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SURVEY

Evolving Electric Mobility Energy Efficiency: In-Depth Analysis of Integrated Electronic Control Unit Development in Electric Vehicles

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ABSTRACT The integrated Electronic Control Unit (ECU) plays a pivotal role in optimizing energy efficiency within electric vehicles (EVs) by coordinating various subsystems, including the Vehicle Control Unit (VCU), Electrical Power Steering (EPS), Electronic Stability Control (ESC), and Body Control Unit (BCU). Our comprehensive review deeply explores the various aspects of integrated ECUs and their sub-disciplines, emphasizing development approaches and algorithms specifically designed for mobility energy efficiency. The study shows the effect of various control units on energy efficiency by carefully examining case studies and real-world applications. Employing a critical assessment, the paper examines the advantages and disadvantages of various control systems utilized in electric vehicles (EVs), providing insight into their effectiveness in various situations. The presented study is typically related to the relationship between ECUs and their sub-branches through an integrated approach. By comparing current control approaches, the study offers a deep knowledge of the role of these units in improving vehicle performance, stability, and overall control. Furthermore, we evaluate the strengths and limitations of integrated ECU algorithms in the context of EV control by comparing them in a fair amount of detail. We identify important research gaps by integrating knowledge of multiple control areas in EV. The research effort will give researchers a path forward and make it possible to pinpoint the prospective dimensions that need further exploration in advancing the area of integrated ECUs in EVs.

INDEX TERMS Electronic control unit, vehicle control unit, electrical power steering, electronic stability control, body control unit.

I. INTRODUCTION

In recent years, the global automotive industry has witnessed a significant shift towards electric vehicles (EVs) as a promising solution to mitigate environmental challenges associated with traditional internal combustion engine (ICE) vehicles [1], [2]. The need to reduce greenhouse gas emissions and tackle climate change has propelled governments, organizations, and individuals to embrace cleaner and more sustainable transportation options. The transition to electric vehicles offers a clear pathway to achieve these environmental goals, primarily focusing on reducing carbon dioxide (CO2) emissions, air pollutants, and dependence on fossil fuels [3].

Fig. 1 shows the graph obtained using the data sourced from the International Energy Agency's Global EV Data Explorer [4], which provides comprehensive information on EV charging points, EV stock, EV sales, and other data

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of different countries. For our analysis, we use stock and sales data for battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) worldwide. In addition, it presents the EV (BEV, PHEV) stocks and sales worldwide from 2020 in projections to 2030. We indicate the years 2020–2030 on the x-axis to provide the pattern of EV sales and stocks chronologically. The sales data for BEVs and PHEVs are displayed on the left y-axis, highlighting the rising demand for electric cars worldwide. The stocks of BEVs and PHEVs, representing the total number of these cars in the market, are on the right y-axis. The graph shows that with the sales of 2 million BEVs and 970,000 PHEVs, the EV market started slowly in 2020. Sales of BEVs and PHEVs saw notable increases by 2022, hitting 7.3 million and 2.9 million units, respectively. While PHEV stocks steadily increased to 7.9 million units, BEV stocks reached 18 million. 2025 is predicted to be a significant turning point, with BEV sales rising to 16 million units and exceeding PHEV sales of 4.5 million units. In conclusion, the graph illustrates a steady growth in EV adoption over the five years, with sales increasing substantially yearly. The noteworthy finding is the increase in BEV sales, which is more than PHEV sales. The graph shows a sharp increase in BEV sales between 2025 and 2030, pointing to a clear shift towards BEVs worldwide.

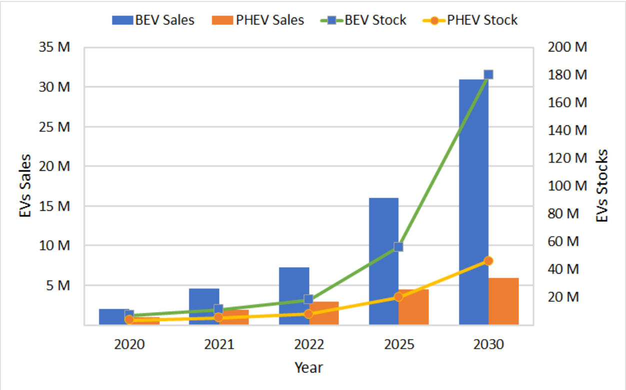

FIGURE 1. Overview of the EV statistics.

The continuous advancements in electric vehicle technology have further bolstered the case for their widespread adoption and continued development. In [5], authors examined how the market for EVs is changing, focusing on technology developments and how they contribute to the goal of a carbon-neutral society. With ongoing research and development efforts, innovative solutions have emerged in areas such as battery technology [6], charging infrastructure [7], and control units, driving significant improvements in EV performance, range, and overall user experience. In [6], the authors explored the most recent advances in battery technology developments for EVs, including a thorough summary of the latest battery charging and switching vehicles. In [7], Acharige et al. provide insights into the changing environment of EV charging systems by considering dedicated converter topologies, control techniques, and standard compliance to improve charging efficiency and grid support. Future trends indicate integrating advanced control units in electric vehicles, enabling enhanced Vehicle-to-Grid (V2G) capabilities, intelligent energy management systems, and seamless connectivity with smart grids [8]. These developments aim to optimize energy consumption [9], minimize charging times [10], and maximize the utilization of renewable energy sources, thereby strengthening the environmental benefits of electric vehicles [11].

Electric vehicles (EVs) have witnessed significant advancements in control technologies, contributing to improved performance, efficiency, and overall driving experience. Modern EVs incorporate various control technologies to manage multiple aspects of their operation [12]. These include powertrain control systems, energy management systems, regenerative braking control, and vehicle stability control. Powertrain control systems optimize the coordination between the electric motor, battery, and other components to deliver efficient and responsive power delivery [13]. Energy management systems monitor and control the energy flow within the vehicle, ensuring optimal utilization of the battery's capacity [14]. Regenerative braking control technologies capture kinetic energy during braking, converting it into electrical energy for recharging the battery [15]. Vehicle stability control systems utilize sensors and actuators to enhance safety and stability during acceleration, deceleration, and cornering [16].

Much research on EV powertrain control systems has been done recently in the literature. The authors of [13] provide a novel method for hybrid Deep Reinforcement Learning (DRL) strategy-based powertrain control optimization in Hybrid Electric Vehicles (HEVs). Using preexisting vehicle data, the authors pre-train offline neural networks (NNs) combined with an online DRL method. This combination method effectively achieves optimal power source management for HEVs while speeding up the learning process and improving fuel efficiency in simulated instances. In [14], authors addressed energy management systems in EVs. They carried out an extensive investigation that centered on the creation of an Energy Management System (EMS) for a plug-in hybrid electric vehicle (HEV) through the use of deep learning techniques, particularly Recurrent Neural Networks (RNNs). Based on Real Driving Emissions (RDE) compliant vehicle missions, the AI models were trained offline to decrease carbon dioxide emissions. The integration of regenerative braking control technology has also gained attention in recent research. With an emphasis on energy savings and increased driving distance, [15] investigated the regenerative braking control approach for EVs with four in-wheel motors. The approach involves splitting the braking force between the hydraulic and motor braking systems and between the front and back axles. The efficacy of the suggested fuzzy control-based method, which uses a Mamdani fuzzy controller, is confirmed by simulation, indicating that it can improve regenerative braking efficiency for EVs. Within vehicle stability control systems, the study of [16] is noteworthy. Their study concentrated on the advantages of using axle electric motors for vehicle stability control in hybrid electric vehicles (HEVs). It presents a combined electrohydraulic braking and axle motor torque control technique for differential braking and driving stability management. The devised technique is compared with current vehicle stability control systems using real-time simulations of intense steering maneuvers, assessing energy consumption, performance, and stability characteristics for hybrid electric sport utility vehicles. Our review study analyzes these different control technologies in a unified form under different control units in EVs to evaluate their capabilities, benefits, and challenges, advancing EV performance, efficiency, and sustainability while ensuring optimal energy management and vehicle control.

The significant contributions of our research study are listed below:

- The study provides a detailed review of different development strategies and control algorithms that can be adapted to efficiently control different EV control units.
- The study highlights the configuration and sensors utilized in each control unit of EVs.
- Moreover, the comparison of different control algorithms adopted to control EVs for mobility energy efficiency is presented.
- Finally, the current research challenges are highlighted to pave the way for future research directions.

The proposed study is organized as shown in Fig. 2. After the introduction section, development strategies and algorithms of integrated ECU for mobility energy efficiency are presented in section II followed by the development strategies and algorithms of VCU, EPS, ESC, and BCU in the next sections III, IV, V, and VI. The comparison of integrated ECU algorithms for mobility energy efficiency is summarized in section VII. Section VIII highlights the shortcomings of available solutions and future directions. Finally, the conclusion is presented in section IX.

A. THE RESEARCH METHODOLOGY FOR ECU

This section highlights a comprehensive overview of the detailed methodology followed for the research. Electronic Control Unit (ECU) and its various types are chosen as research methods for determining electric vehicle control strategies.

B. PLANNING THE REVIEW

Review planning involves key components such as formulating research questions, identifying relevant data sources, and creating search strings.

C. RESEARCH QUESTIONS

The research questions addressed in this review are:

RQ1: What are the different types of electronic control units used in electric vehicles?

RQ2: What are the emerging control techniques in electronic control units for electric vehicles?

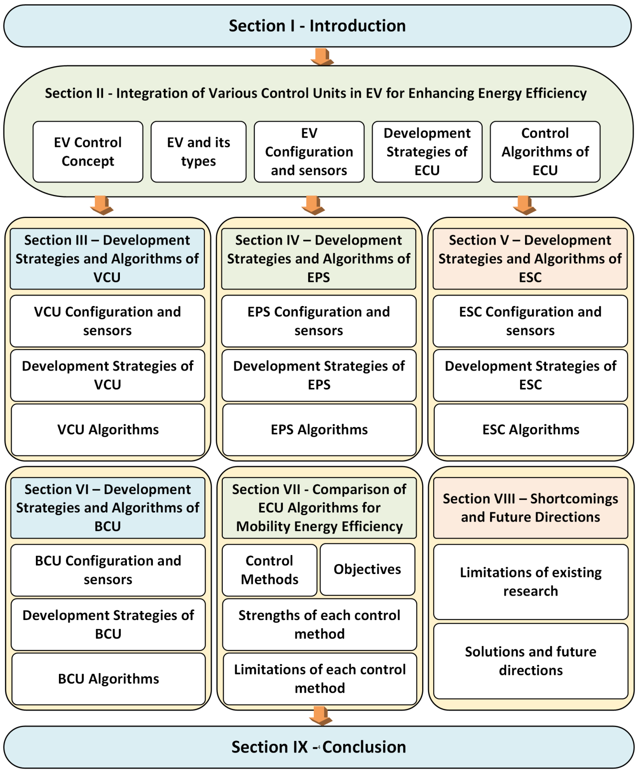

FIGURE 2. Detailed flow of the proposed research study.

D. DATA SOURCES FOR LITERATURE STUDY

An iterative technique was utilized to comprehensively explore various scientific databases and digital libraries. The selection of these libraries was based on current research trends. Data sources included are:

- Google Scholar
- Science Direct
- Wiley Online Library
- IEEE Xplore Library

E. SEARCH STRINGS

In this research study, we derived keywords from the existing literature that aligned with our research questions to construct the search strings. Boolean operators "OR" and "AND" combine these keywords effectively. The search strings used to explore online databases were as follows: ("Control Technology" OR "Control Method") AND ("Electronic Control Unit" OR "Vehicle Control Unit" OR "Electrical Power Steering" OR "Body Control Unit") AND ("Electric Vehicles" OR "Hybrid Electric Vehicles" OR "Autonomous Vehicle") AND ("Energy Management" OR "Energy Efficiency").

II. INTEGRATION OF VARIOUS CONTROL UNITS IN EV FOR ENHANCING ENERGY EFFICIENCY

As Electric Vehicles (EVs) continue to gain popularity, the automotive industry is constantly evolving to meet the demands of this emerging market. One crucial aspect of EV development is integrating various control units to ensure the efficient and coordinated functioning of different vehicle systems. In this context, the concept of an integrated Electronic Control Unit (ECU) has emerged as a significant advancement in EV technology. An integrated ECU combines multiple control units into one unit, streamlining communication and enhancing overall vehicle performance [17].

The integrated ECU in an electric vehicle typically incorporates four main control units: Vehicle Control Unit (VCU), Electric Power Steering (EPS), Electronic Stability Control (ESC), and Body Control Unit (BCU). All these control units are crucial in ensuring the safety, efficiency, and smooth operation of EVs [18].

Furthermore, the VCU acts as the central brain of the integrated ECU system, managing and coordinating various subsystems and components of the electric vehicle. It controls the powertrain, battery management system, and other auxiliary systems. The VCU receives data from multiple sensors and makes real-time decisions to optimize the vehicle's performance, including torque distribution, regenerative braking, and energy management [19].

The EPS control unit gives the driver precise and effortless control over the vehicle's steering. It uses sensors to measure driver input and vehicle parameters, allowing the EPS system to adjust the steering assistance accordingly. Integrating the EPS control unit into the ECU allows the EV steering response to coordinate seamlessly with other control functions, enhancing overall vehicle stability and safety [20].

Similarly, the ESC control unit is designed to ensure vehicle stability and prevent loss of control in critical situations. It monitors various parameters, including steering angle, wheel speed, and yaw rate. By applying individual wheel braking and adjusting power distribution, the ESC control unit can selectively intervene to correct understeer or oversteer conditions. Integrating the ESC control unit with the integrated ECU allows faster and more precise response times, enhancing vehicle safety during cornering and emergency maneuvers [21].

Furthermore, the BCU controls various electrical and electronic systems within the vehicle's body, including lighting, climate control, door locks, windows, and other comfort and convenience features. Integrating the Body Control Unit into the integrated ECU allows the coordination and management of these body-related functions to be streamlined, enhancing overall vehicle functionality and user experience [22].

Moreover, Fig. 3 shows the layout of ECU in EV. The front axle is driven by a permanent magnet synchronous motor connected to a transmission. The motor is regulated by a Motor Control Unit (MCU) supervised by VCU. The Battery Management System (BMS) controls the battery pack, supplying energy to move the vehicle and storing recovered electric energy. Each wheel has a disc brake, monitored by the Electronic Stability Control (ESC) system. Electric Power Steering (EPS) assists in controlling the vehicle's steering, reducing energy consumption, and ensuring stability. Additionally, BCU manages various electronic systems in the vehicle, including exterior and interior lighting and windshield wipers. The ECUs coordinate the control of all these components by communicating and exchanging their requests. [23].

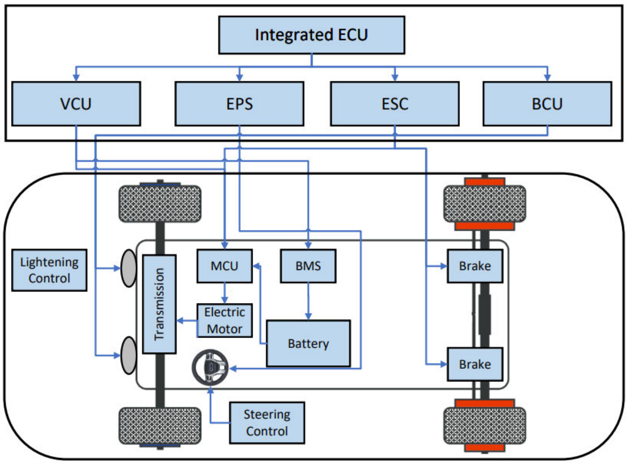

FIGURE 3. Layout of integrated ECU control in EV.

A. ELECTRIC VEHICLE CONTROL CONCEPT

Electric vehicle control plays an important part in EVs' efficient operation and optimization. As the world shifts towards sustainable transportation, developing advanced control systems for EVs becomes increasingly important. These control systems are responsible for managing and coordinating different units of EV, such as the powertrain, energy storage system, and auxiliary systems. By intelligently controlling these components by introducing integrated ECU control, EVs can achieve optimal performance, maximize energy efficiency, and enhance the overall driving experience [24].

Effective control of electric vehicles offers several significant advantages [25]. Firstly, it optimizes power distribution and utilization within the vehicle, improving energy efficiency. By effectively regulating the power transfer to the motor using the battery, control systems can optimize energy usage, minimize losses, and extend the vehicle's driving range [26]. Moreover, efficient control of EVs helps achieve better overall performance, including acceleration, braking, and handling. Moreover, ensuring effective control of EVs is critical for upholding vehicle safety. Control systems are responsible for monitoring and protecting the battery pack, ensuring proper charging and discharging behavior, and preventing hazardous conditions, such as overcharging or overheating [27]. Additionally, control algorithms play a crucial role in integrating various safety features, such as regenerative braking and stability control systems, in enhancing the overall safety of the EV [28].

To enable effective control of electric vehicles, certain requirements must be fulfilled. These include precise sensing and measurement systems to provide accurate data on vehicle parameters like speed, position, battery state of charge, and temperature [29]. Additionally, sophisticated control algorithms are needed to process this data and make real-time decisions regarding power distribution, torque control, energy management, and vehicle dynamics. These algorithms should be capable of adapting to changing driving conditions, optimizing power flow, and ensuring the seamless integration of different vehicle subsystems [30]. Moreover, electric vehicle control requires a reliable and robust communication network to facilitate the exchange of information between various components, such as the battery management system, motor controller, and vehicle control unit. This network enables coordinated control actions and ensures the proper functioning of the entire EV system [31].

