components include battery performance, motor capabilities, chassis and suspension quality, infotainment systems, interior comfort, and safety technologies.

After evaluating these specific components, magazines provide an overall assessment of the electric vehicle. They consider how each component contributes to the vehicle's overall performance and the driving experience. This holistic evaluation aims to help consumers make informed decisions about electric vehicles based on their preferences and needs.

In essence, the car magazine's approach to reviewing electric vehicles is thorough and multifaceted, ensuring that readers receive a detailed understanding of each EV's strengths, weaknesses, and suitability for various lifestyles and requirements.

6.2 Conclusion

In this section, the analysis will delve into the conclusions derived from an examination of various academic papers focused on the evaluation of electric vehicles (EVs). These papers have been methodically grouped into three categories: Components Comparison, Vehicles Comparison, and In-depth Analysis of Components. The primary aim is to synthesize the collective insights within each category, identifying commonalities and disparities among the papers. Subsequently, the section will shed light on the emerging trends and future outlook in the realm of electric vehicle technology and its components. This exploration seeks to offer a comprehensive overview of the current state of research in the field of electric vehicles, providing valuable insights for both researchers and industry professionals.

6.2.1 Components comparison

The methodologies employed across the papers on component evaluation in electric vehicles share several commonalities. First and foremost, they all begin by identifying specific problems or challenges within the electric vehicle domain, which serve as the foundation for their research objectives. For instance, the first paper focuses on improving lithium-ion batteries for enhanced safety and energy density [68], while the second paper aims to optimize DC-DC converters for electric vehicles and charging stations [69].

Secondly, these papers rely heavily on extensive literature reviews and data analysis to gather relevant information and insights. Whether it's critical reviews of scientific and technical sources for battery advancements [68], a comprehensive survey of literature for DC-DC converter topologies [69], or the exploration of different drive train systems and technical issues for electric machines [69], the reliance on existing knowledge is a common thread.

Thirdly, each of these papers presents its findings based on the respective methodologies used. They all share the objective of providing valuable insights and solutions within their specific research areas. This can be observed in the results showing improvements in battery performance [68], the detailed comparison table of DC-DC converter topologies [69], or the discussions on the state-of-the-art technologies in electric motors and energy storage [14].

While these papers share common methodological approaches, they also exhibit distinct differences based on their specific research objectives and areas of focus.

For instance, the first paper on lithium-ion batteries [68] employs advanced technologies like DFT calculations and artificial intelligence for in-depth analysis of battery components and materials. In contrast, the second paper on DC-DC converters [68] emphasizes the utilization of various converter topologies and control techniques without delving into advanced computational methods.

In another example, the fourth paper on structural battery composites [71] adopts an interdisciplinary modelling approach that combines mechanical, electrical, and thermal modelling for a holistic evaluation. Meanwhile, the fifth paper on fuel cell electric vehicles [72] conducts an extensive literature review to provide a comprehensive overview, lacking the intensive modelling seen in the fourth paper.

Furthermore, the seventh paper on powertrain evaluation in pure electric vehicles [73] employs differential equations and simulation tools to optimize design and development, while other papers do not delve into this level of mathematical analysis.

In summary, while these papers share common starting points and objectives, the specific methodologies employed vary to suit the unique requirements of their research areas. This diversity in approach allows each paper to contribute distinct insights and solutions within the realm of electric vehicle component evaluation.

6.2.2 Vehicles comparison

Across the selected papers ([74] to [79]) on electric vehicle (EV) comparison, there are common elements in their methodologies. All these papers share a commitment to advancing the understanding and development of EV technology. They rely on scientific data, modelling tools, and rigorous analysis to evaluate various aspects of EVs, including their environmental impact, powertrain efficiency, and emerging technologies. Furthermore, they acknowledge the importance of addressing challenges and gaps in the EV industry to promote sustainability and energy efficiency.