B. ELECTRIC VEHICLE AND ITS TYPES

Much research is going on on electric vehicles, which promise future solutions to environmental issues. The goals of these research studies are the focus of many electric vehicle configurations and their control. Battery Electric Vehicles (BEVs) run entirely on electricity and are powered by rechargeable batteries. Hybrid Electric Vehicles (HEVs) combine an internal combustion engine with an electric motor and a battery; Plug-in Hybrid Electric Vehicles (PHEVs) have both an internal combustion engine and a rechargeable battery, and Fuel Cell Electric Vehicles (FCEVs) use a fuel cell to generate electricity on board by combining hydrogen gas from a tank with oxygen from the air are examples of EVs [23]. BEVs often face challenges primarily related to their batteries, making them more suitable for smaller electric vehicles with short distances and lower speeds in local transportation. These vehicles require smaller battery capacities. While cost remains a significant concern, HEVs can meet consumer demands and offer additional benefits. FCEVs have the potential to become popular vehicles in the future. However, the technology is in its early stages, with price and fueling infrastructure being the main areas of concern [24]. The user's daily commute, availability of charging infrastructure, financial restraints, and environmental concerns are some variables that influence the choice of EV. While some consumers choose PHEVs because of their flexibility and extended driving range, others may emphasize lowering the environmental impact and go for BEVs [8]. The EV types and their characteristics, along with issues in each type and the example models, are explained in Table 1.

C. EV CONFIGURATION AND SENSORS

Sensors play a vital role in electric vehicles (EVs) by providing crucial information to control units, enabling precise monitoring and control of various subsystems [39]. These sensors serve as the sensory organs of the EV, capturing real-time data on key parameters such as speed, position, temperature, battery state of charge, and environmental conditions. This information allows the control units to make informed decisions and implement effective control strategies, enhancing electric vehicles' performance, efficiency, and fault detection for vehicle safety [40].

The EV system can be categorized into three primary blocks, shown in Fig. 4. To perceive the surrounding environment, the EV is equipped with various sensors, which are hardware devices responsible for collecting data. The gathered sensor data is then processed in the optimal control block, where different components work together to extract meaningful information from the sensor inputs. The optimal control block utilizes optimal control algorithms to generate controlled commands for actuators. To ensure the following path, the control module sends control commands to the vehicle, thereby overseeing its movement and trajectory [41].

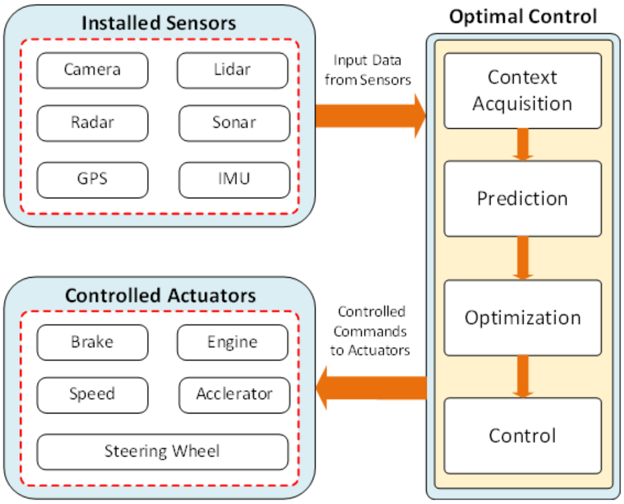

FIGURE 4. Block diagram of EV system based on installed sensing and actuating devices.

D. DEVELOPMENT STRATEGIES OF INTEGRATED ECU FOR MOBILITY ENERGY EFFICIENCY

The development strategy for integrated ECU in an electric vehicle involves ensuring the system is reliable, efficient, and safe. To achieve these goals, the ECU must be designed to operate in various conditions and environments, including extreme temperatures, high humidity, and high vibrations. The ECU must also be designed to handle large amounts of data quickly and efficiently while maintaining low power consumption. Additionally, the ECU must be designed with safety in mind since it controls critical systems in the vehicle. This involves implementing fail-safe mechanisms, such as redundant sensors and controllers, to ensure that the vehicle can operate safely in case of a failure inside the system. Overall, the design of an ECU for an electric vehicle requires a balance of performance, efficiency, and safety [42].

Fig. 5 shows the main development strategies of integrated ECU to improve mobility energy efficiency.

Development strategies for integrated ECU include predictive analytics, optimal operation based on machine learning, thermal management, power electronics, and energy recuperation. Predictive analytics can be used to analyze data

TABLE 1. Critical analysis of the characteristics of EV types.

Ref.	Electric Vehicle Type	Advantages	Disadvantages	Example Models
[24], [32]	Battery Electric Vehicle (BEV)	• No tailpipe emissions • Lower operating costs • Simple drivetrain with fewer moving parts	• Limited driving range per charge • Long charging time • Insufficient charging infrastructure • High initial cost of batteries	Tesla Model S, Nissan Leaf, Chevrolet Bolt
[24], [33], [34]	Hybrid Electric Vehicle (HEV)	• Improved fuel efficiency • Regenerative braking reduces energy wastage • No need for external charging	• Complex powertrain systems • Battery degradation over time • Reliance on fossil fuels for the internal combustion engine	Toyota Prius, Honda Accord Hybrid, Ford Fusion Hybrid
[35], [36]	Plug-in Hybrid Electric Vehicle (PHEV)	• All-electric driving range for short trips • Flexibility for longer trips with the internal combustion engine • Regenerative braking and reduced emissions	• Additional weight and complexity from larger batteries • Charging infrastructure availability • Balancing power demands between electric and internal combustion engines	Chevrolet Volt, Mitsubishi Outlander PHEV, BMW i3 REx
[24], [37], [38]	Fuel Cell Electric Vehicle (FCEV)	• Longer driving range compared to BEVs • Fast refueling time • Zero tailpipe emissions	• Limited hydrogen fueling infrastructure • High cost and limited availability of fuel cell technology • Hydrogen production and storage challenges	Toyota Mirai, Hyundai Nexo, Honda Clarity Fuel Cell

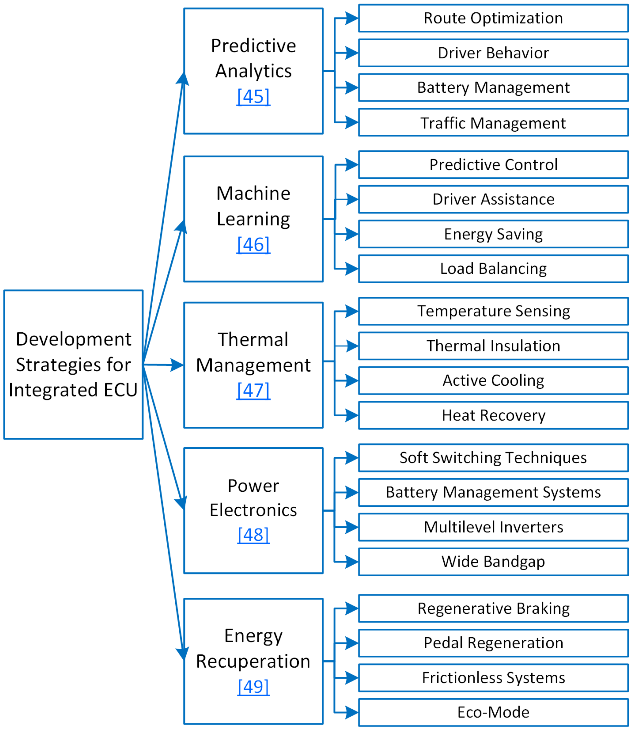

FIGURE 5. Taxonomy of the development strategies for integrated ECU.

from sensors and other sources to help optimize the operation of the ECU and the electric vehicle. Predictive analytics can anticipate driving behavior [43], road conditions for route optimization [44], and other factors that can affect energy consumption and adjust power distribution and battery management accordingly. Machine Learning (ML) algorithms can be used to optimize the operation of the ECU and the electric vehicle. ML can identify patterns in driving behavior and road conditions and adjust the power distribution and battery management accordingly. This can help to improve energy efficiency and reduce carbon emissions [45]. Efficient thermal management of the ECU can help to reduce power consumption and improve energy efficiency. This can be achieved using advanced cooling systems and heat-dissipation materials [46]. Advanced power electronics, such as wide-bandgap semiconductors, can improve the efficiency of the ECU and the electric vehicle. Wide-bandgap semiconductors have lower resistance and switching losses, which results in less heat generation and higher efficiency [47]. Energy Recuperation involves using energy recuperation systems, such as regenerative braking, which can help capture the energy that would otherwise be lost during braking and recharge the battery. This can improve energy efficiency and reduce the need for external charging [48].

Table 2 shows current developments in the field of EV technology, with an emphasis on development techniques for integrated ECU. The table highlights several noteworthy research papers demonstrating innovative methods to improve EV performance, energy efficiency, and sustainability. The most common development strategies include machine learning algorithms to analyze data from the ECU and predict driving behavior. This information can then be used to optimize the performance of the EV and improve energy efficiency [49]. Integrating real-world data combines data from the ECU with real-world data, such as driving conditions and weather information, to develop more accurate and robust control models [50]. Advanced electronics technologies, such as field-programmable gate arrays (FPGAs), are used to develop more efficient and powerful ECUs [51].

Table 2 offers a comprehensive overview of the latest research on development strategies of Integrated ECU in EVs. Bangroo et al.'s approach [52] utilizing AI-based predictive analytics stands out for its potential to enhance decision-making, energy efficiency, and cybersecurity in electric/hybrid vehicles. However, using large datasets raises concerns about data privacy that need to be addressed for practical implementation. Canal et al.'s study (Ref. [53]) integrating real ECU data with machine learning algorithms demonstrates impressive accuracy in identifying driving patterns, emphasizing the real-world applicability of their methodology. Nevertheless, concerns about overfitting and the need for robust regularization techniques are vital aspects to consider in further applications. Broatch et al.'s research (Ref. [54]) on integrated thermal management systems stands out for its incorporation of extensive real-world data, enhancing the accuracy of simulation results. However, expanding the scope to other vehicle platforms like plug-in hybrids and fully electric cars could offer more comprehensive insights. Gong et al.'s emphasis (Ref. [55]) on modern power electronics technologies in EV powertrains paves the way for future innovations. Yet, the lack of quantitative analysis regarding energy efficiency remains a notable limitation. Chengqun et al.'s innovative regenerative braking system ([56]) stands out for its efficient energy recovery, especially for aggressive driving styles, but could benefit from adaptability enhancements considering diverse factors affecting regenerative braking efficiency.

Each development strategy has advantages and disadvantages, as mentioned in Table 2. For example, AI-based predictive analytics can effectively improve energy efficiency, but it requires large amounts of data and can be complex to implement [52]. Integration of real-world data can improve the accuracy of control models, but it can be challenging to collect and process large amounts of real-world data [57]. Advanced electronics technology can lead to more efficient and powerful ECUs, but it can be expensive to develop and implement [51]. Integrated ECUs can potentially improve EVs' performance, efficiency, and safety. Still, they are facing a few challenges mentioned in this section, which can be addressed for future research to improve EV energy efficiency.

E. CONTROL ALGORITHMS OF INTEGRATED ECU FOR MOBILITY ENERGY EFFICIENCY

In an EV, the integrated ECU refers to the central electronic control unit responsible for managing and coordinating various electrical systems and components within the vehicle. It serves as the "brain" of the EV, overseeing the operation of critical functions and ensuring their proper integration. An ECU is an embedded system in EVs that controls one or multiple systems or subsystems within a vehicle. In modern vehicles, numerous ECUs are utilized, including but not limited to the powertrain control unit (PCU), transmission control unit (TCU), engine control unit (ECU), brake control module (BCM), suspension control unit (SCU), and body control unit (BCU). [58].

Furthermore, Fig. 6 shows the sub-division of ECU, which is required to be controlled in EV for energy management.

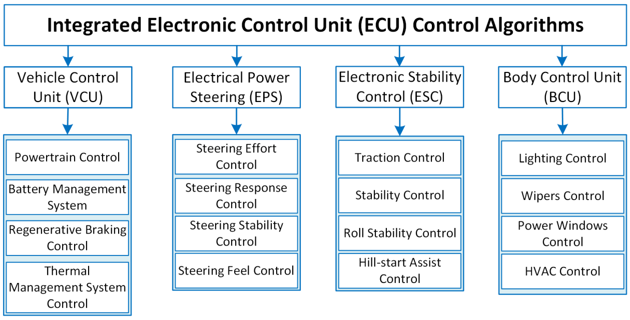

FIGURE 6. Taxonomy of the control algorithms of integrated ECU.

III. DEVELOPMENT STRATEGIES AND ALGORITHMS OF VCU FOR MOBILITY ENERGY EFFICIENCY

A. VCU CONFIGURATION AND SENSORS

In an autonomous vehicle, the VCU has a critical role in controlling various aspects of the vehicle's operation. To achieve this, the VCU relies on a range of sensors, enabling it to make informed decisions and optimize the vehicle's performance. Several key sensor types used in the VCU of autonomous vehicles include powertrain control sensors, battery management system sensors, regenerative braking control sensors, and thermal management system sensors [59], as shown in Fig. 7.

Powertrain control sensors, such as the throttle position sensor, measure the position of the accelerator pedal and provide input to the VCU regarding the desired power output from the electric motor. These sensors allow the VCU to regulate the powertrain system and optimize its efficiency and performance [60].

Furthermore, Battery management system sensors are crucial for monitoring the battery pack's state. They provide data on parameters like the State of Health (SoH), temperature, and State of Charge (SoC). By analyzing this data, the VCU can ensure optimal battery performance, manage energy consumption, and protect the battery from overcharging or overheating [61].

In addition, Regenerative braking control sensors, including wheel speed sensors and brake pressure sensors, enable the VCU to engage regenerative braking, which converts the kinetic energy into electrical energy for energy storage in the battery. These sensors provide critical input for

TABLE 2. Latest research on development strategies of integrated ECU in EV.

Ref.	Development Strategy	Description	Merits	Demerits
[52]	AI-based predictive analytic approach	Use of AI technology to enhance decision-making and energy efficiency in integrated control of electric/hybrid vehicles while also addressing cybersecurity vulnerabilities	**Sustainability:** Encourages the usage of electric/hybrid vehicles to mitigate climate change and promotes sustainable transportation **Efficiency:** AI-based predictive analysis can improve the energy efficiency, emissions reduction, and general sustainability of electric/hybrid vehicles **Security:** Use of AI technology to address cybersecurity flaws in electric/hybrid vehicles	**Data Privacy:** Large data sets frequently used in predictive analytics must be protective to mitigate privacy issues and legal consequences.
[53]	Machine Learning Algorithms: K-Means, Logistic Regression, XG-Boost	Combined real data from the ECU of an EV with machine learning algorithms to assess driving patterns, enhance safety, and save fuel consumption.	**Efficiency Improvement:** Attaining 100% accuracy, precision, and recall over several algorithms indicates the resilience and efficacy of the suggested methodology in precisely identifying driving behavior. **Real-World Applicability:** By utilizing actual data from a test car, the results are more applicable to real-world driving situations and are, therefore, more useful and relevant.	**Over-fitting Risk:** Over-fitting prevention strategies may be the problem while implementing such ML techniques. Inadequate regularization techniques might cause machine learning models to learn the training data by heart rather than the underlying patterns, resulting in poor generalization on unobserved data.
[54]	Integrated thermal management system	In-depth experimental measurements are carried out to investigate the integration of thermal flows. Two heat management systems were tested at different temperatures and real driving emission cycles.	**Integration of Real-World Data:** To ensure accurate model development and validation, the study incorporates a large amount of experimental data from an Internal Combustion Engine (ICE). Incorporating real-world data improves the simulation results' accuracy and dependability. **Novel Co-Simulation Technique:** Using Functional Mock-up Interface (FMI), the research presents an innovative approach to co-simulation that integrates high-fidelity ICE, thermohydraulic, and battery models.	**Limited Relevance Scope:** Subsequent investigations may examine the customization of integrated thermal management systems for other platforms, such as plug-in hybrids and completely electric cars, to promote more extensive progress in thermal management techniques.
[55]	Advanced Power Electronics Technology	Analysis of Controller Hardware-in-the-Loop (CHIL) simulations in EV powertrains with a focus on power electronics technologies	**Emphasis on modern Technology:** To ensure simulation accuracy, emphasis was placed on modern power electronics technologies, such as field-programmable gate arrays (FPGAs). **Prospects for the Future:** EV powertrain control innovation is being encouraged by presenting future directions, including model refinement and integration with Digital Twin configurations.	**Energy Efficiency Evaluation:** This study does not analyze The use of modern power electronics devices in electric vehicle powertrains to boost energy efficiency.
[56]	Regenerative braking-based energy recovery management control strategy	An innovative EV regenerative braking system maximizes energy recovery by utilizing a driver model to predict driving behavior.	**Efficient Energy Optimization:** Improved energy recovery efficiency, especially for aggressive drivers using advanced IDP (Iterative dynamic programming)-BLSTM (Bidirectional Long Short Term Memory) control approach	**Limited Adaptability to Diverse Factors:** Various factors (battery state, temperature, and brake system health) that affect the efficiency of the regenerative braking system can also be included

the VCU to adjust the regenerative braking force and optimize energy recovery. Thermal management system sensors monitor the temperature of various components in the vehicle, such as the battery pack, motor, and power electronics. These sensors provide feedback to the VCU, enabling it to implement appropriate thermal management strategies, including cooling or heating, to maintain optimal operating temperatures and prevent overheating [62]. All these sensors are controlled by the VCU and coordinated by the Electronic Control Unit (ECU), which serves as the central control hub. The ECU processes data from these sensors and inputs from other subsystems to make decisions and send control commands to various vehicle components.

B. DEVELOPMENT STRATEGIES OF VCU FOR MOBILITY ENERGY EFFICIENCY

The development strategies of VCU focus on improving the vehicle's performance while reducing energy consumption. This is achieved through advanced strategies that optimize the vehicle's systems operation. For example, the VCU can be designed to optimize the regenerative braking system to recover energy during braking [63].