However, the main differences lie in the specific approaches and research focuses of these papers. Each paper tailors its methodology to its distinct objectives. For instance, while some emphasize a comprehensive analysis encompassing battery material sciences and market considerations [74] others concentrate on fine-tuning powertrains for energy efficiency considerations [75]. There are also differences in the scope of data collection and analysis, ranging from a performance analysis of specific BEVs considerations [76] to a focus on drivetrain technology and meeting DOE targets considerations [77]. Additionally, methodologies vary from comprehensive reviews of EV technology and its impacts considerations [78] to the creation of new datasets for estimating vehicle energy consumption considerations [79]. These variations reflect the multifaceted nature of EV research, with each paper contributing uniquely to the broader understanding and improvement of EV technology.

6.2.3 In-depth analysis

The methodology employed in both papers ([15] and [80]) involves a comprehensive analysis of electric vehicle powertrains. In both cases, the authors aim to provide a detailed understanding of the technical aspects and performance of electric vehicles. They utilize a combination of real-world testing and laboratory experiments to gather data for analysis. Additionally, both papers acknowledge the importance of assessing various components within the powertrain, such as motors, batteries, controllers, and vehicle construction. Moreover, both investigations emphasize the significance of evaluating efficiency and performance, ultimately contributing to the advancement of electric vehicle technology.

However, the main differences in the methodologies employed between the two texts are notable. In the first paper [80], which focuses on a specific light electric vehicle (LEV), the analysis primarily centres around a single vehicle model, Mia Electric, and its powertrain. The authors conduct roller dyno tests and actual driving condition tests to evaluate this specific model comprehensively. In contrast, the second paper [15] takes a broader approach by studying the Volkswagen ID.3 Electric Vehicle as a representative case. It assesses the ID.3's performance in terms of range, efficiency, and battery lifetime but does not delve into the vehicle's construction or individual components to the same degree as the first text. Furthermore, the second text [15] places a strong emphasis on accessing and analysing vehicle data through standardized interfaces, such as OBD-II, and includes a teardown analysis of battery modules, providing insights into battery pack behaviour. Overall, while both texts share a common goal of analysing electric vehicle powertrains, they differ in their scope and specific focus on vehicle models and testing methodologies.

6.2.4 Trends and outlook.

In conclusion, the evaluation of electric vehicles (EVs) presents a fascinating juxtaposition between the scientific rigor of academic papers and the consumer-centric approach of car magazines. Through our analysis, several trends and conclusions emerge:

Focus on Components vs. the Whole Car: The primary distinction lies in the scope of evaluation. Scientific papers tend to delve into the intricacies of individual components, dissecting everything from batteries to motors, while car magazines place their emphasis on the holistic driving experience. This disparity can be attributed to the divergent readerships and objectives of these publications. Papers are geared towards manufacturers and industry professionals who require detailed technical insights, whereas magazines cater to consumers who prioritize the overall car ownership experience.

The Quest for Real-World Data: Both scientific papers and car magazines share a common pursuit of real-world data. They acknowledge the value of data collected from actual driving scenarios as it offers a more accurate representation of how EVs perform in everyday life. This approach, while more challenging to obtain, is considered more cost-effective than relying solely on dynamometer testing, which may not fully capture the intricacies of real-world usage.

Creating a Scale for Benchmarking: Both forms of evaluation contribute to the development of a scale that defines the state of the art in the EV industry. Whether it's for components like batteries or the overall EV performance, the practice of comparing different models against one another helps establish benchmarks and identify areas for improvement. This shared objective highlights the synergy between scientific research and consumer-oriented journalism in advancing the electric vehicle landscape.

Efficiency vs. User Experience: The distinction between scientific papers and car magazines can also be attributed to their intended audiences. Papers are more inclined to scrutinize efficiency metrics, such as energy consumption and range, which are crucial for manufacturers seeking to optimize their products. In contrast, magazines place greater emphasis on the user experience, considering factors like comfort, features, and design, as these are of paramount importance to potential buyers.

In summary, the evaluation of electric vehicles is a multifaceted endeavour that involves both scientific research and consumer-focused journalism. These two realms, while different in their approaches and objectives, ultimately complement each other, contributing to the overall growth and improvement of electric vehicle technology.