Development Strategies for VCU to improve mobility energy efficiency are illustrated in Fig. 8. Integrating advanced sensors is crucial to enhance the capabilities of the VCU. These sensors include position, wheel speed, accelerometer, gyroscopes, and other environmental and vehicle condition sensors. The VCU relies on accurate

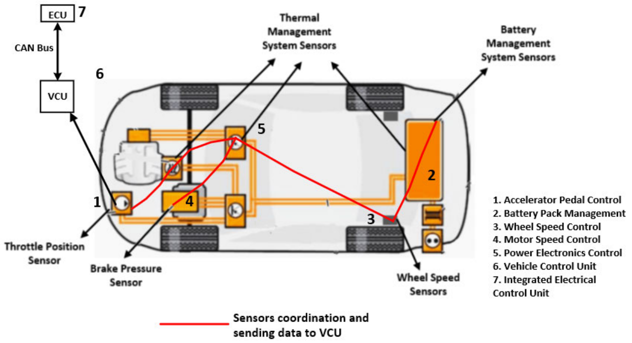

FIGURE 7. Sensors for vehicle control unit.

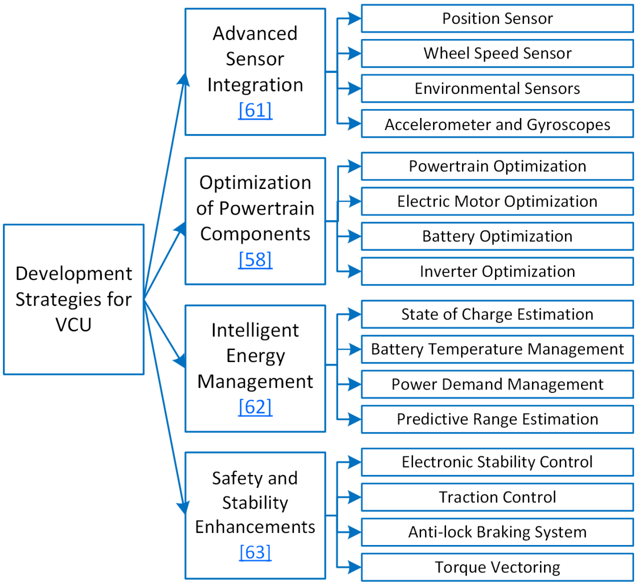

FIGURE 8. Taxonomy of the development strategies for VCU.

and real-time data from these sensors to make informed decisions regarding powertrain control, energy management, and vehicle stability [64]. Efficient powertrain control is also required to maximize the performance and range of EVs. The VCU should optimize powertrain components such as the electric motor, battery, inverter, and transmission. Development strategies involve fine-tuning control algorithms to manage torque distribution, regenerative braking, energy recuperation, and thermal management. This ensures smooth power delivery, improved energy efficiency, and optimal utilization of the electric powertrain system [65]. Effective energy management is critical for electric vehicles. The VCU should incorporate intelligent algorithms that monitor the state of charge, battery temperature, and power demand. By dynamically adjusting power distribution, the VCU can optimize energy usage and balance the power demands of various vehicle systems.

Additionally, the VCU can facilitate features like predictive range estimation, route planning, and energy-saving modes to increase the overall efficiency of EVs [66]. The VCU contributes to ensuring the safety and stability of EVs. Development strategies involve integrating advanced stability control systems, like Electronic Stability Control (ESC), traction control, anti-lock braking systems (ABS), and torque vectoring. The VCU should employ sophisticated control algorithms that continuously monitor vehicle dynamics and make necessary adjustments to prevent loss of control, improve stability, and enhance overall driving safety [67].

Table 3 thoroughly reviews current research on VCU's development strategies in EVs. These strategies include many innovative techniques and deal with multiple aspects of VCU development. An EV transportation system that uses supervised machine learning technologies to improve incentive mechanisms for the betterment of security is presented in the research by [68]. However, there is room for future development in fine-tuning the system for better response time and overall performance. A two-step technique for accurate EV powertrain optimization is presented in [65], greatly reducing computation time. The article may, however, benefit from emphasizing the energy efficiency gains made possible by well-optimized engine components. Additionally, a new co-simulation method is demonstrated by the study presented in [69], which carries out extensive experimental measurements to explore the integration of thermal fluxes. By developing integrated thermal management systems specifically for different car platforms, the research's applicability might be increased, and a more thorough comprehension of thermal management strategies could be encouraged. Lastly, the examination presented in [70] concentrates on EV powertrain power electronics technology. The influence of power electronics devices on energy efficiency in EV powertrains is not quantitatively evaluated in the study, although it highlights current technology and opportunities for future research paths. These critical assessments underscore opportunities for refinement and further exploration of VCU strategies in EVs.

C. VCU ALGORITHMS FOR MOBILITY ENERGY EFFICIENCY

The VCU is a control unit that controls various functions of EVs, including steering, acceleration, and braking control. The VCU is designed to optimize the performance of EVs while also ensuring the safety of the passengers [71]. The VCU can be designed to control the operation of various powertrain components (engine, transmission, electric motor) to reduce energy consumption. This can be achieved through optimal gear selection, intelligent engine starts/stop systems, and regenerative braking [23]. The VCU can be designed to control the battery pack that powers the vehicle. It manages battery charging and discharging and monitors its temperature and state of charge (SoC) while ensuring battery safety and efficiency [72]. VCU can be designed to capture and store energy that would otherwise be wasted (e.g., through regenerative braking or exhaust gas heat recovery) and use it to power auxiliary systems, reducing the load on the primary power source [73]. VCU can also be designed to ensure the primary goal of EV thermal management is to control the

TABLE 3. Latest research on development strategies of VCU in EV.

Ref.	Development Strategy	Description	Merits	Demerits
[68]	Sensor data collection and secure processing	Developed an effective EV transit system by utilizing blockchain and machine learning technology	**Data Security:** Utilized cutting-edge technology (Blockchain, Machine Learning) to improve security and privacy while exchanging data about EVs.	**Response Time Improvement:** Refinement and optimization are needed to reduce latency and improve overall system performance.
[65]	Precise and effective EV powertrain optimization	Developed a two-step analytical methodology for optimizing EV powertrains. The first stage examined motor features and efficiency mapping, while the second stage used motor data to assess vehicle performance.	**Computational Efficiency:** Considerable reduction in calculation time (approximately 250 times quicker) by the use of surrogate models in multi-objective optimization	**Energy Efficiency Improvement:** Optimized powertrain components result in noticeable increases in energy efficiency, which is not highlighted in the paper and can be explored in the future.
[69]	Energy management	In-depth experimental measurements are carried out to investigate the integration of thermal flows. Two heat management systems were tested at different temperatures and real driving emission cycles.	**Integration of Real-World Data:** To ensure accurate model development and validation, the study incorporates a large amount of experimental data from an Internal Combustion Engine (ICE). Incorporating real-world data improves the simulation results' accuracy and dependability. **Novel Co-Simulation Technique:** Using Functional Mock-up Interface (FMI), the research presents an innovative approach to co-simulation that integrates high-fidelity ICE, thermohydraulic, and battery models.	**Limited Relevance Scope:** Subsequent investigations may examine the customization of integrated thermal management systems for other platforms, such as plug-in hybrids and completely electric cars, to promote more extensive progress in thermal management techniques.
[70]	Stability	Analysis of Controller Hardware-in-the-Loop (CHIL) simulations in EV powertrains with a focus on power electronics technologies	**Emphasis on modern Technology:** To ensure simulation accuracy, emphasis was placed on modern power electronics technologies, such as field-programmable gate arrays (FPGAs). **Prospects for the Future:** EV powertrain control innovation is being encouraged by presenting future directions, including model refinement and integration with Digital Twin configurations.	**Energy Efficiency Evaluation:** This study does not analyze The use of modern power electronics devices in electric vehicle powertrains to boost energy efficiency.

temperatures of the battery, motor, and crew cabin to ensure that all are working at optimal temperatures. The vehicle's capacity for heat dissipation is coordinated and controlled by a thermal management system [74]. Table 4 highlights the control algorithms, strength, and limitation of VCU for mobility energy efficiency in EVs.

IV. DEVELOPMENT STRATEGIES AND ALGORITHMS OF EPS FOR MOBILITY ENERGY EFFICIENCY

A. EPS CONFIGURATION AND SENSORS

In EVs, precise and reliable steering control is paramount for safe and accurate navigation. Steering control sensors are crucial in providing essential input to the autonomous vehicle's control system [85]. Two key sensors involved in steering control are the torque sensor and steering angle sensor, which work in conjunction with the Electrical Power Steering (EPS) system, ultimately controlled by the Electronic Control Unit (ECU) as illustrated in Fig. 9.

The steering angle sensor measures the rotational position of the steering wheel, providing real-time information on the driver's intended direction. It enables the autonomous vehicle's control system to accurately interpret the driver's steering inputs and translate them into appropriate commands for the steering actuator [86]. On the other hand, the torque sensor measures the level of torque applied to the steering column. It detects the driver's effort to turn the steering wheel, providing critical feedback on the driver's intentions and the resistance encountered while maneuvering the vehicle. The control system utilizes This torque information to enhance steering control precision and implement advanced driver assistance features, such as torque-based steering interventions and lane-keeping assistance [87].

Furthermore, the steering angle and torque sensors are integrated into the EPS system, replacing traditional hydraulic power steering with an electrically assisted mechanism. The EPS system utilizes electrical power, controlled by the ECU, to assist the driver's steering inputs and deliver the appropriate steering response. The ECU processes the steering angle and torque sensor data, applying sophisticated control algorithms to regulate the EPS system's behavior and provide the desired steering assistance [88]. Integrating these sensors and the EPS system into the overall control architecture of autonomous vehicles enables precise and dynamic steering control, allowing for smooth maneuvering and accurate trajectory tracking. The ECU, the central control unit, coordinates the interactions between the sensors, EPS system, and other control modules to achieve safe and reliable autonomous steering [89].

B. DEVELOPMENT STRATEGIES OF EPS FOR MOBILITY ENERGY EFFICIENCY

Fig. 10 illustrates the main development strategies for EPS to improve mobility energy efficiency. The development

TABLE 4. Control algorithms of vehicle control unit in electric vehicles.

Ref.	Control Algorithm	Description	Strength	Limitation
[75], [76]	Proportional-Integral-Derivative (PID) Control	PID control is a commonly used algorithm that adjusts the control signal based on the error between the desired and actual states of the vehicle, helping maintain stability and accuracy.	Easy Implementation, low Computational cost, work well for linear systems	Parameter tuning is required for optimal performance, limited adaption for systems with varying dynamics
[77], [78]	Model Predictive Control (MPC)	MPC is an advanced control algorithm that uses a dynamic system model to optimize control inputs. It considers predictions of future states and constraints to determine the optimal control action.	Optimal control based on future prediction, handle multiple constraints at a time	High computational cost, sensitive to model inaccuracies
[78], [79]	Field-Oriented Control (FOC)	FOC is a motor control algorithm that enables precise control of torque and flux in an electric motor. It decouples the torque and flux components, allowing independent control and efficient utilization of the motor's capabilities	Accurate torque and speed control. It enhances motor performance by reducing motor losses	Accurate motor parameters setting required, vulnerable to varying parameters and noise from the sensor.
[80], [81], [82]	Direct Torque Control (DTC)	TDTC is a control algorithm that directly regulates torque and flux in an electric motor without calculating or controlling the motor currents. It offers fast torque response and precise control by selecting the optimal voltage vectors	Simple implementation compared to FOC, fast torque response with fewer ripples	Switching frequency is increased, and sensitivity to parameter variations.
[83], [84]	Adaptive Control	Adaptive control algorithms adjust the control parameters based on real-time changes in system dynamics. These algorithms continuously estimate and update the model parameters to accommodate variations in vehicle and environmental conditions	Robust control in varying operating conditions, adaptable to different vehicles and driving scenarios	Precise parameter tuning is required, limitations for highly non-linear systems.

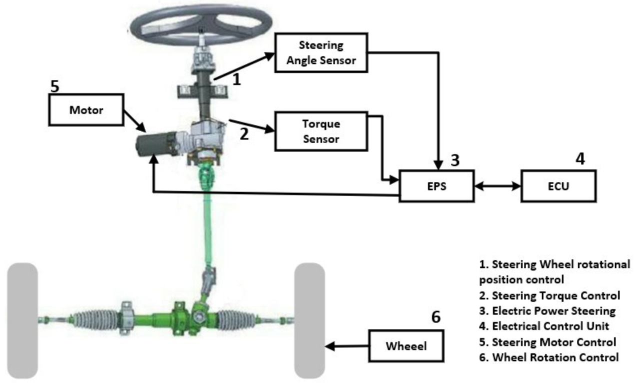

FIGURE 9. Overview model of the steering control based on different installed sensors.

strategies for EPS in electric vehicles for mobility energy efficiency revolve around efficient power assistance control, regenerative energy harvesting, intelligent steering assistance, variable assistance levels, vehicle dynamics control systems integration, lightweight component design, and advanced sensor integration. Implementing these strategies can optimize the EPS system's performance, minimize energy consumption, and contribute to the overall energy efficiency of electric vehicles.

Furthermore, EPS systems are more energy-efficient than traditional hydraulic power steering systems. The electric motor in an EPS system only consumes power when steering assistance is required, whereas hydraulic systems consume power continuously [90]. High-efficiency electric motors can be used in EPS systems to reduce energy consumption. These motors have higher efficiency levels, resulting in lower energy losses during operation [91]. Another effective strategy for enhancing mobility energy efficiency is the

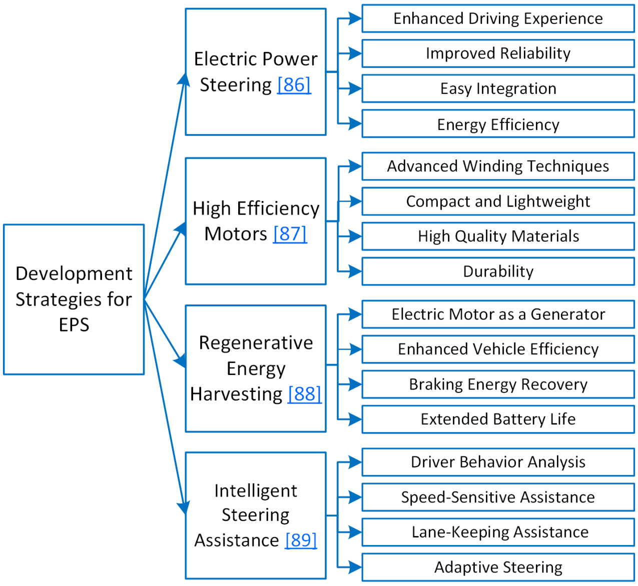

FIGURE 10. Taxonomy of the development strategies for EPS.

implementation of regenerative energy harvesting in EPS systems. By utilizing regenerative braking technology, the EPS system can recover energy during braking or deceleration and convert it into electrical energy that can be stored in the vehicle's battery. This harvested energy can then be utilized to power other vehicle systems, reducing the overall energy consumption of the electric vehicle [92]. Integrating intelligent steering assistance capabilities in EPS systems can significantly improve mobility energy efficiency. This involves developing algorithms that adaptively adjust the steering assistance based on various factors, such as road conditions, vehicle speed, and driver behavior. The

EPS system can minimize energy consumption and optimize steering control by providing the right assistance at the right time, resulting in improved energy efficiency [93]. Efforts to enhance mobility energy efficiency in electric vehicles should consider lightweight component design for EPS systems. Lightweight materials and efficient design can help reduce the overall mass of the EPS components, thereby reducing energy requirements for operation. Optimizing the mechanical design, such as reducing friction and improving bearing efficiency, can further contribute to improved energy efficiency [94].

An overview of current research on EPS system development strategies in EVs is given in Table 5. Although the table provides insightful information on novel strategies for improving torque output and energy efficiency in EPS, a few important points need to be addressed. Firstly, questions concerning the Differential Drive Collaborative Steering (DDCS) control system's adaptability to a range of working situations and vehicle characteristics are raised by the system's lack of real-time optimization and performance assessment metrics [95]. Secondly, the study concentrating on torque production enhancement via flux-switching Permanent Magnet Machines (FSPMMs) shows encouraging results; however, the absence of a thorough assessment regarding its improvement in energy efficiency leaves room for additional research on this topic [96]. Furthermore, examining the energy efficiency of electric SUVs in real-world driving situations gets recognition for its practical methodology, even though the complexity brought about by the variety of real-world driving scenarios may make energy efficiency assessments more difficult [97]. Finally, a promising technological advancement is presented by the creative application of a triboelectric nanogenerator (TENG)-based sensor for driver intention detection in EPS [98]. However, consistent performance of the sensor requires addressing its sensitivity to environmental factors. These important elements draw attention to areas that need more research and improvement in EPS strategies for EVs.

C. EPS ALGORITHMS FOR MOBILITY ENERGY EFFICIENCY

EPS is a system that uses an electric motor to assist in steering a vehicle. EPS is designed to improve the efficiency and performance of the vehicle's steering system while reducing its energy consumption. EPS focuses on reducing the energy consumption of the vehicle's steering system while improving its performance. This is achieved using advanced control algorithms that optimize the electric motor operation [99]. For example, the EPS system can be designed to adjust the electric motor's level of assistance based on the vehicle's speed and steering angle. The EPS system can adapt the necessary steering effort required by the driver for turning the steering wheel. Making it easier for the driver to steer the vehicle [100]. The EPS system can adjust the responsiveness of the steering, making it more or less sensitive to driver input [101]. The EPS system can adjust the steering assist to help stabilize the vehicle in different driving conditions, such as during high-speed driving or in crosswinds [102]. The EPS system can also adjust the feedback the driver receives from the steering, providing a more or less connected feeling between the driver and the road [103]. Table 6 summarizes the EPS control algorithms for mobility energy efficiency in EVs, including strength and limitation.

V. DEVELOPMENT STRATEGIES AND ALGORITHMS OF ESC FOR MOBILITY ENERGY EFFICIENCY

A. ESC CONFIGURATION AND SENSORS

Electronic Stability Control (ESC) systems in electric vehicles rely on sensors to accurately determine the driver's intentions and monitor the vehicle's response. These sensors play a crucial role in ensuring the effectiveness of the ESC system. One key aspect is using speed and steering angle measurements to ascertain the driver's desired heading [111]. Concurrently, onboard silicon-based sensors, manufactured using micromachining technologies, measure the vehicle's lateral acceleration and yaw rate. Over the past decade, these Micro-Electro-Mechanical Systems (MEMS) sensors have revolutionized ESC systems by significantly enhancing their size, cost, and reliability, surpassing traditional high-precision mechanical sensors [112].

Furthermore, the ESC system's control algorithm, residing in the ESC controller, continuously receives data from the wheel speed sensors, steering angle sensor, and yaw rate sensor, as illustrated in Fig. 11. The controller stores an application algorithm that incorporates equations representing the vehicle's dynamics [113]. By comparing driver inputs to the vehicle's response, the control algorithm determines the need for intervention, such as applying the brakes through hydraulic modulator valves or adjusting the throttle. When the vehicle's yaw rate aligns with lateral acceleration and speed, it indicates a balanced response to the steering input [114].

In addition, the ESC controller can exchange data with other controllers in connection with the vehicle network (controller area network). This capability enables further enhancements to the stability and control of EV [61]. Additionally, ESC systems typically offer an option to disable the function, which proves beneficial in specific off-road driving conditions or when using a smaller spare tire that may interfere with the sensors. Some vehicle manufacturers even provide an additional mode that allows drivers to explore the limits of tire grip with reduced electronic intervention. However, the ESC system automatically returns to normal operation upon ignition restart, ensuring continued safety and stability control [115].

B. DEVELOPMENT STRATEGIES OF ESC FOR MOBILITY ENERGY EFFICIENCY

The development strategies for ESC in electric vehicles are similar to those in traditional combustion engine vehicles. The system typically uses sensors to monitor various vehicle parameters, including speed, acceleration, steering angle, and

TABLE 5. Latest research on development strategies of EPS in EV.

Ref.	Development Strategy	Description	Merits	Demerits
[95]	Differential Drive Collaborative Steering (DDCS) control system	Designed a DDCS optimal control approach with an energy-saving mechanism that prioritizes reducing steering energy usage.	**Energy Efficiency Enhancement:** The innovative DDCS technology offers an exceptional way to save energy in EVs with articulated steering.	**Real-Time Optimization:** Absence of real-time optimization for performance assessment under diverse working conditions and vehicle parameters.
[96]	Enhancement of torque production by FSPMMs (Flux-switching permanent magnet machines) in EPS system	Proposed a strategy to improve torque generation that neutralizes negative torque contributions by inserting harmonic currents.	**Enhanced Torque Output:** By optimizing harmonic current parameters, a 9% increase in mean torque was obtained.	**Energy Efficiency Evaluation:** Lack of conclusive energy efficiency improvement opens room for future research.
[97]	Electric SUV's (Sport Utility Vehicle) energy efficiency under real-world driving conditions	Determined the effect of driving speed and the phases of regenerative braking on energy consumption	**Real-World Analysis:** Analyzing energy efficiency under various driving scenarios offers insights into actual performance.	**Complex Real-World Impact:**Energy efficiency evaluation is complicated by real-world driving conditions
[98]	Intelligent steering wheel utilizing a triboelectric nanogenerator (TENG)-based sensor	Developed a TENG-based sensor incorporated into the steering wheel to determine the driver's intentions.	**Innovative Sensor Technology:** Proposed a new TENG-based sensor with quicker response time and efficient driver intention detection	**Sensitivity to Environmental Factors:** Environmental factors may impact the sensor's efficacy in different situations.

TABLE 6. Control algorithms of electric power steering in electric vehicles.

Ref.	Control Algorithm	Description	Strength	Limitation
[104], [89]	Torque Overlay Control	Torque overlay control is a basic EPS algorithm that adds an electric motor-generated torque to the driver's steering input to assist the driver in steering maneuvers and provides adjustable steering effort	Improved driver comfort by providing adjustable steering effort, easy implementation and cost-effective	Limited usefulness in complex driving situations, depends upon inputs from driver for precise control
[105], [99]	Active Front Steering	AFS is a control algorithm that modulates the steering angle of the front wheels in response to various vehicle and sensor inputs by adjusting the front wheel steering angle	Enhances maneuverability during high-speed or emergency maneuvers	Certain limitations persist in extreme driving scenarios, increase complexity of steering system.
[106], [107]	Active Return Control	Active return control is an EPS algorithm that automatically assists the driver in returning the steering wheel to its neutral position after completing a turn	Improves vehicle stability, provides smoother steering inputs	Highly reliable response from actuators, more complex EPS system with higher cost.
[108], [109]	Variable Gear Ratio Control	Variable gear ratio control adjusts the steering gear ratio based on various parameters, such as vehicle speed, steering angle, and driving conditions	Improves vehicle stability at high speeds, optimizes steering characteristics	Requires additional mechanical components, increases complexity and cost
[110]	Active Damping Control	Active damping control is an advanced EPS algorithm that adjusts the damping characteristics of the steering system in real-time	Improves vehicle stability with ride comfort, efficiently adjusting damping force based on changing road conditions	Highly reliable on actuators and sensors, increases system complexity and cost

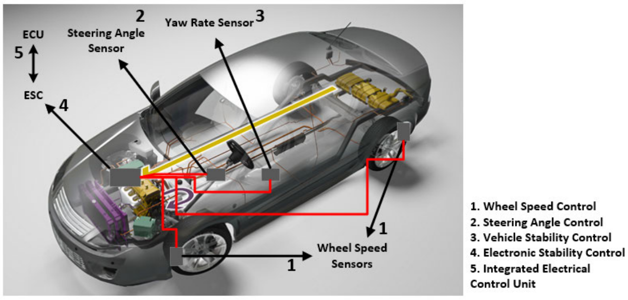

FIGURE 11. Overview of the stability control using different installed sensors [116].

wheel rotation. Using this information, the ESC control unit can detect when a loss of traction is about to happen and intervene by reducing engine power or applying individual brakes to specific wheels. However, in an electric vehicle, there may be some differences in the design strategy for ESC. For example, because electric motors can deliver instant torque, ESC in an EV may need to respond even more quickly than in a traditional vehicle. Additionally, some EVs may use regenerative braking, which can complicate the control strategy for ESC, as the system needs to balance the regenerative braking force with the conventional friction brakes to maintain stability [117].

Furthermore, Fig. 12 illustrates the main development strategies for ESC to improve mobility energy efficiency.

ESC can be designed to encourage smoother driving by reducing unnecessary acceleration and deceleration. By minimizing sudden speed changes, the vehicle can maintain a more consistent energy output, which can help improve efficiency and extend the battery's range [118].

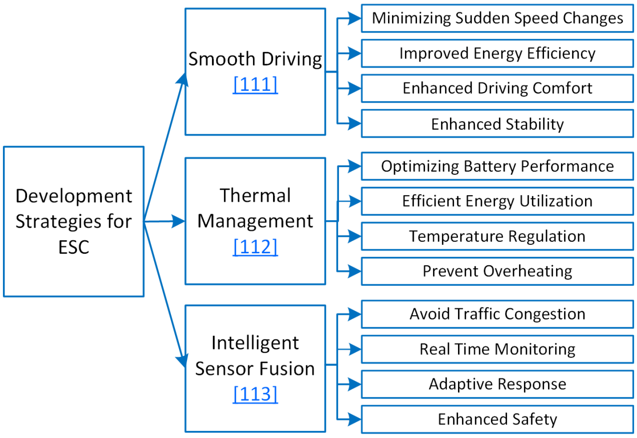

FIGURE 12. Taxonomy of the development strategies for ESC.

The vehicle's design, including the placement of the battery and electric motor, can affect the stability of the vehicle and its energy efficiency. By optimizing the weight distribution, ESC can help ensure that the vehicle stays stable and balanced, reducing the need for corrective maneuvers that can waste energy [119]. ESC can be designed to handle sensor fusion, which involves combining data from multiple sensors such as LIDAR (light detection and ranging), RADAR (Radio detection and ranging), wheel speed sensors, steering angle sensors, and gyroscope, etc., to integrate data for real-time monitoring resulting in enhanced accuracy [120].

A thorough summary of current research on ESC system development techniques in EVs can be found in Table 7. Although the table presents novel strategies to improve the effectiveness and functionality of ESC, there are significant factors that require taking into account. Firstly, handling stability and motor efficiency are significantly improved in the study using a torque distribution strategy based on Deep Reinforcement Learning (DRL) [121]. Future improvements will likely be necessary because of the computing demands of large-scale implementations, which might provide difficulties. Secondly, it is noteworthy that Phase Change Material (PCM) has been included in Battery Thermal Management Systems (BTMS) to improve thermal efficiency [122]. However, long-term dependability issues with PCM deterioration and ideal material combinations indicate areas that need more investigation. Lastly, to maximize energy efficiency without sacrificing perception performance, Adaptive Sensor Fusion with Energy Awareness for object detection in autonomous vehicles (AVs) presents a potential method [123]. However, given the model's restricted application to particular settings, more research should be conducted using comparative assessments and thorough data-driven analysis. These important considerations highlight areas where ESC techniques for EVs should be worked upon to advance the research in this field for further energy efficiency improvement.

C. ESC ALGORITHMS FOR MOBILITY ENERGY EFFICIENCY

ESC is a safety system in EVs designed to help drivers maintain control of their vehicles during emergencies or in hazardous road conditions [124]. ESC works by detecting and reducing instances of oversteer or understeer, which occur when a vehicle loses traction with the road surface, causing it to spin or slide out of control. In an electric vehicle, ESC can also play a role in improving energy efficiency and range [125]. By monitoring the vehicle's stability and reducing unnecessary acceleration or deceleration, ESC can help prevent wasteful energy consumption and extend the battery's range. To provide stability, the ESC monitors the yaw rate and steering wheel sensors to detect a lack of steering control. Once detected, the ESC activates the ABS (Antilock Braking System) and ECM (Engine control module) to reduce the vehicle's speed. The ESC system can detect when one or more wheels are slipping and apply the brakes or adjust the power to the motor to help maintain traction and prevent the vehicle from skidding or spinning out of control. The ESC system can detect when the vehicle is starting to oversteer or understeer and apply the brakes or power adjustment of the motor to help keep the vehicle on the intended path [126]. The ESC system can detect when the vehicle is at risk of rolling over and apply the brakes or adjust the power supply to the motor to help prevent the vehicle from rolling over [127]. The ESC system can also hold the brakes for a short period when the vehicle is stopped on a hill, allowing the driver to start the vehicle without rolling backward [128]. Table 8 shows the ESC control algorithms for mobility energy efficiency in EVs along with their strength and limitations.

VI. DEVELOPMENT STRATEGIES AND ALGORITHMS OF BCU FOR MOBILITY ENERGY EFFICIENCY

A. BCU CONFIGURATION AND SENSORS

The body control unit (BCU) in electric vehicles incorporates various sensors to monitor and control different systems within the vehicle's body, as shown in Fig. 13. These sensors enhance the occupants' safety, convenience, and comfort. Some of the key sensors used in the BCU of electric vehicles include those for lighting control, windshield wipers, power windows, door locks, and the HVAC (Heating, Ventilation, and Air Conditioning) system [136].

Furthermore, lighting sensors enable the automatic control of lighting systems, such as automatic headlights and interior lighting. These sensors detect ambient light levels and adjust the vehicle's lighting accordingly, enhancing visibility and reducing driver distraction. Windshield wiper sensors detect rain or moisture on the windshield and activate the wipers automatically. These sensors ensure optimal visibility for the driver, enhancing safety during inclement weather conditions. Power window sensors detect obstacles in the window's path, preventing injuries and damage. They automatically stop the window movement if an obstruction is detected, ensuring the safe operation of the power windows [137].

Similarly, door lock sensors are vital to the vehicle's security. They detect whether the doors are open or closed and provide feedback to the BCU. This information is used

TABLE 7. Latest research on development strategies of ESC in EV.

Ref.	Development Strategy	Description	Merits	Demerits
[121]	Torque Distribution Strategy Based on Deep Reinforcement Learning (DRL)	DRL-based approach for torque distribution in EVs. Torque distribution is a decision-making process that incorporates motor efficiency in cumulative reward.	**Better Handling Stability:** The proposed strategy significantly lowers energy loss in the range of 5.25% to 10.51% during typical steering motions and greatly increases average motor efficiency.	**Large-scale computational capability:** Optimization of algorithms can be done in the future for more effective computation
[122]	Phase change material (PCM) assisted battery thermal management system (BTMS)	The study proposed the integration of jute fibers with PCM-based cooling techniques to increase the thermal efficiency of BTMS in EVs	**Enhanced Thermal Efficiency:** Compared to conventional cooling techniques, the proposed novel strategy produces noticeably lower maximum temperatures, indicating improved thermal efficiency	**Long-term Reliability:** Interior performance of PCM, degradation of jute fibers, and determining the optimal number of jute layers can be studied as the future work for developing robust and durable BTMS
[123]	Adaptive Sensor Fusion with Energy Awareness for object detection in autonomous vehicles (AVs)	The proposed method optimizes energy usage without sacrificing perception performance by adapting the fusion mechanism based on circumstances.	**Improved Efficiency with Reduced Energy Utilization:** The suggested approach performs up to 9.5% better than the current sensor fusion techniques while using around 60% less energy and reducing latency by 58%.	**Restricted Applicability:** The study concentrates on particular scenarios or circumstances. To improve the flexibility of the proposed model, future work could involve comparative evaluations and data-driven analysis

TABLE 8. Control algorithms of electronic stability control in electric vehicles.

Ref.	Control Algorithm	Description	Strength	Limitation
[129], [130]	Anti-lock Braking System (ABS) Control	ABS control is a fundamental component of ESC systems that modulates the braking force at each wheel to prevent wheel lock-up during braking	Prevents wheel lock-up during braking, improves stability and control of EV	Low capability to address lateral stability issues, does not actively involve in vehicle yaw motion
[131], [132]	Traction Control System (TCS) Control	TCS control is designed to prevent wheel slip during acceleration by utilizing wheel speed sensors to monitor individual wheel speeds and modulates the power or torque delivered to the wheels to optimize traction	Improve the traction and stability control during acceleration, avoid excessive wheel spin and loss of control	Focuses primarily on acceleration and traction, not lateral stability, limited control over yaw motion
[133], [134]	Roll Stability Control (RSC)	Active return control is an EPS algorithm that automatically assists the driver in returning the steering wheel to its neutral position after completing a turn	Improves vehicle stability, provides smoother steering inputs	Highly reliable response from actuators, more complex EPS system with higher cost.
[135]	Hill Start Assist Control (HSAC)	HSAC is an ESC algorithm that prevents a vehicle from rolling backward when starting on an incline by holding the brake pressure for a short period, allowing the driver to smoothly transition from the brake pedal to the accelerator without the vehicle rolling backward	Enhances driver convenience and control, reduces the likelihood of accidents during hill starts	Limited functionality specifically for hill start situations, requires accurate detection and control of the slope gradient.

for various functions, such as automatically locking the doors when the vehicle is in motion or unlocking the doors when the vehicle is parked. The HVAC system sensors monitor parameters like temperature, humidity, and cabin occupancy. They enable the BCU to control the HVAC system effectively, maintaining a comfortable environment inside the vehicle. These sensors work with the BCU to provide intelligent control over various body systems in electric vehicles, ensuring enhanced safety, convenience, and comfort for the occupants.

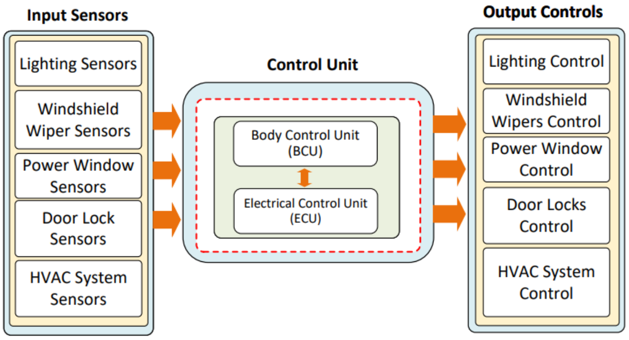

FIGURE 13. Basic configuration of BCU using input sensors and output controls.

B. DEVELOPMENT STRATEGIES OF BCU FOR MOBILITY ENERGY EFFICIENCY

Different development strategies are presented in Fig. 14 for a BCU to improve mobility energy efficiency. These strategies include power management, regenerative braking, lightweight design, and V2V communication. The BCU can manage the power consumption of various electronic systems in the vehicle by turning them off when not in use. For example, the BCU can turn off the climate control system when the vehicle is not occupied [138]. Advanced thermal control systems can be designed to guarantee that the BCU operates within ideal temperature ranges, hence lowering the requirement for energy-intensive cooling systems and reducing the load on the electrical system by utilizing the thermal energy produced within the car for heating [74]. The BCU can be designed to communicate with other vehicles on the road. This can allow for more efficient driving by sharing information about traffic conditions and optimizing the operation of electronic systems in the vehicle [139].