7 Conclusion and outlook

7.1 Conclusion

In this section, we delve into the pivotal outcomes of our comprehensive research, shedding light on the key discoveries that have emerged from our investigation. Through rigorous analysis and meticulous study, we have unearthed critical insights that promise to significantly contribute to our understanding of the potential of benchmarking for electric vehicle concepts. These findings represent the culmination of dedicated effort, rigorous methodology, and innovative approaches, offering valuable perspectives that not only enrich our academic discourse but also hold profound implications for this field. In the following pages, we will elucidate these main findings, their implications, and their potential to shape future research and practical applications in this domain.

Within the realm of CAN data analysis, machine learning and clustering techniques have made remarkable strides. These methods have become increasingly sophisticated, capable of handling the diverse and complex data generated by electric vehicles. Importantly, they are also effective at addressing challenges such as false positives, ensuring that the insights extracted from CAN data are both accurate and reliable.

One of the key areas where machine learning and clustering have had a significant impact is in the grouping of CAN messages and the extraction of valuable signals. This allows researchers and engineers to gain a deeper understanding of how information flows within the vehicle's communication network, leading to improved system performance and diagnostics.

Reverse engineering, a critical task in the study of CAN data, has also benefited immensely from these techniques. By combining supervised learning with clustering, researchers can unravel the intricate architecture of CAN data. This not only aids in deciphering the underlying structure of the data but also helps identify crucial features and patterns that might otherwise go unnoticed.

The versatility of machine learning and clustering techniques is evident throughout the research landscape. In various contexts, from anomaly detection to feature selection and classification, these methods have demonstrated their adaptability and effectiveness. For instance, in anomaly detection, neural-network models have proven highly adept at identifying irregularities within CAN data, enhancing the safety and reliability of electric vehicles.

Lastly, the combination of physical models with unsupervised learning and Convolutional Neural Network (CNN)-based approaches, as seen in driver intention classification, underscores the diversity of analytical methodologies made possible by machine learning.

Also, in the landscape of data acquisition in electric vehicle, a groundbreaking finding is emerging, one that promises to revolutionize the way we reverse engineer Controller Area Network data from these modern marvels of engineering. At the forefront of this discovery is the pivotal role of data preprocessing, which is swiftly shaping the future of EV research and development.

One of the paramount aspects of this revelation is the growing need to reduce manual labour and usher in a new era of automation in the realm of data preprocessing. With the surge in the complexity and sheer volume of data generated by electric vehicles, the conventional methods of manual data cleaning and formatting have proven to be increasingly cumbersome and inefficient. To address this challenge, researchers are ardently working on streamlining data preprocessing procedures, particularly in real-time applications. This endeavour aims to minimize the necessity for human intervention, allowing for swifter and more accurate data preparation.

As this finding unfolds, it becomes evident that there is no singular, dominant methodology leading the charge in the arena of data preprocessing for electric vehicles. Rather, the field is marked by a multitude of diverse technologies and approaches, each contributing to the ongoing evolution of data processing techniques.

Within this rapidly developing landscape, data preprocessing automation stands out as a prominent trend. Researchers are actively focused on optimizing data cleaning and formatting processes, aligning them with the demands of the modern EV industry. This trend not only promises to enhance efficiency but also to facilitate real-time data analysis by minimizing latency in the preprocessing phase.

In the ever-evolving landscape of electric vehicles (EVs), real-world testing has emerged as a game-changer, offering a unique way to obtain genuine parameters of the crucial components within these vehicles. Unlike traditional laboratory-based testing or simulations, real-world testing takes place on actual roads, providing a comprehensive understanding of how EVs perform under practical conditions. This approach, highlighted in several recent papers, promises a more accurate reflection of an EV's capabilities in everyday life.

The trend towards real-world testing in the EV industry is gaining momentum, with researchers increasingly relying on it to capture essential data. One of the key advantages of this method is its ability to replicate real-world scenarios closely, making it an indispensable tool for assessing EV efficiency and performance. As this trend continues, there is a growing need to ensure that these testing methodologies are adaptable across various EV types, operating conditions, and applications. Addressing concerns and criticisms, as noted in some studies, will be vital to validate and refine these methods.

Moreover, real-world testing is becoming an attractive approach for EV research and development due to its accessibility and cost-effectiveness. Its potential for improvement lies in enhanced sensor technology, more advanced data analysis techniques, and the establishment of standardized testing protocols. These enhancements are expected to provide even more accurate and comprehensive insights into EV efficiency in the future.

Another recurring theme in the realm of EV research is the importance of validation and practical application. Researchers and engineers are increasingly recognizing the necessity of validating proposed EV designs through real-world testing and data collection. This shift towards practicality aligns with the industry's growing demand for field-tested powertrain solutions, ensuring that innovations perform as expected when put to the test on the road.

Furthermore, the quest for real-world data is not limited to scientific papers alone; it extends to car magazines and enthusiasts who seek to understand how EVs perform in everyday life. This collective acknowledgment stems from the understanding that real-world data offers a more accurate representation of EV performance compared to laboratory-based or simulated testing. While obtaining such data may pose challenges, it is considered a cost-effective alternative to relying solely on controlled testing environments, which may not fully capture the nuances of real-world usage.

In conclusion, real-world testing has become a cornerstone of EV research and development, providing invaluable insights into EV performance, validating findings, and enabling meaningful comparisons in practical driving conditions. As researchers and engineers continue to refine testing methodologies, the future of electric vehicles appears promising, with the potential for more efficient, reliable, and field-tested innovations on the horizon.

Mathematical modelling and simulation have become pivotal aspects of the ongoing quest to optimize electric vehicles (EVs). In the dynamic landscape of EV development, researchers are increasingly relying on mathematical tools to unleash the full potential of electric powertrains. This growing trend underscores the essential role of mathematical precision in enhancing the performance of EVs.

A notable facet of this trend is the application of mathematical optimization techniques. Researchers are utilizing methods such as the Nelder-Mead approach and quadratic penalty functions to fine-tune crucial elements of EVs, such as gear ratios and motor curves. These optimization techniques offer a means to navigate the intricate domain of powertrain design with remarkable precision, ultimately leading to improvements in efficiency, range, and overall performance.

Nevertheless, mathematical optimization is only one component of the broader picture. Simulation and modelling have also emerged as indispensable tools, as they are highlighted in various contexts. Researchers are turning to advanced simulation tools like MATLAB/Simulink and electromagnetic finite-element analysis to construct virtual representations of powertrain components. These models serve as dynamic testing grounds for evaluating and validating proposed designs, providing engineers with the capability to predict how different configurations will perform under diverse conditions.

The role of modelling cannot be overstated. It enables researchers to gain profound insights into the behaviour of powertrains, facilitating fine-tuning across all aspects of EV design. By creating virtual replicas of component interactions, engineers can identify bottlenecks, optimize energy flow, minimize losses, and ensure the overall safety and reliability of the system.

As this trend unfolds, it is evident that researchers are actively exploring a plethora of optimization techniques tailored for electric powertrains. The adoption of mathematical optimization methods is indicative of the increasing recognition of the need for precision in powertrain design. This suggests that the future of electric vehicles will likely involve even more advanced optimization algorithms and strategies, pushing the boundaries of achievable powertrain efficiency.

Mathematical modelling and simulation have taken centre stage in the drive to optimize electric vehicles. These tools, combined with mathematical optimization approaches, are revolutionizing the design and performance of electric powertrains.

In the evaluation of electric vehicles field, a notable observation has come to light: researchers and car magazines approach the evaluation of these cutting-edge automobiles from divergent perspectives, driven by their distinct interests and readerships.

One of the fundamental distinctions between these two evaluation methodologies lies in the scope of examination. Scientific research papers, typically authored by experts and academics, delve deep into the intricate details of individual components that constitute an electric vehicle. These papers meticulously dissect everything from the intricacies of batteries to the mechanics of motors, scrutinizing every technological nuance. This exhaustive analysis caters to the specific needs and demands of manufacturers and industry professionals who seek in-depth technical insights. For them, understanding the underlying engineering marvels is essential to advancing EV technology, optimizing performance, and ensuring reliability.