Table 9 comprehensively describes current research on the development approaches used for BCUs in EVs. These strategies demonstrate creative methods for improving energy efficiency and maximizing vehicle performance. The study introducing the Long Short-Term memory-based improved Model Predictive Control algorithm (LSTM-IMPC) showed promising results in increasing fuel efficiency, ultimately resulting in improved energy efficiency [140]. However, it's crucial to remember that the algorithm solely addresses internal vehicle energy management; real-time sensor data and significant external elements are not included, indicating a potential area for future research. Additionally, it is noteworthy that Nonlinear Model Predictive Control (NMPC) is used for cabin cooling systems since it may increase efficiency while lowering energy consumption [141]. However, there is still a need for more research and development into how resistant the NMPC model is to uncertainties such as unmodeled dynamics and disturbances. Furthermore, fuel consumption is significantly reduced by the Multi-Agent Reinforcement Learning (MARL) based optimal energy-saving strategy for Hybrid Electric Vehicles (HEVs) presented by [142]. Nonetheless, optimization and practical application issues may impact the method's adaptability, which can be considered for future research. These considerations underscore possible paths for future study in BCU techniques in EVs and emphasize improving these strategies to guarantee their efficacy in real-world circumstances.

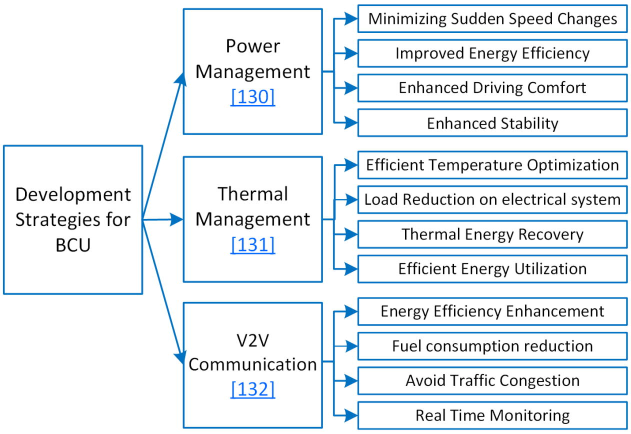

FIGURE 14. Taxonomy of development strategies for BCU.

C. BCU ALGORITHMS FOR MOBILITY ENERGY EFFICIENCY

The body control unit (BCU) is a component in electric vehicles (EVs) that controls the various electronic systems in the vehicle, including lighting, climate control, and the locking system. By optimizing the operation of these systems, the BCU can improve the vehicle's energy efficiency. The BCU controls the exterior and interior lighting systems, including headlights, taillights, brake lights, turn signals, and interior lights [143]. The BCU controls the windshield wipers, including the speed and frequency of the wipers. The BCU controls the power windows' operation, including the windows' opening and closing. The BCU controls the operation of the door locks, including the locking and unlocking of the doors [136]. Besides, the BCU controls the heating, ventilation, and air conditioning (HVAC) system, including the temperature, fan speed, and airflow [144]. Table 10 illustrates the BCU control algorithms for mobility energy efficiency in EVs, mentioning their strength and limitations.

VII. COMPARISON OF INTEGRATED ECU ALGORITHMS FOR MOBILITY ENERGY EFFICIENCY

Table 11 presents a critical analysis of existing control approaches for energy efficiency in EVs using regenerative braking. Different factors are considered to analyze existing control strategies to highlight the research gap critically. The factors incorporate the type of control method used, the main objective of the proposed study, strengths, and limitations.

In [149], Adeleke et al. presented an in-depth torque distribution approach for four in-wheel motor drive EVs. With an emphasis on energy efficiency, they use the dynamic programming (DP) technique to optimize the torque distribution between the front and rear in-wheel motors. The suggested DP algorithm has been shown through thorough modeling and experimental research to dramatically reduce the vehicle's energy consumption across various driving cycle situations, demonstrating notable increases in energy efficiency. It's important to remember that DP necessitates more time and space due to its comprehensive computations. Future areas for research need to concentrate on refining the method to augment computational effectiveness while maintaining the capacity for real-time monitoring.

In [150], Lee et al. proposed a model to reduce energy consumption in autonomous EVs by optimizing speed in various driving circumstances. The model-based Reinforcement Learning (RL) method is used for eco-driving. The RL algorithm outperformed the global optimum solution by 93.8% using vehicle powertrain dynamics. Future work could focus on experiments in the real world and more validation under various driving circumstances. Reducing algorithm complexity and increasing convergence speed via techniques like transfer learning is crucial for improving practical implementation, which can be explored in future studies.

In [151], Pei et al. proposed an efficiency optimization strategy for EV motors, enhancing efficiency by 4-7% through a novel Loss Minimization Algorithm (LMA) based on the motor's energy balance equation. The LMA adjusts excitation current, improving efficiency during steady-state operations. However, the method assumes constant motor parameters, limiting its applicability. Real-world experiments

TABLE 9. Latest research on development strategies of BCU in EV.

Ref.	Development Strategy	Description	Merits	Demerits
[140]	Long short-term memory based improved model predictive control algorithm (LSTM-IMPC)	Proposed an LSTM-IMPC algorithm for the energy management strategy in plug-in hybrid electric vehicles (PHEV) and evaluated performance in comparison to rule-based techniques	**Enhanced Fuel Efficiency:** The proposed model shows considerable fuel-saving rates of 3.81%, 5.6%, and 18.71% over the traditional energy management systems	**External Factors and Real-Time Data:** The proposed EMS addresses internal vehicle energy management, ignoring external variables and real-time data from sensors which could be added in future work
[141]	Nonlinear Model Predictive Control (NMPC) for Cabin Cooling System	The proposed model ensures thermal comfort while consuming the least amount of energy by optimizing the air mass flow trajectories and cabin inlet air temperature	**Improved Efficiency with Reduced Energy Utilization:** The suggested approach performs up to 9.5% better than the current sensor fusion techniques while using around 60% less energy and reducing latency by 58%.	**Robustness and Real-World Implementation:** Robustness of the proposed NMPC has uncertainty concerns like unmodeled dynamics and disturbances, which could be explored in the future to improve the NMPC's robustness
[142]	Multi-Agent Reinforcement Learning (MARL) based optimal energy-saving strategy for Hybrid Electric Vehicle (HEV)	The proposed model enables cooperative control of the engine and the car-following behaviors by actively reducing energy consumption.	**Significant Fuel Consumption Reduction:** The paper's proposed MARL model demonstrates fuel consumption reduction by 15.8% compared to the hierarchical Model Predictive Control (MPC) strategy, ensuring significant advancement in energy efficiency	**Enhancing Algorithm's Adaptability:** The suggested MARL algorithm could face challenges in optimization and real-world applicability, which can be improved in future research

TABLE 10. Control algorithms of body control unit in electric vehicles.

Ref.	Control Algorithm	Description	Strength	Limitation
[145]	Lighting Control	Lighting control algorithms in the BCU manage various lighting functions, including exterior lighting, interior lighting, and adaptive lighting systems	Automated lighting control for enhanced safety, optimizes energy efficiency by adjusting lighting levels	Requires accurate sensor inputs for optimal performance, vulnerable to sensor malfunctioning
[146]	Wiper Control	Wiper control algorithms in the BCU regulate the operation and speed of windshield wipers based on input from rain sensors, vehicle speed, and user settings	Automated wiper control for improved visibility and safety, adapt wiper operation to varying rain intensities	Relies on accurate rain sensor inputs for optimal control, requires fine-tuning for different weather conditions
[147]	Power Windows Control	Power windows control algorithms in the BCU manage the operation and positioning of the vehicle's power windows	Precise control over power window operation, incorporates anti-pinch functionality for user safety	Requires reliable sensor inputs for anti-pinch functionality, vulnerable to motor or sensor malfunctioning
[148]	HVAC Control	HVAC control algorithms in the BCU regulate the operation of the Heating, Ventilation, and Air Conditioning system in the vehicle	optimize energy efficiency by adjusting HVAC parameters as needed	rely on accurate sensor inputs for optimal control and vulnerable to sensor malfunctioning

and parameter variations, such as temperature, are necessary for comprehensive validation and practical implementation in diverse EV scenarios, which can be researched in the future.

In [152], Nassar et al. developed multi-objective energy management strategies for pre- and post-transmission parallel hybrid electric vehicles (HEVs). These strategies use genetic algorithms to optimize fuel consumption, electric system efficiency, and battery life. Results show improved battery performance and varied effects on fuel consumption compared to a baseline strategy. However, the study's limited applicability requires further validation, and real-time implementation complexities suggest the need for adaptive algorithms in future research.

In [153], Mehbodniya et al. investigated optimization methodologies for three-phase induction motors, emphasizing field-oriented control and direct torque control techniques. The study shows improved performance and energy efficiency using fractional order Darwinian particle swarm optimization (FODPSO), especially for the direct torque control method. Nevertheless, comprehensive comparison assessments of different optimization strategies should be included in the work. Future work should incorporate comprehensive performance comparisons and real-world applications to facilitate decision-making in the real world effectively.

In [154], Xu et al. investigate deep reinforcement learning-based energy management strategy (EMS) for hybrid electric vehicles (HEVs). The study investigates how deep reinforcement learning (DRL) approaches might be applied to transfer learning. It evaluates several exploration methods inside the Deep Deterministic Policy Gradient (DDPG) algorithm architecture, such as introducing noise into the parameter and action spaces. The findings show that, in comparison to the combination of parameter space noise and action space noise, adding parameter space noise in the network is more stable and converges faster for transferable EMS. One limitation of the study is that it investigates only the noise addition technique. It leaves up the potential for future research by investigating a wider variety of exploratory approaches with robust DRL algorithms to enhance EMS in HEVs.

In [155], Zhang et al. proposed and simulated a hierarchical model predictive control algorithm for the thermal management of EV by using the energy restored through regenerative braking. The upper layer MPC controller optimally plans the vehicle's speed, while the lower layer focuses on implementing thermal management strategies based on the planned regenerative braking for energy efficiency. By conducting experiments, the proposed method demonstrates a reduction in energy consumption by 3.38% and a decrease in battery aging of up to 29.15% when compared to the benchmark method. The study may have focused on a specific vehicle or air conditioning system, and the findings may not apply to other vehicle types or HVAC (heating, ventilation, and air conditioning) systems. The study may have yet to fully consider the impact of other factors, such as weather conditions or driver behavior. The cost and complexity of retrofitting existing vehicles with the necessary equipment to implement the proposed strategy may be prohibitively high, limiting its adoption.

In [156], Satzger and Ricardo de Castroa introduce a predictive braking control method for EVs that uses a predictive control framework to optimize energy recuperation and wheel slip regulation. The algorithm is designed for EVs with redundant braking actuators. The algorithm was experimented on the ROboMObil (ROMO) research vehicle, and results showed up to a 60 percent reduction in torque tracking error and a 10 percent improvement in emergency deceleration compared to other control techniques.

There could be several limitations to this study. One limitation could be the specific experimental setup used for validation. The ROboMObil (ROMO) research vehicle used in the study may only represent some types of electric vehicles, which could limit the generalizability of the findings. Additionally, the proposed algorithm's effectiveness may depend on specific driving conditions and scenarios not explored in the study. Finally, the cost and complexity of implementing the proposed algorithm in a production vehicle may also limit its practical application.

In [157], Chen et al. proposed a hierarchical framework for regenerative braking control in independently operated EVs. The upper-layer sliding mode controller (SMC) estimates vehicle states by a modular observer, which tracks desired velocity profiles. After calculating the overall braking torque, a lower-layer controller uses a control allocation algorithm to split the braking torque between the front and rear wheels as efficiently as possible to maximize energy recovery, ultimately improving EV efficiency. Although useful, the study's dependence on certain tire characteristics for velocity estimation has limitations and points to the need for adaptable methodologies to be explored in the future.

In [158], Kousalya et al. proposed the implementation of predictive torque control (PTC) as an energy-saving approach for the motor used in EV. The PTC method was used to overcome the torque ripple problem in conventional direct torque control (DTC). The electric motor's torque ripple and speed response in EVs are analyzed across various operating modes. This examination aims to generate an energy-saving plan designed for the electric motor. The paper's limitation lies in the high computational burden, dependence on system models, and challenges in tuning weighting factors for Predictive Torque Control (PTC). Future studies could focus on developing efficient computational methods, adaptive algorithms for changing parameters, and automated tuning techniques to enhance PTC's applicability in traction motors.

In [159], Zerdali and Demir proposed a novel speed-sensorless finite control set-predictive torque control for EVs utilizing induction motor (IM) drives. The method combines the advantages of IM with the ability to handle nonlinearities and eliminates speed sensors, increasing reliability and reducing costs. An adaptive fading extended Kalman filter is introduced to approximate load torque and enhance torque response. The proposed method shows improved control performance, making it a promising solution for electric vehicle propulsion systems. One potential limitation of the research study is that the proposed method may have limitations in high-speed applications due to the finite control set and prediction errors. Moreover, the proposed method requires an exact approximation of the load torque, which can be challenging in some operating conditions. Additionally, the experimental studies were performed on a small-scale motor, and further research may be required to validate the proposed method on larger-scale motors and under different operating conditions. Finally, the cost and complexity associated with implementing the adaptive fading extended Kalman filter may be a limitation for practical applications.

In [160], Vajedi and Azad introduced an ecological adaptive cruise control (Eco-ACC) system for plug-in hybrid EVs that optimizes fuel economy and safety by utilizing nonlinear MPC to adjust vehicle speed based on the surrounding environment and adapts its driving behavior accordingly. The developed model is tested and compared with PID and linear MPC controllers in simulations. The findings demonstrate that utilizing Nonlinear Model Predictive Control significantly improves total energy cost, with an increase of up to 19 percent. while maintaining vehicle safety. The Eco-ACC's performance limitations under specific traffic conditions and the critical influence of the prediction horizon parameter highlight the necessity for future research in adaptive systems. Developing advanced algorithms for autonomous prediction horizon optimization based on real-time traffic data can enhance Eco-ACC adaptability and efficiency across diverse driving scenarios.

In [161], Zhu et al. presented an MPC approach for EVs to accurately track a desired speed profile while ensuring safety and stability. The proposed approach uses a kinematic model to predict the vehicle's future behavior and adjust control inputs accordingly. Simulation results validate the effectiveness of the proposed approach in

TABLE 11. Comparison of integrated ECU algorithms related to EV control.

Ref.	Control Method	Objective	Strength	Limitation
[149]	Dynamic Programming Control Algorithm	Optimal Torque Distribution and energy efficiency for four in-wheel motor drive (4IWMD) EV	Reduced energy consumption by 23.01% (IM240), 23.12% (NEDC), and 23.89% (WLTC).	Exhaustive nature of the Dynamic Programming (DP) algorithm demands significant computational and time resources
[150]	Model-Based Reinforcement Learning (RL)	Reduce energy consumption by optimizing vehicle speed under a range of driving scenarios	Near-optimal performance of 93.8% is attained	RL algorithm's complexity and convergence time need to be improved
[151]	New Loss Minimization Algorithm (LMA)	Efficiency optimization of permanent magnet synchronous motor (PMSM) for EVs	Improved efficiency by about 4-7% compared with the conventional LMA methods	Limited to the steady-state operation of PMSM
[152]	Multi-objective Genetic Algorithm	Improvements in efficiency for the electric system, battery life, and fuel economy	significant increase in battery efficiency resulting in enhanced energy management strategy applicable to diverse driving scenarios	Complex offline computations for various driving conditions with results storage in optimum look-up tables
[153]	Fractional Order Darwinian Particle Swarm Optimization (FODPSO)	FODPSO based Field oriented control (FOC) to optimize motor performance and improve energy efficiency	Proposed model outperforms traditional Field oriented control (FOC) and Direct torque control (DTC) methods in terms of efficiency	Limited performance comparison with other optimization techniques
[154]	Deep reinforcement learning (DRL) combined with transfer learning	To find the most effective and optimal energy management strategy (EMS) for hybrid electric vehicles (HEVs)	Transfer learning algorithm enhances the efficiency of EMS selection	Only one exploration method (i.e, adding noise for action selection) of DRL is considered.
[155]	Hierarchical MPC (model predictive control) strategy	Minimization of battery degradation to extend its life	The developed model achieves energy savings of 3.38% and significantly reduces battery aging by 29.15%	The hierarchical MPC control strategy is not suited for cabin thermal management scenario in winter
[156]	Model predictive control (MPC)	Predictive braking control approach for EVs is presented	The torque tracking error is reduced by up to 60%, while there is an improvement of up to 10% in deceleration during emergency braking	MPC can be made more robust with online algorithms for estimating tire-road friction and optimal wheel-slip
[157]	Modular observer combined with hierarchical feedback control	Control of regenerative braking	Stability of the proposed control algorithm is analyzed using input-to-state stability theory	Reliance on longitudinal tire forces for velocity estimation.
[158]	Predictive torque control (PTC)	Energy saving for electric motor with decreased motor copper losses	Outperforms DTC with reduced torque ripple, lower Total harmonic distortion (THD) in stator current, less noise, and improved speed tracking accuracy	Challenges in tuning weighting factors for Predictive Torque Control (PTC)
[159]	Speed-sensorless finite control set-predictive torque control (FSC-PTC)	Improvement in the control performance of the IM drive by estimating the load torque	Improved control performance in various operating conditions by combining adaptive fading extended Kalman filter with the proposed control technique	Proposed method may have limitations in high-speed applications due to the finite control set.
[160]	Ecological Adaptive Cruise Control (ECO-ACC) with Non-linear Model Predictive Control (NMPC)	Fuel economy and safety by optimally adjusting vehicle speed based on upcoming trip data	Improve in energy cost to about 19%	Careful tuning of prediction horizon parameter for optimal performance across diverse driving conditions.
[161]	Model predictive control	Implementation of speed control strategy based on MPC	Safe and stable speed tracking with minimum error while considering the constraints	Only the speed tracking aspect of autonomous driving is considered avoiding other aspects which may affect the proposed system performance.
[162]	Model predictive control (MPC)	Minimize the battery aging while maintaining good braking performance	Effective management of the battery current and braking force distribution	The proposed strategy is not tested for different driving styles or road conditions
[163]	Parameterized model predictive control	Steering performance improvement of EVs	Real-time optimization of control inputs are employed to enhance the steering performance of EVs.	Sensitivity to prediction horizon requires precise tuning for real-world applications.
[164]	Global search algorithm combined with Model predictive controller (MPC)	Improvement in energy efficiency of in-wheel motors through optimal torque distribution	Reduces energy consumption by 21.66% and 11.18% in specific maneuvers; 10.13% in slalom test	Using only the wheel slip ratio to optimize torque.
[165]	Modular Optimal Control (High-Level Model Predictive Control and Low-Level Torque Regulation)	Integrated Longitudinal and Lateral Vehicle Stability to prevent real-time accidents	The proposed system enhances vehicle stability in challenging driving maneuvers compatible with various actuation systems	Limited validation on vehicles with active steering and differential braking systems.

achieving the desired speed profile with minimal tracking error and smooth control actions. The proposed approach only considers speed tracking and does not address other aspects of autonomous driving, such as path planning, obstacle avoidance, and decision-making. The approach may be sensitive to the model's parameters and assumptions, affecting its performance in different scenarios.

In [162], Wu et al. introduced a hierarchical control strategy for regenerative braking in hybrid electric vehicles considering battery aging. The strategy involves two levels of control: a high-level controller that determines the braking force distribution and a low-level controller that regulates the battery current. The proposed approach is evaluated through experimentation and simulation, and the results affirm that it can effectively prolong the battery lifespan while maintaining good braking performance. This study has a few areas for improvement in that it focuses solely on the battery aging aspect of the regenerative braking system and does not consider other factors that could affect the battery lifespan, such as temperature and cycling rate. Also, this study assumes a specific driving scenario. It does not consider the effects of different driving styles or road conditions, which could impact the performance of the regenerative braking system and the battery's lifespan.

In [163], Murilo et al. proposed a parameterized model predictive control approach for the electric power-assisted steering system, enabling tuning control parameters to meet different performance objectives and handle various operating conditions. The approach relies on the Electric Power Assisted Steering (EPAS) system model, utilizing real-time optimization of control inputs to enhance the steering performance of EVs. The simulation results demonstrate that the proposed control strategy can outperform traditional control methods, indicating its potential to enhance the overall steering performance of EPAS systems. Future research might improve the prediction horizon selection procedure to improve the parameterized MPC's robustness. Furthermore, doing a field test on a vehicle will yield important information on how well the suggested control technique works in actual EPAS systems.

In [164], Changqing et al. suggested an integrated control mechanism for EVs using active front steering and MPC control. The strategy aims to enhance the vehicle's stability, energy efficiency, and driving comfort by coordinating torque distribution between front and rear wheels and adjusting the steering angle. Simulations show that the proposed strategy surpasses traditional handling and energy consumption control. The results indicate that an integrated approach can enhance the overall performance of EVs. One potential limitation of this study is that it only considers improving driving torque distribution based on the wheel slip ratio, potentially ignoring other important aspects that significantly impact the vehicle's performance and energy economy. Subsequent investigations may examine a more thorough optimization strategy considering other variables besides the wheel slip ratio. This might result in a more comprehensive and sophisticated control approach for EVs, considering environmental parameters, vehicle speed, and road surface conditions.

In [165], Nahidi et al. introduced a modular optimal control method to highlight the challenge of integrated lateral and longitudinal stability control for EVs. The proposed system utilizes high and low-level controllers to regulate yaw moment and longitudinal force, enabling real-time optimization of torque distribution among the wheels. The experimental tests on an electric Chevrolet Equinox show improved vehicle stability and dynamic response. While the system exhibits adaptability to various vehicles and compatibility with various actuation systems, a more thorough study should include a wider range of EVs and actuation systems. To ensure practical application, future research should concentrate on expanding the control structure to a larger range of vehicles and actuation systems.

Furthermore, EV data is acquired from the Kaggle website to investigate the hidden patterns and trends of the different models of Tesla EV [166]. This way, different analysis methods, such as correlation, boxplot, and comparison analysis, are adopted to investigate the EV data. Our analysis revealed interesting insights into the relationship between the selected performance metrics and energy efficiency of electric cars from Tesla, as shown in Fig. 15. Specifically, we investigated the correlation between the following variables: Acceleration Time (AccelSec), Top Speed (TopSpeed_KmH), Range (Range_Km), Fast Charge (KmH) and Energy Efficiency (Efficiency_WhKm).

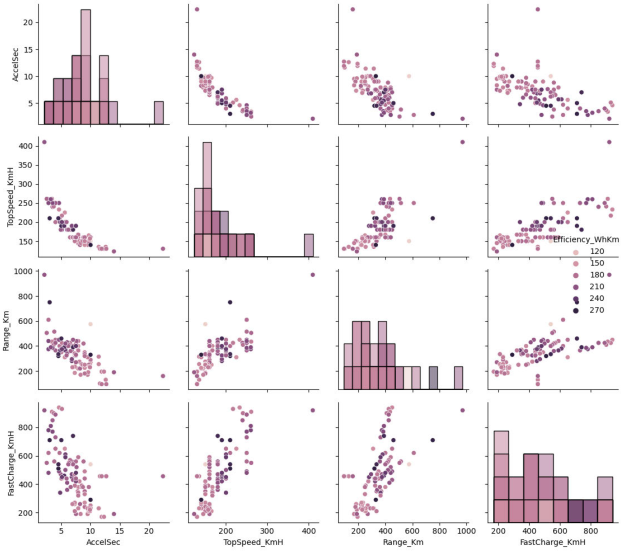

FIGURE 15. Correlation of selected performance metrics and energy efficiency of EVs.

We employed the Pearson correlation coefficient to quantify the degree of correlation between variables. The Pearson correlation coefficient measures the linear relationship between two variables, ranging from −1 to +1. A value close to +1 indicates a strong positive correlation, while a value close to -1 indicates a strong negative correlation. A value close to 0 suggests a weak or no correlation.

To visually represent the correlations, a correlation heatmap is generated as shown in Fig. 16. The heatmap illustrates the strength and direction of the correlations between the variables of interest. The color gradient in the heatmap helps intuitively identify the correlations' magnitude. The resulting correlation heatmap indicates that top speed has the strongest positive correlation with energy efficiency, followed by range and fast charge with a slightly lower correlation. Acceleration time shows a negative correlation with efficiency, indicating that if acceleration time increases, then the efficiency of the EV decreases. Furthermore, the correlation analysis and heatmap provide valuable insights into the relationship between key performance metrics and the energy efficiency of electric cars from Tesla. These findings can assist researchers, manufacturers, and policymakers understand the factors influencing energy efficiency in electric vehicles.

The findings of the correlation analysis are summarized as listed below:

- **Acceleration Time (AccelSec) vs. Energy Efficiency (Efficiency_WhKm):** A moderate negative correlation is observed between the acceleration time and energy efficiency of electric cars (-0.38). This suggests that vehicles with high acceleration time have lower energy efficiency.
- **Top Speed (TopSpeed_KmH) vs. Energy Efficiency (Efficiency_WhKm):** A positive correlation is observed between the top speed of EVs and their energy efficiency (0.36). This implies that vehicles with higher top speeds exhibit higher energy efficiency.
- **Range (Range_Km) vs. Energy Efficiency (Efficiency_WhKm):** A moderate positive correlation is observed between the range of electric cars and their energy efficiency (0.31). This implies that vehicles with a longer range tend to exhibit higher energy efficiency.
- **Fast Charge (Km_H) vs. Energy Efficiency (Efficiency_WhKm):** A positive correlation is observed between the fast charge and energy efficiency of EV (0.3). This implies that vehicles with a fast charge exhibit higher energy efficiency.

In addition to the correlation study results regarding rapid charging, it is critical to understand the fundamental trade-off of fast charging rates because they may result in a shorter battery life. Xie et al. [167] provided a thorough analysis that clarified important variables in this trade-off. Their results highlight the need for a balanced approach, as they show that high-rate charging can have mechanical effects on battery components, such as physical stresses and strains, thermal runaway (a phenomenon marked by an uncontrollably high battery temperature), and even loss of lithium inventory, which denotes a gradual decrease in the amount of lithium that is available in the battery cells. In [167], optimum charging algorithms for Li-ion batteries are examined to avoid battery degradation and achieve the shortest charging interval. Therefore, as we explore the benefits of rapid charging for energy efficiency, we must balance these advantages with potential effects on battery life. This comprehensive approach ensures that the development and utilization of fast charging for electric vehicles (EVs) consider both performance enhancement and the long-term sustainability of the EV batteries.

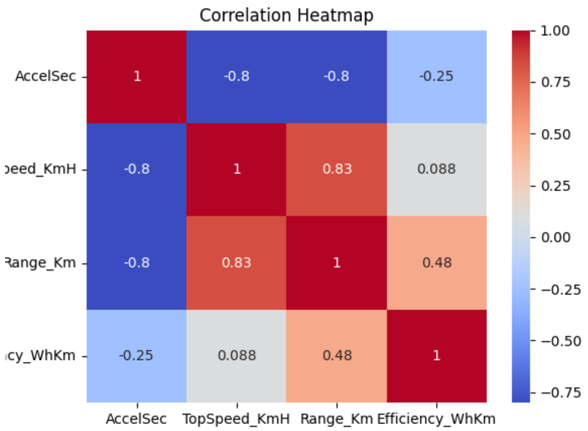

FIGURE 16. Correlation Heatmap of selected performance metrics and energy efficiency of EVs.

VIII. SHORTCOMINGS OF AVAILABLE SOLUTIONS AND FUTURE DIRECTIONS

Considering the findings presented in our study on the development strategies and algorithms of an integrated ECU for mobility energy efficiency, it becomes apparent that significant progress has been made in the overall EV control, including VCU, EPS, ESC, and BCU. Even with these developments, it is clear that every method and algorithm still needs more advancement to guarantee a sustainable future for the broad use of EVs.

- **Shortcomings of Integrated ECU Development:** Despite the integration of predictive analytics, machine learning, thermal management, power electronics, and energy recuperation techniques, real-time data processing and accuracy in predictive modeling persist.
- **Shortcomings of VCU Development:** While advancements in sensor integration, powertrain component optimization, and intelligent energy management have enhanced Vehicle Control Units (VCUs), issues concerning the interoperability of different components and standardized communication protocols still pose challenges.
- **Shortcomings of EPS Development:** Electric Power Steering (EPS) systems have come a long way by introducing high-efficiency motors and regenerative energy harvesting. Yet, achieving a balance between power efficiency and steering precision, especially in diverse driving conditions, remains a challenge.
- **Shortcomings of ESC Development:** While smooth driving and intelligent sensor fusion have improved

the driving experience, thermal management and sensor accuracy challenges during extreme driving scenarios need to be addressed for enhanced safety and stability.

- **Shortcomings of BCU Development:** Power management, thermal regulation, and V2V communication in Battery Control Units (BCUs) have limitations, particularly in managing power distribution optimally and ensuring seamless communication between vehicles.

The solutions of the problems mentioned above are summarized in Table 12 below:

TABLE 12. Problems and solutions in EV control research.

Problems	Solutions
Limited predictive analytics accuracy	Implementation of advanced machine learning algorithms for predictive modeling, along with integrating real-time feedback loops for data validation, is required.
Insufficient real-time data processing	Research on high-speed processors and hardware accelerators for real-time data processing and developing parallel computing techniques needs to be researched.
Limited adaptability to diverse driving conditions	Research is required to implement AI-based algorithms that analyze driving patterns, weather conditions, and traffic data to develop adaptive energy management systems.
Insufficient cybersecurity measures for VCU communication	Strong encryption methods and authentication procedures are needed to avoid emerging risks and weaknesses and protect VCU communication networks.
Limited adaptive steering control technology	Future research must focus on creating AI-based systems that use adaptive steering control, which modifies responsiveness and sensitivity to assess driving behavior and road conditions in real-time.
Limited accuracy in sensor fusion algorithms	More research is needed to improve sensor fusion algorithms, enable real-time data integration from many sensors, and increase sensor data interpretation and accuracy through machine learning techniques.
Inadequate thermal control in BCU components	By creating passive and active thermal management systems suited to the individual requirements of BCU components, researchers may investigate effective thermal insulation materials and cooling strategies to control temperatures within the BCU.

Focusing on the challenges mentioned above and working on possible solutions to these problems can open potential directions for future research to improve energy efficiency and ensure seamless integration of all control units. By directing research efforts toward refining control strategies and algorithms, researchers can contribute to EV systems' overall efficiency and safety, thus laying the groundwork for future advancements in this vital aspect of integrated ECUs.

Moreover, it would be beneficial to expand the analysis by contrasting the conventional control units in non-EVs to explore potential areas for research in EV control units. This comparative analysis may highlight important differences or similarities in the development processes, offering suggestions for future advances across disciplines. Furthermore, as this survey focuses on increasing energy efficiency, future studies may examine the relationship between electrical control units and sustainability. An in-depth understanding of the wider implications of EV control technology would be possible by considering environmental factors and investigating how the findings contribute to more environment-friendly electric mobility solutions.

IX. CONCLUSION

In this comprehensive study, we have examined and detailed the development strategies and algorithms of integrated Electronic Control Unit (ECU) and their crucial subsystems, including Vehicle Control Unit (VCU), Electrical Power Steering (EPS), Electronic Stability Control (ESC), and Body Control Unit (BCU). By thoroughly examining different development strategies and algorithms for each control unit, we have highlighted their importance in attaining efficient control in EVs, ultimately resulting in improved energy efficiency.

Our research has emphasized the paramount importance of an integrated ECU in optimizing the performance and efficiency of diverse vehicle systems. The integrated ECU enables energy management, refines vehicle dynamics, and significantly enhances overall energy efficiency by facilitating seamless communication and coordinated control actions across subsystems. A vital aspect of our research includes carefully examining sensors incorporated into every control module. Precise control decisions are greatly aided by these sensors, which record real-time data on acceleration, steering angle, yaw rate, battery state of charge, and ambient factors. By utilizing this data, the integrated ECU can optimize energy use and increase the efficiency of the vehicle by making well-informed modifications.

Additionally, our study has included a thorough review of the state-of-the-art control methods presented in recent research publications, providing a strong basis for our investigation and preparing for further research in this area. The knowledge gathered from this in-depth analysis offers researchers useful avenues to explore the field of EV control systems further, enabling continued progress in the hunt for more energy-efficient mobility solutions.

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Syed Shehryar Ali Naqvi and Faiza Qayyum contributed toward conceptualization, methodology, and software. Furthermore, Syed Shehryar Ali Naqvi, Harun Jamil, and Faiza Qayyum performed a formal analysis and prepared an original draft. Similarly, Naeem Iqbal, Murad Ali Khan, and Do-Hyeun Kim contributed toward data curation, visualization, and supervision. In addition, Salabat Khan reviewed and edited the original draft and validated and investigated the overall manuscript. The authors declared no conflict of interest regarding publishing the role of Evolving Electric Mobility: In-Depth Analysis of Integrated Electronic Control Unit Development in Electric Vehicles.

(Syed Shehryar Ali Naqvi, Harun Jamil, and Faiza Qayyum contributed equally to this work.)

REFERENCES

[1] IEA. (2023). *Global Ev Outlook 2023*. [Online]. Available: https://www.iea.org/reports/global-ev-outlook-2023

[2] M. Kumar, K. P. Panda, J. Moharana, R. Thakur, and G. Panda, ‘‘Hybrid energy source based BLDC motor drive for electric vehicle application,’’ in *Proc. 2nd Int. Conf. Innov. Technol. (INOCON)*, Mar. 2023, pp. 1–6.

[3] H. Hao, X. Cheng, Z. Liu, and F. Zhao, ‘‘Electric vehicles for greenhouse gas reduction in China: A cost-effectiveness analysis,’’ *Transp. Res. D, Transp. Environ.*, vol. 56, pp. 68–84, Oct. 2017.

[4] *International Energy Agency's Global Ev Data Explorer*. Accessed: Oct. 10, 2023. [Online]. Available: https://www.iea.org/data-and-statistics/data-product/global-ev-outlook-2023

[5] M. Bharathidasan, V. Indragandhi, V. Suresh, M. Jasiński, and Z. Leonowicz, ‘‘A review on electric vehicle: Technologies, energy trading, and cyber security,’’ *Energy Rep.*, vol. 8, pp. 9662–9685, Nov. 2022.

[6] Z. Liu, Y. Wu, and J. Feng, ‘‘Competition between battery switching and charging in electric vehicle: Considering anticipated regret,’’ *Environ., Develop. Sustainability*, pp. 1–22, Jul. 2023, doi: 10.1007/s10668-023-03592-4.

[7] S. S. G. Acharige, M. E. Haque, M. T. Arif, N. Hosseinzadeh, K. N. Hasan, and A. M. T. Oo, ‘‘Review of electric vehicle charging technologies, standards, architectures, and converter configurations,’’ *IEEE Access*, vol. 11, pp. 41218–41255, 2023.

[8] M. Kumar, K. P. Panda, R. T. Naayagi, R. Thakur, and G. Panda, ‘‘Comprehensive review of electric vehicle technology and its impacts: Detailed investigation of charging infrastructure, power management, and control techniques,’’ *Appl. Sci.*, vol. 13, no. 15, p. 8919, Aug. 2023.

[9] C. Min, Y. Pan, W. Dai, I. Kawsar, Z. Li, and G. Wang, ‘‘Trajectory optimization of an electric vehicle with minimum energy consumption using inverse dynamics model and servo constraints,’’ *Mechanism Mach. Theory*, vol. 181, Mar. 2023, Art. no. 105185.

[10] Y. An, Y. Gao, N. Wu, J. Zhu, H. Li, and J. Yang, ‘‘Optimal scheduling of electric vehicle charging operations considering real-time traffic condition and travel distance,’’ *Exp. Syst. Appl.*, vol. 213, Mar. 2023, Art. no. 118941.