On the flip side, car magazines adopt a more holistic approach when evaluating electric vehicles. Their focus extends beyond the technical minutiae and dives headfirst into the overall driving experience. Magazines prioritize the sensations, comfort, and practicality that come with owning and operating an electric car. This approach reflects the interests of their readership, predominantly comprised of consumers who are considering an EV purchase. For these potential buyers, what truly matters is not just the sum of individual components but the synergy they create when the vehicle is put to the test in real-world conditions.

The contrasting approaches of researchers and car magazines can be attributed to the divergent objectives of these publications. Scientific papers aim to push the boundaries of EV technology, offering invaluable insights to engineers and industry insiders who are constantly striving for innovation and improvement. In contrast, car magazines cater to the broader public, helping consumers make informed decisions by evaluating the practical aspects and overall appeal of electric vehicles.

In essence, the field of electric vehicle evaluation serves a dual purpose. While researchers scrutinize the nuts and bolts of EV technology, magazines provide a bridge between the technical world and the everyday driver. Both perspectives are crucial, as they contribute to the advancement and widespread adoption of electric vehicles, ensuring that they not only perform exceptionally on the inside but also provide an exceptional driving experience for all.

7.2 Outlook

In this outlook section, we'll explore the key factors driving the evolution of electric vehicles (EVs). From machine learning and data preprocessing to real-world testing, mathematical modelling, and evaluation, we'll delve into the pivotal aspects shaping the future of EVs.

The field of reverse engineering of Controller Area Network (CAN) data in electric vehicles has seen remarkable progress, offering insights into vehicle operation and performance. However, several critical challenges persist, necessitating ongoing research and innovation. This outlook explores the key hurdles that researchers and practitioners must address to advance the understanding and utilization of CAN data in electric vehicles.

One of the foremost challenges in the field of reverse engineering CAN data in electric vehicles is achieving seamless hardware compatibility across various vehicle models. Despite technological advancements, ensuring that data interfaces work universally and reliably remains a persistent concern. A standardized approach is required to develop hardware interfaces that can effectively communicate with the diverse CAN systems in different EVs [16]. Solving this challenge is crucial for ensuring the accuracy and reliability of data extraction and analysis in the ever-expanding world of electric mobility.

Machine learning and clustering techniques have shown great promise in reverse engineering CAN data, but they often grapple with the issue of false positives. Detecting and mitigating false positives is a significant challenge that must be addressed to enhance the accuracy of data extraction and analysis in EVs. Researchers must focus on refining algorithms and implementing effective anomaly detection mechanisms to reduce the occurrence of false positives in CAN data interpretation [17]. Overcoming this challenge is essential to prevent erroneous conclusions that could have real-world safety implications.

Another critical aspect of advancing reverse engineering capabilities in electric vehicles is ensuring that the methods developed are applicable to a wide range of car models and diverse driving conditions. Achieving robustness across different scenarios is a priority, as electric vehicle technology continues to evolve. Researchers need to devise methods and tools that can adapt to the ever-expanding variety of EV models and their distinct CAN data formats. This challenge necessitates collaboration between automotive manufacturers, researchers, and regulatory bodies to establish industry standards for data access and analysis [17, 20]. The ability to generalize reverse engineering techniques is key to making EVs safer, more efficient, and easier to maintain.

In the landscape of data preprocessing for electric vehicles, it becomes evident that there is no singular, dominant methodology leading the charge. Instead, this field is characterized by a diverse array of technologies and approaches, all contributing to the ongoing evolution of data processing techniques. In this outlook, we delve into the key challenges and opportunities that lie ahead.

One of the most pressing challenges in the realm of data preprocessing for electric vehicles is the integration of privacy concerns and regulatory compliance. While the inclusion of these considerations is undoubtedly a positive development, it also poses significant challenges. Striking the delicate balance between data security and user control, all while staying in alignment with the ever-evolving regulatory landscape, requires meticulous attention and a commitment to adaptability. As privacy and data protection regulations continue to evolve, researchers and practitioners must continuously assess and update their preprocessing methods to ensure they meet the necessary standards and expectations [21].

As modern electric vehicles produce an ever-increasing volume of data, the optimization of data analysis pipelines for scalability and efficiency is paramount. The sheer magnitude of data generated by these vehicles necessitates innovative solutions to handle it effectively. Researchers are confronted with the challenge of developing systems and methodologies capable of processing, analysing, and extracting valuable insights from this massive influx of data. Scalability and efficiency will be key determinants in harnessing the full potential of the data generated by electric vehicles, ultimately contributing to advancements in vehicle technology and safety [22] and [35].

Achieving generalization in reverse engineering and data analysis methods is another persistent challenge in the field of data preprocessing for electric vehicles. Ensuring that these methods can be applied across a wide range of car models and diverse driving conditions is essential for practical utility. Electric vehicles come in various shapes and sizes, with diverse sensor configurations and operational contexts. Researchers face the formidable task of developing preprocessing techniques that remain robust and reliable in different scenarios. The ability to generalize these methods will not only enhance the versatility of electric vehicle data analysis but also facilitate broader advancements in the electric vehicle industry [17] and [20].

The assessment of electric vehicles (EVs) through on-road test drives is essential, yet it poses considerable challenges due to a multitude of uncontrollable variables. These include unpredictable weather conditions, fluctuating traffic patterns, diverse driver behaviours, and varying road topographies. Such factors can disrupt data collection, rendering it challenging to determine which aspects need adjustments. Additionally, the extended charging times associated with EVs make large-scale testing in real-world conditions time-consuming and often impractical, given the resource demands. This outlook delves into the complexities associated with evaluating EVs in real-world scenarios, emphasizing the hurdles surrounding data acquisition and the monitoring of energy consumption.

The evaluation of EVs during on-road test drives is susceptible to a host of uncontrollable factors, each contributing to data disturbances. These factors, such as the ever-changing climate, traffic dynamics, driver idiosyncrasies, and the diverse nature of road terrains, can make it challenging to discern which data points need adjustment. Furthermore, time becomes a challenge associated with conducting large-scale testing of electric vehicles. While on-road testing remains indispensable for capturing real-world performance, its logistical constraints often pose dilemmas, particularly when dealing with a substantial fleet of electric vehicles.

Gathering precise real-world driving data to evaluate energy consumption in EVs represents a fundamental challenge. To effectively assess an EV's energy efficiency, an extensive array of driving information must be collected onboard. This necessitates the integration of supplementary instruments like CAN bus data loggers, global positioning systems (GPS), data storage systems, or wireless data synchronization systems. The associated costs and intricacies of incorporating these systems into the vehicle can be cost-prohibitive. Moreover, synchronizing charging and driving data to monitor real driving energy consumption on a large scale introduces yet another layer of complexity to the evaluation process. These challenges underscore the urgency of developing innovative methodologies and solutions to streamline data acquisition and analysis within the realm of EV real-world testing.

In summary, while real-world testing is indispensable for comprehending the true capabilities of electric vehicles, it presents formidable challenges. Unpredictable external factors can disrupt data collection, and the intricate process of gathering and analysing real-world driving data introduces logistical and financial impediments. Addressing these issues will be pivotal in devising accurate and efficient strategies for assessing the performance of an ever-expanding fleet of electric vehicles on the road.

The mathematical modelling of electric vehicles (EVs) is a complex and essential field with a myriad of challenges that must be addressed to advance the understanding, optimization, and development of EV technology. In this outlook text, we delve into some of the critical issues faced by researchers and engineers in this domain.

One of the primary technical challenges in mathematical modelling of electric vehicles is the inherent complexity of the task. As we endeavour to create accurate representations of EVs, we must account for numerous intricate components and subsystems. Integrating propulsion systems, battery dynamics, vehicle aerodynamics, and driver behaviour into a comprehensive model result in a highly intricate mathematical framework. These models often demand significant computational resources, pushing the boundaries of available hardware capabilities. Additionally, the dynamic nature of EVs, influenced by variables such as weather conditions, road surfaces, and driving patterns, compounds the challenge. Striking the right balance between capturing sufficient detail for accuracy and maintaining computational feasibility remains a technical hurdle.