[11] P. Barman, L. Dutta, S. Bordoloi, A. Kalita, P. Buragohain, S. Bharali, and B. Azzopardi, ‘‘Renewable energy integration with electric vehicle technology: A review of the existing smart charging approaches,’’ *Renew. Sustain. Energy Rev.*, vol. 183, Sep. 2023, Art. no. 113518.

[12] F. R. Salmasi, ‘‘Control strategies for hybrid electric vehicles: Evolution, classification, comparison, and future trends,’’ *IEEE Trans. Veh. Technol.*, vol. 56, no. 5, pp. 2393–2404, Sep. 2007.

[13] Z. Yao and H.-S. Yoon, ‘‘Mild hybrid electric vehicle powertrain control using offline–online hybrid deep reinforcement learning strategy,’’ *SAE Int. J. Electrified Vehicles*, vol. 12, no. 3, pp. 331–341, Jan. 2023.

[14] F. Millo, L. Rolando, L. Tresca, and L. Pulvirenti, ‘‘Development of a neural network-based energy management system for a plug-in hybrid electric vehicle,’’ *Transp. Eng.*, vol. 11, Mar. 2023, Art. no. 100156.

[15] Y. Tao, X. Xie, H. Zhao, W. Xu, and H. Chen, ‘‘A regenerative braking system for electric vehicle with four in-wheel motors based on fuzzy control,’’ in *Proc. 36th Chin. Control Conf. (CCC)*, Jul. 2017, pp. 4288–4293.

[16] K. Bayar, J. Wang, and G. Rizzoni, ‘‘Development of a vehicle stability control strategy for a hybrid electric vehicle equipped with axle motors,’’ *Proc. Inst. Mech. Engineers, D, J. Automobile Eng.*, vol. 226, no. 6, pp. 795–814, Jun. 2012.

[17] A. Ajanovic, ‘‘The future of electric vehicles: Prospects and impediments,’’ *Wiley Interdiscipl. Rev., Energy Environ.*, vol. 4, no. 6, pp. 521–536, 2015.

[18] W. Deng, Y. H. Lee, and A. Zhao, ‘‘Hardware-in-the-loop simulation for autonomous driving,’’ in *Proc. 34th Annu. Conf. IEEE Ind. Electron.*, Nov. 2008, pp. 1742–1747.

[19] Y. Zhu, H. Hu, G. Xu, and Z. Zhao, ‘‘Hardware-in-the-loop simulation of pure electric vehicle control system,’’ in *Proc. Int. Asia Conf. Informat. Control, Autom. Robot.*, Feb. 2009, pp. 254–258.

[20] R. A. Hanifah, S. F. Toha, S. Ahmad, and Mohd. K. Hassan, ‘‘Swarm-intelligence tuned current reduction for power-assisted steering control in electric vehicles,’’ *IEEE Trans. Ind. Electron.*, vol. 65, no. 9, pp. 7202–7210, Sep. 2018.

[21] L. Zhai, T. Sun, and J. Wang, ‘‘Electronic stability control based on motor driving and braking torque distribution for a four in-wheel motor drive electric vehicle,’’ *IEEE Trans. Veh. Technol.*, vol. 65, no. 6, pp. 4726–4739, Jun. 2016.

[22] X. Yang, Y. Lin, F. Gao, G. Wang, and Y. Zhang, ‘‘Automated test system design of body control module,’’ in *Proc. Int. Conf. Inf. Sci., Electron. Electr. Eng.*, vol. 3, Apr. 2014, pp. 1542–1546.

[23] K. Ç. Bayindir, M. A. Gözüküçük, and A. Teke, ‘‘A comprehensive overview of hybrid electric vehicle: Powertrain configurations, powertrain control techniques and electronic control units,’’ *Energy Convers. Manage.*, vol. 52, no. 2, pp. 1305–1313, Feb. 2011.

[24] J. Xu, X. Zhang, S. H. Park, and K. Guo, ‘‘The alleviation of perceptual blindness during driving in urban areas guided by saccades recommendation,’’ *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 9, pp. 16386–16396, Sep. 2022.

[25] C. Liu, K. T. Chau, C. H. T. Lee, and Z. Song, ‘‘A critical review of advanced electric machines and control strategies for electric vehicles,’’ *Proc. IEEE*, vol. 109, no. 6, pp. 1004–1028, Jun. 2021.

[26] R. Khan, K. K. Mehmood, S. B. A. Bukhari, K. Imran, A. Wadood, S. B. Rhee, and S. Park, ‘‘An optimization-based reliability enhancement scheme for active distribution systems utilizing electric vehicles,’’ *IEEE Access*, vol. 9, pp. 157247–157258, 2021.

[27] L. Zhang, C. Sun, G. Cai, and L. H. Koh, ‘‘Charging and discharging optimization strategy for electric vehicles considering elasticity demand response,’’ *eTransportation*, vol. 18, Oct. 2023, Art. no. 100262.

[28] X. Zhao, Y. Fang, H. Min, X. Wu, W. Wang, and R. Teixeira, ‘‘Potential sources of sensor data anomalies for autonomous vehicles: An overview from road vehicle safety perspective,’’ *Exp. Syst. Appl.*, vol. 236, Feb. 2024, Art. no. 121358.

[29] T. S. Haque, Md. H. Rahman, Md. R. Islam, Md. A. Razzak, F. R. Badal, Md. H. Ahamed, S. I. Moyeen, S. K. Das, M. F. Ali, Z. Tasneem, D. K. Saha, R. K. Chakrabortty, and M. Ryan, ‘‘A review on driving control issues for smart electric vehicles,’’ *IEEE Access*, vol. 9, pp. 135440–135472, 2021.

[30] P. Dong, J. Zhao, X. Liu, J. Wu, X. Xu, Y. Liu, S. Wang, and W. Guo, ‘‘Practical application of energy management strategy for hybrid electric vehicles based on intelligent and connected technologies: Development stages, challenges, and future trends,’’ *Renew. Sustain. Energy Rev.*, vol. 170, Dec. 2022, Art. no. 112947.

[31] A. A. Malikopoulos, ‘‘Supervisory power management control algorithms for hybrid electric vehicles: A survey,’’ *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 5, pp. 1869–1885, Oct. 2014.

[32] F. Schmalfuß, K. Mühl, and J. F. Krems, ‘‘Direct experience with battery electric vehicles (BEVs) matters when evaluating vehicle attributes, attitude and purchase intention,’’ *Transp. Res. F, Traffic Psychol. Behaviour*, vol. 46, pp. 47–69, Apr. 2017.

[33] C. Shen, P. Shan, and T. Gao, ‘‘A comprehensive overview of hybrid electric vehicles,’’ *Int. J. Veh. Technol.*, vol. 2011, pp. 1–7, Nov. 2011.

[34] A. Zia, ‘‘A comprehensive overview on the architecture of hybrid electric vehicles (HEV),’’ in *Proc. 19th Int. Multi-Topic Conf. (INMIC)*, Dec. 2016, pp. 1–7.

[35] L. Sun, J. Liang, C. Zhang, D. Wu, and Y. Zhang, ‘‘Meta-transfer metric learning for time series classification in 6G-supported intelligent transportation systems,’’ *IEEE Trans. Intell. Transp. Syst.*, pp. 1–11, Mar. 2023, doi: 10.1109/TITS.2023.3250962.

[36] S. Amjad, S. Neelakrishnan, and R. Rudramoorthy, ‘‘Review of design considerations and technological challenges for successful development and deployment of plug-in hybrid electric vehicles,’’ *Renew. Sustain. Energy Rev.*, vol. 14, no. 3, pp. 1104–1110, Apr. 2010.

[37] M. Muthukumar, N. Rengarajan, B. Velliyangiri, M. A. Omprakas, C. B. Rohit, and U. K. Raja, ‘‘The development of fuel cell electric vehicles—A review,’’ *Mater. Today, Proc.*, vol. 45, no. 2, pp. 1181–1187, 2021.

[38] M. Inci, M. Büyük, M. H. Demir, and G. Ilbey, ‘‘A review and research on fuel cell electric vehicles: Topologies, power electronic converters, energy management methods, technical challenges, marketing and future aspects,’’ *Renew. Sustain. Energy Rev.*, vol. 137, Mar. 2021, Art. no. 110648.

[39] I. Nagy, ‘‘Hierarchical mapping of an electric vehicle sensor and control network,’’ *Acta Polytechnica Hungarica*, vol. 18, no. 9, pp. 161–180, 2021.

[40] H. Min, Y. Fang, X. Wu, X. Lei, S. Chen, R. Teixeira, B. Zhu, X. Zhao, and Z. Xu, ‘‘A fault diagnosis framework for autonomous vehicles with sensor self-diagnosis,’’ *Exp. Syst. Appl.*, vol. 224, Aug. 2023, Art. no. 120002.

[41] C. Ding, C. Li, Z. Xiong, Z. Li, and Q. Liang, ‘‘Intelligent identification of moving trajectory of autonomous vehicle based on friction nano-generator,’’ *IEEE Trans. Intell. Transp. Syst.*, pp. 1–8, Aug. 2023, doi: 10.1109/TITS.2023.3303267.

[42] M. Vafaeipour, M. El Baghdadi, F. Verbelen, P. Sergeant, J. Van Mierlo, and O. Hegazy, "Experimental implementation of power-split control strategies in a versatile hardware-in-the-loop laboratory test bench for hybrid electric vehicles equipped with electrical variable transmission," *Appl. Sci.*, vol. 10, no. 12, p. 4253, Jun. 2020.

[43] J. Xu, S. Pan, P. Z. H. Sun, S. Hyeong Park, and K. Guo, "Human-factors-in-driving-loop: Driver identification and verification via a deep learning approach using psychological behavioral data," *IEEE Trans. Intell. Transp. Syst.*, vol. 24, no. 3, pp. 3383–3394, Mar. 2023.

[44] B. Cao, W. Zhang, X. Wang, J. Zhao, Y. Gu, and Y. Zhang, "A memetic algorithm based on two_Arch2 for multi-depot heterogeneous-vehicle capacitated arc routing problem," *Swarm Evol. Comput.*, vol. 63, Jun. 2021, Art. no. 100864.

[45] G. Balan, S. Arumugam, S. Muthusamy, H. Panchal, H. Kotb, M. Bajaj, S. S. M. Ghoneim, and Kitmo, "An improved deep learning-based technique for driver detection and driver assistance in electric vehicles with better performance," *Int. Trans. Electr. Energy Syst.*, vol. 2022, pp. 1–16, Nov. 2022.

[46] D. Gehringer, T. Kuthada, and A. Wagner, "Thermal management system of the UNICARagil vehicles—A comprehensive overview," *World Electric Vehicle J.*, vol. 14, no. 1, p. 6, Dec. 2022.

[47] P. K. Maroti, S. Padmanaban, M. S. Bhaskar, V. K. Ramachandaramurthy, and F. Blaabjerg, "The state-of-the-art of power electronics converters configurations in electric vehicle technologies," *Power Electron. Devices Compon.*, vol. 1, Mar. 2022, Art. no. 100001.

[48] A. Yildiz and M. A. Özel, "A comparative study of energy consumption and recovery of autonomous fuel-cell hydrogen–electric vehicles using different powertrains based on regenerative braking and electronic stability control system," *Appl. Sci.*, vol. 11, no. 6, p. 2515, Mar. 2021.

[49] A. Norouzi, H. Heidarifar, H. Borhan, M. Shahbakhti, and C. R. Koch, "Integrating machine learning and model predictive control for automotive applications: A review and future directions," *Eng. Appl. Artif. Intell.*, vol. 120, Apr. 2023, Art. no. 105878.

[50] W. A. Ali, M. P. Fanti, M. Roccotelli, and L. Ranieri, "A review of digital twin technology for electric and autonomous vehicles," *Appl. Sci.*, vol. 13, no. 10, p. 5871, May 2023.

[51] M. S. Kumar, A. T. Y. Srinivas, and S. Aurelia, "Simulation of the electrical control unit (ECU) in automated electric vehicles for reliability and safety using on-board sensors and Internet of Things," in *Proc. 5th Int. Conf. Electr., Comput. Commun. Technol. (ICECCT)*, Feb. 2023, pp. 1–5.

[52] I. S. Bangroo, "AI-based predictive analytic approaches for safeguarding the future of electric/hybrid vehicles," 2023, *arXiv:2304.13841*.

[53] R. Canal, F. K. Riffel, and G. Gracioli, "Driving profile analysis using machine learning techniques and ECU data," in *Proc. IEEE 32nd Int. Symp. Ind. Electron. (ISIE)*, Jun. 2023, pp. 1–6.

[54] A. Broatch, P. Olmeda, B. Plá, A. Dreif, A. Onorati, and A. Marinoni, "Numerical assessment of integrated thermal management systems in electrified powertrains," *Appl. Thermal Eng.*, vol. 221, Feb. 2023, Art. no. 119822.

[55] W. Gong, C. Liu, X. Zhao, and S. Xu, "A model review for controller-hardware-in-the-loop simulation in EV powertrain application," *IEEE Trans. Transport. Electrific.*, early access, Jul. 7, 2023, doi: 10.1109/TTE.2023.3290999.

[56] Q. Chengqun, X. Wan, N. Wang, S. Cao, X. Ji, K. Wu, Y. Hu, and M. Meng, "A novel regenerative braking energy recuperation system for electric vehicles based on driving style," *Energy*, vol. 283, Nov. 2023, Art. no. 129055.

[57] D. Cui, Z. Wang, P. Liu, S. Wang, Z. Zhang, D. G. Dorrell, and X. Li, "Battery electric vehicle usage pattern analysis driven by massive real-world data," *Energy*, vol. 250, Jul. 2022, Art. no. 123837.

[58] H. Wang, T. Sun, X. Zhou, and Q. Fan, "Research on the electric vehicle control system," *Int. J. u-and e-Service, Sci. Technol.*, vol. 8, no. 8, pp. 103–110, 2015.

[59] Y. Zhang, W. Wang, C. Xiang, C. Yang, H. Peng, and C. Wei, "A swarm intelligence-based predictive regenerative braking control strategy for hybrid electric vehicle," *Vehicle Syst. Dyn.*, vol. 60, no. 3, pp. 973–997, Mar. 2022.

[60] H. Wu, H. Zhang, V. Motevalli, Y. Qian, and A. Wolfe, "Hybrid electric vehicle powertrain controller development using hardware in the loop simulation," SAE, Warrendale, PA, USA, Tech. Rep. 2013-01-0156, 2013, doi: 10.4271/2013-01-0156.

[61] D. Li, H. Yu, K. P. Tee, Y. Wu, S. S. Ge, and T. H. Lee, "On time-synchronized stability and control," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 52, no. 4, pp. 2450–2463, Apr. 2022.

[62] G. Zhao, X. Wang, M. Negnevitsky, and H. Zhang, "A review of air-cooling battery thermal management systems for electric and hybrid electric vehicles," *J. Power Sources*, vol. 501, Jul. 2021, Art. no. 230001.

[63] C. Qiu and G. Wang, "New evaluation methodology of regenerative braking contribution to energy efficiency improvement of electric vehicles," *Energy Convers. Manage.*, vol. 119, pp. 389–398, Jul. 2016.

[64] O. Vermesan, M. Sans, P. Hank, G. Farrall, J. Packer, N. Cesario, H. Gall, L.-C. Blystad, M. Sciolla, and A. Harrar, "Advanced electronic architecture design for next electric vehicle generation," in *Electric Vehicle Systems Architecture and Standardization Needs: Reports of the PPP European Green Vehicles Initiative*. Cham, Switzerland: Springer, 2015, pp. 117–141.

[65] K. Kwon, M. Seo, and S. Min, "Multi-objective optimization of powertrain components for electric vehicles using a two-stage analysis model," *Int. J. Automot. Technol.*, vol. 21, no. 6, pp. 1495–1505, Dec. 2020.

[66] Y. Xiao, Y. Zhang, I. Kaku, R. Kang, and X. Pan, "Electric vehicle routing problem: A systematic review and a new comprehensive model with nonlinear energy recharging and consumption," *Renew. Sustain. Energy Rev.*, vol. 151, Nov. 2021, Art. no. 111567.

[67] J. Xu, K. Guo, X. Zhang, and P. Z. H. Sun, "Left gaze bias between LHT and RHT: A recommendation strategy to mitigate human errors in left- and right-hand driving," *IEEE Trans. Intell. Vehicles*, vol. 8, no. 10, pp. 4406–4417, Oct. 2023.

[68] Y. Fu, C. Li, F. R. Yu, T. H. Luan, and P. Zhao, "An incentive mechanism of incorporating supervision game for federated learning in autonomous driving," *IEEE Trans. Intell. Transp. Syst.*, vol. 24, no. 12, pp. 14800–14812, Dec. 2023.

[69] N. Lei, H. Zhang, H. Wang, and Z. Wang, "An improved co-optimization of component sizing and energy management for hybrid powertrains interacting with high-fidelity model," *IEEE Trans. Veh. Technol.*, vol. 72, no. 12, pp. 15585–15596, Dec. 2023.

[70] S. Gao, J. Wang, C. Guan, Z. Zhou, and Z. Liu, "Wheel torque distribution control strategy for electric vehicles dynamic performance with an electric torque vectoring drive-axle," *IEEE Trans. Transport. Electrific.*, early access, Apr. 17, 2023, doi: 10.1109/TTE.2023.3267817.

[71] Z. Yunzheng, Q. Shaofei, A. C. Huang, and X. Jianhong, "Smart vehicle control unit—An integrated BMS and VCU system," *IFAC-PapersOnLine*, vol. 51, no. 31, pp. 676–679, 2018.

[72] L. Zhang, Q. Yin, W. Zhu, L. Lyu, L. Jiang, L. H. Koh, and G. Cai, "Research on the orderly charging and discharging mechanism of electric vehicles considering travel characteristics and carbon quota," *IEEE Trans. Transport. Electrific.*, early access, Jul. 19, 2023, doi: 10.1109/TTE.2023.3296964.