Model validation is a technical concern that lies at the heart of mathematical modelling for electric vehicles. This scarcity of real-world data for EVs complicates efforts to comprehensively verify model accuracy. Moreover, conducting exhaustive testing of EVs under diverse conditions is both resource-intensive and time-consuming. Therefore, ensuring that mathematical models align with empirical observations becomes a critical technical requirement. Bridging the divide between theoretical predictions and real-world outcomes is not just a matter of scientific rigor but also a prerequisite for practical utility. Consequently, addressing the challenges of model validation is essential for the successful application of mathematical models in the realm of electric vehicles.

In summary, the mathematical modelling of electric vehicles is a demanding undertaking that requires addressing inherent complexities and uncertainties. Researchers employ advanced probabilistic methods, model simplification techniques, and rigorous validation procedures to navigate these challenges. By continually refining their approaches and incorporating real-world data, mathematical modelling contributes significantly to the advancement of EV technology and plays a pivotal role in realizing the potential of sustainable and electrified transportation.

In the dynamic landscape of electric vehicles (EVs), researchers and car magazines serve as vital sources of information, each offering unique perspectives and insights. However, these two entities often diverge in their approach to evaluating EVs, creating a contrast in how consumers receive information. This outlook will delve into the key differences between researchers and magazines when assessing electric cars, shedding light on integration of technical and user experience data, communication challenges, concerns related to bias and objectivity, and the ongoing struggle to standardize evaluation metrics.

One noticeable difference between researchers and magazines in the evaluation of electric cars is the integration of technical insights and user experience evaluations. In the future, there could be a promising trend towards merging these two perspectives. Researchers predominantly focus on the technical aspects, offering in-depth analysis of EV technologies, battery performance, and efficiency metrics. In contrast, magazines place a greater emphasis on user experiences, including factors like driving comfort, infotainment systems, and overall satisfaction. Combining these two sets of data could yield a more holistic understanding of electric vehicles, empowering consumers to make well-informed decisions that consider both the technology under the hood and the day-to-day user experience.

Another challenge in the realm of EV evaluation lies in bridging the communication gap between researchers and magazines. Researchers often publish their findings in highly technical research papers, which can be inaccessible or challenging for the average consumer to decipher. On the other hand, car magazines aim to cater to a wider audience and may oversimplify or misrepresent technical details, potentially leading to misinformation. Effective communication is vital to ensure that accurate and understandable information reaches consumers, enabling them to grasp the intricacies of EV technology while also appreciating the practical aspects of owning and driving an electric car.

Both researchers and car magazines are susceptible to accusations of bias in their evaluations of electric cars. Researchers may face scrutiny for appearing to favour certain manufacturers or technologies, potentially impacting the credibility of their findings. Similarly, car magazines may be criticized for potential biases stemming from advertising revenue or commercial interests, potentially influencing their editorial decisions. Maintaining objectivity is paramount for both parties, as it ensures that consumers receive unbiased and trustworthy information, enabling them to make impartial decisions about electric vehicles.

Establishing standardized evaluation metrics for electric cars is yet another challenge faced by researchers and car magazines alike. Different stakeholders may have varying criteria for success, making it difficult to arrive at universally accepted standards for assessing EV performance, safety, and sustainability. This ongoing struggle highlights the need for collaboration and consensus among researchers, manufacturers, magazines, and other stakeholders to develop a set of comprehensive and reliable metrics that can guide consumers in their EV purchasing decisions.

In conclusion, the evaluation of electric cars by researchers and car magazines serves as a critical source of information for consumers. While each entity brings its unique perspective and expertise to the table, there are notable differences in their approach. The integration of technical and user experience data, addressing communication challenges, maintaining objectivity, and standardizing evaluation metrics are all key areas where researchers and magazines can work together to provide consumers with a more comprehensive and reliable understanding of electric vehicles.

8 List of figures

9 List of tables

10 Literature

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