[73] M. K. Yoong, Y. H. Gan, G. D. Gan, C. K. Leong, Z. Y. Phuan, B. K. Cheah, and K. W. Chew, "Studies of regenerative braking in electric vehicle," in *Proc. IEEE Conf. Sustain. Utilization Develop. Eng. Technol.*, Nov. 2010, pp. 40–45.

[74] J. Ma, Y. Sun, S. Zhang, J. Li, and S. Li, "Experimental study on the performance of vehicle integrated thermal management system for pure electric vehicles," *Energy Convers. Manage.*, vol. 253, Feb. 2022, Art. no. 115183.

[75] D. Baidya, S. Dhopte, and M. Bhattacharjee, "Sensing system assisted novel PID controller for efficient speed control of DC motors in electric vehicles," *IEEE Sensors Lett.*, vol. 7, no. 1, pp. 1–4, Jan. 2023.

[76] C. Guo and J. Hu, "Fixed-time stabilization of high-order uncertain nonlinear systems: Output feedback control design and settling time analysis," *J. Syst. Sci. Complex.*, vol. 36, no. 4, pp. 1351–1372, Aug. 2023.

[77] X. Huang and J. Wang, "Model predictive regenerative braking control for lightweight electric vehicles with in-wheel motors," *Proc. Inst. Mech. Engineers, D, J. Automobile Eng.*, vol. 226, no. 9, pp. 1220–1232, Sep. 2012.

[78] W. Xu, H. Chen, H. Zhao, and B. Ren, "Torque optimization control for electric vehicles with four in-wheel motors equipped with regenerative braking system," *Mechatronics*, vol. 57, pp. 95–108, Feb. 2019.

[79] X. Yang, X. Wang, S. Wang, K. Wang, and M. B. Sial, "Finite-time adaptive dynamic surface synchronization control for dual-motor servo systems with backlash and time-varying uncertainties," *ISA Trans.* vol. 137, pp. 248–262, Jun. 2023.

[80] M. Aktas, K. Awaili, M. Ehsani, and A. Arisoy, "Direct torque control versus indirect field-oriented control of induction motors for electric vehicle applications," *Eng. Sci. Technol., Int. J.*, vol. 23, no. 5, pp. 1134–1143, Oct. 2020.
[81] B. Gasbaoui, A. Chaker, A. Laoufi, B. Allaoua, and A. Nasri, "The efficiency of direct torque control for electric vehicle behavior improvement," *Serbian J. Electr. Eng.*, vol. 8, no. 2, pp. 127–146, 2011.
[82] P. S. Rekha, M. Kumar, G. Panda, and T. Vijayakumar, "Switched reluctance motor drive control for electric vehicle application," in *Proc. Int. Symp. Sustain. Energy Technological Advancements*. Singapore: Springer, 2023, pp. 445–458.
[83] X. Zhang, Z. Lu, X. Yuan, Y. Wang, and X. Shen, "L2-gain adaptive robust control for hybrid energy storage system in electric vehicles," *IEEE Trans. Power Electron.*, vol. 36, no. 6, pp. 7319–7332, Jun. 2021.
[84] S. Geraee, H. Mohammadbagherpoor, M. Shafiei, M. Valizadeh, F. Montazeri, and M. R. Feyzi, "Regenerative braking of electric vehicle using a modified direct torque control and adaptive control theory," *Comput. Electr. Eng.*, vol. 69, pp. 85–97, Jul. 2018.
[85] X. Zhang, W. Pan, R. Scattolini, S. Yu, and X. Xu, "Robust tube-based model predictive control with Koopman operators," *Automatica*, vol. 137, Mar. 2022, Art. no. 110114.
[86] W. Kim, C. Kang, Y.-S. Son, and C. Chung, "Nonlinear steering wheel angle control using self-aligning torque with torque and angle sensors for electrical power steering of lateral control system in autonomous vehicles," *Sensors*, vol. 18, no. 12, p. 4384, Dec. 2018.
[87] A. Marouf, M. Djemai, C. Sentouh, and P. Pudlo, "A new control strategy of an electric-power-assisted steering system," *IEEE Trans. Veh. Technol.*, vol. 61, no. 8, pp. 3574–3589, Oct. 2012.
[88] X. He, Y. Liu, C. Lv, X. Ji, and Y. Liu, "Emergency steering control of autonomous vehicle for collision avoidance and stabilisation," *Vehicle Syst. Dyn.*, vol. 57, no. 8, pp. 1163–1187, Aug. 2019.
[89] W. Kim, Y. S. Son, and C. C. Chung, "Torque-overlay-based robust steering wheel angle control of electrical power steering for a lane-keeping system of automated vehicles," *IEEE Trans. Veh. Technol.*, vol. 65, no. 6, pp. 4379–4392, Jun. 2016.
[90] M. E. Sulistyo, R. Ristiana, S. Kaleg, A. Hapid, Sudirja, A. Muharam, A. C. Budiman, A. Q. Jaelani, and Amin, "A comparison of hydraulic and electro-hydraulic power steering control systems for increasing energy efficiency," *Evergreen*, vol. 10, no. 3, pp. 1951–1960, 2023.
[91] S.-M. Lu, "A review of high-efficiency motors: Specification, policy, and technology," *Renew. Sustain. Energy Rev.*, vol. 59, pp. 1–12, Jun. 2016.
[92] J. Choi, D. Kim, J. S. Eo, K. Nam, Z. Wang, J. Wang, and S. Oh, "Coordinated steering angle and yaw moment distribution to increase vehicle regenerative energy in autonomous driving," in *Proc. IEEE 25th Int. Conf. Intell. Transp. Syst. (ITSC)*, Oct. 2022, pp. 3083–3088.
[93] N. Minoiu Enache, S. Mammar, M. Netto, and B. Lusetti, "Driver steering assistance for lane-departure avoidance based on hybrid automata and composite Lyapunov function," *IEEE Trans. Intell. Transp. Syst.*, vol. 11, no. 1, pp. 28–39, Mar. 2010.
[94] C. M. Kang, W. Kim, and H. Baek, "Cascade backstepping control with augmented observer for lateral control of vehicle," *IEEE Access*, vol. 9, pp. 45367–45376, 2021.
[95] Y. Gao, C. Jiang, D. Yu, and M. Ahmad, "A novel electric differential and synchronization control method for 4WD/4WS electric vehicles based on fictitious master," *Energy*, vol. 274, Jul. 2023, Art. no. 127292.
[96] A. Abdelkefi, A. Souissi, I. Abdennadher, and A. Masmoudi, "On the analysis and torque enhancement of flux-switching permanent magnet machines in electric power steering systems," *World Electric Vehicle J.*, vol. 13, no. 4, p. 64, Apr. 2022.
[97] G. Lee, J. Song, J. Han, Y. Lim, and S. Park, "Study on energy consumption characteristics of passenger electric vehicle according to the regenerative braking stages during real-world driving conditions," *Energy*, vol. 283, Nov. 2023, Art. no. 128745.
[98] L. Chen, K. Yuan, S. Chen, Y. Huang, H. Askari, N. Yu, J. Mo, N. Xu, M. Wu, H. Chen, A. Khajepour, and Z. Wang, "Triboelectric nanogenerator sensors for intelligent steering wheel aiming at automated driving," *Nano Energy*, vol. 113, Aug. 2023, Art. no. 108575.
[99] K. Nam, S. Oh, H. Fujimoto, and Y. Hori, "Robust yaw stability control for electric vehicles based on active front steering control through a steer-by-wire system," *Int. J. Automot. Technol.*, vol. 13, no. 7, pp. 1169–1176, Dec. 2012.
[100] J. Wang, X. Wang, Z. Luo, and F. Assadian, "Active disturbance rejection control of differential drive assist steering for electric vehicles," *Energies*, vol. 13, no. 10, p. 2647, May 2020.
[101] J. Wang, Q. Wang, L. Jin, and C. Song, "Independent wheel torque control of 4WD electric vehicle for differential drive assisted steering," *Mechatronics*, vol. 21, no. 1, pp. 63–76, Feb. 2011.
[102] X. Guo, Y. Chen, and H. Li, "Research on steering stability control of electric vehicle driven by dual in-wheel motor," in *Proc. 10th Inst. Electr. Electron. Engineers Int. Conf. Cyber Technol. Autom., Control, Intell. Syst. (CYBER)*, Oct. 2020, pp. 394–399.
[103] J. Wang, H. Wang, C. Jiang, Z. Cao, Z. Man, and L. Chen, "Steering feel design for steer-by-wire system on electric vehicles," in *Proc. Chin. Control Conf. (CCC)*, Jul. 2019, pp. 533–538.
[104] J. Choi, K. Yi, J. Suh, and B. Ko, "Coordinated control of motor-driven power steering torque overlay and differential braking for emergency driving support," *IEEE Trans. Veh. Technol.*, vol. 63, no. 2, pp. 566–579, Feb. 2014.
[105] K. Nam, H. Fujimoto, and Y. Hori, "Advanced motion control of electric vehicles based on robust lateral tire force control via active front steering," *IEEE/ASME Trans. Mechatronics*, vol. 19, no. 1, pp. 289–299, Feb. 2014.
[106] P.-P. Du, H. Su, and G.-Y. Tang, "Active return-to-center control based on torque and angle sensors for electric power steering systems," *Sensors*, vol. 18, no. 3, p. 855, Mar. 2018.
[107] Z. Li, S. Shi, and C. Zhang, "Active return control strategy of electric power steering system based on disturbance observer," *J. Eng. Sci. Technol. Rev.*, vol. 11, no. 3, pp. 61–69, Apr. 2018.
[108] P. V. Kulkarni, S. Iqbal, S. Salunkhe, N. Joshi, and N. Shabadi, "Optimized variable gear ratio steering system with reduced EPAS motor size achieving performance targets," SAE, Warrendale, PA, USA, Tech. Rep. 2022-01-0874, 2022, doi: 10.4271/2022-01-0874.
[109] P. Zhai, H. Du, and Z. Li, "Bilateral control of vehicle steer-by-wire system with variable gear-ratio," in *Proc. IEEE 8th Conf. Ind. Electron. Appl. (ICIEA)*, Jun. 2013, pp. 811–815.
[110] Z. He and M. Gu, "Dynamic research on control strategy of electric power steering system," SAE, Warrendale, PA, USA, Tech. Rep. 2012-01-0212, 2012, doi: 10.4271/2012-01-0212.
[111] W. Han, A. Li, X. Huang, W. Li, J. Cao, and H. Bu, "Trajectory tracking of in-wheel motor electric vehicles based on preview time adaptive and torque difference control," *Adv. Mech. Eng.*, vol. 14, no. 4, Apr. 2022, Art. no. 168781322210899.
[112] M. Reze and M. Osajda, "MEMS sensors for automotive vehicle stability control applications," in *MEMS for Automotive and Aerospace Applications*. Amsterdam, The Netherlands: Elsevier, 2013, pp. 29–53.
[113] D. Paul and T. H. Kim, "On the feasibility of the optical steering wheel sensor: Modeling and control," *Int. J. Automot. Technol.*, vol. 12, no. 5, pp. 661–669, Oct. 2011.
[114] M. Gözü, B. Ozkan, and M. T. Emirler, "Disturbance observer based active independent front steering control for improving vehicle yaw stability and tire utilization," *Int. J. Automot. Technol.*, vol. 23, no. 3, pp. 841–854, Jun. 2022.
[115] Z. Xiao, J. Shu, H. Jiang, G. Min, J. Liang, and A. Iyengar, "Toward collaborative occlusion-free perception in connected autonomous vehicles," *IEEE Trans. Mobile Comput.*, early access, Jul. 25, 2023, doi: 10.1109/TMC.2023.3298643.
[116] M. Ahmed, Y. Zheng, A. Amine, H. Fathiannasab, and Z. Chen, "The role of artificial intelligence in the mass adoption of electric vehicles," *Joule*, vol. 5, no. 9, pp. 2296–2322, Sep. 2021.
[117] Y. E. Papelis, G. S. Watson, and T. L. Brown, "An empirical study of the effectiveness of electronic stability control system in reducing loss of vehicle control," *Accident Anal. Prevention*, vol. 42, no. 3, pp. 929–934, May 2010.
[118] H. Dong, W. Zhuang, B. Chen, Y. Lu, S. Liu, L. Xu, D. Pi, and G. Yin, "Predictive energy-efficient driving strategy design of connected electric vehicle among multiple signalized intersections," *Transp. Res. C, Emerg. Technol.*, vol. 137, Apr. 2022, Art. no. 103595.
[119] V. Mali, R. Saxena, K. Kumar, A. Kalam, and B. Tripathi, "Review on battery thermal management systems for energy-efficient electric vehicles," *Renew. Sustain. Energy Rev.*, vol. 151, Nov. 2021, Art. no. 111611.
[120] F. A. Butt, J. N. Chattha, J. Ahmad, M. U. Zia, M. Rizwan, and I. H. Naqvi, "On the integration of enabling wireless technologies and sensor fusion for next-generation connected and autonomous vehicles," *IEEE Access*, vol. 10, pp. 14643–14668, 2022.
[121] H. Wei, N. Zhang, J. Liang, Q. Ai, W. Zhao, T. Huang, and Y. Zhang, "Deep reinforcement learning based direct torque control strategy for distributed drive electric vehicles considering active safety and energy saving performance," *Energy*, vol. 238, Jan. 2022, Art. no. 121725.

[122] R. Youssef, M. S. Hosen, J. He, M. AL-Saadi, J. Van Mierlo, and M. Berecibar, "Novel design optimization for passive cooling PCM assisted battery thermal management system in electric vehicles," *Case Stud. Thermal Eng.*, vol. 32, Apr. 2022, Art. no. 101896.

[123] A. V. Malawade, T. Mortlock, and M. A. A. Faruque, "EcoFusion: Energy-aware adaptive sensor fusion for efficient autonomous vehicle perception," in *Proc. 59th ACM/IEEE Design Autom. Conf.*, Jul. 2022, pp. 481–486.

[124] B.-C. Chen and C.-C. Kuo, "Electronic stability control for electric vehicle with four in-wheel motors," *Int. J. Automot. Technol.*, vol. 15, no. 4, pp. 573–580, Jun. 2014.

[125] H. Liu, L. Zhang, P. Wang, and H. Chen, "A real-time NMPC strategy for electric vehicle stability improvement combining torque vectoring with rear-wheel steering," *IEEE Trans. Transport. Electrific.*, vol. 8, no. 3, pp. 3825–3835, Sep. 2022.

[126] M. Jalali, A. Khajepour, S.-K. Chen, and B. Litkouhi, "Integrated stability and traction control for electric vehicles using model predictive control," *Control Eng. Pract.*, vol. 54, pp. 256–266, Sep. 2016.

[127] K. Kawashima, Y. Hori, T. Uchida, and S. Oh, "Robust bank angle estimation for rolling stability control on electric vehicle," in *Proc. 11th IEEE Int. Workshop Adv. Motion Control (AMC)*, Mar. 2010, pp. 448–453.

[128] Z. Feng, Z. Hong-Liang, and W. Tong, "Research on hill-start control of pure electric vehicle," in *Proc. 3rd Int. Conf. Mechanic Autom. Control Eng.*, 2012, pp. 3141–3144.

[129] A. Dadashnialehi, A. Bab-Hadiashar, Z. Cao, and A. Kapoor, "Intelligent sensorless ABS for in-wheel electric vehicles," *IEEE Trans. Ind. Electron.*, vol. 61, no. 4, pp. 1957–1969, Apr. 2014.

[130] F. Song, Y. Liu, D. Shen, L. Li, and J. Tan, "Learning control for motion coordination in wafer scanners: Toward gain adaptation," *IEEE Trans. Ind. Electron.*, vol. 69, no. 12, pp. 13428–13438, Dec. 2022.

[131] S. Zhu, X. Fan, G. Qi, and P. Wang, "Review of control algorithms of vehicle anti-lock braking system," *Recent Patents Eng.*, vol. 17, no. 2, pp. 30–45, Mar. 2023.

[132] D. Tavernini, M. Metzler, P. Gruber, and A. Sorniotti, "Explicit nonlinear model predictive control for electric vehicle traction control," *IEEE Trans. Control Syst. Technol.*, vol. 27, no. 4, pp. 1438–1451, Jul. 2019.

[133] K. Kawashima, T. Uchida, and Y. Hori, "Rolling stability control of in-wheel electric vehicle based on two-degree-of-freedom control," in *Proc. 10th IEEE Int. Workshop Adv. Motion Control*, Mar. 2008, pp. 751–756.

[134] K. Kawashima, T. Uchida, and Y. Hori, "Rolling stability control based on electronic stability program for in-wheel-motor electric vehicle," *World Electric Vehicle J.*, vol. 3, no. 1, pp. 34–41, Mar. 2009.

[135] L. Wu, H. Wang, D. Pi, E. Wang, and X. Wang, "Hill-start of distributed drive electric vehicle based on pneumatic electronic parking brake system," *IEEE Access*, vol. 8, pp. 64382–64398, 2020.

[136] L. I. Farfan-Cabrera, "Tribology of electric vehicles: A review of critical components, current state and future improvement trends," *Tribology Int.*, vol. 138, pp. 473–486, Oct. 2019.

[137] K. P. Srinivasan, T. Muthuramalingam, and A. H. Elsheikh, "A review of flexible printed sensors for automotive infotainment systems," *Arch. Civil Mech. Eng.*, vol. 23, no. 1, p. 67, Jan. 2023.

[138] G. Seenumani, J. Sun, and H. Peng, "Real-time power management of integrated power systems in all electric ships leveraging multi time scale property," *IEEE Trans. Control Syst. Technol.*, vol. 20, no. 1, pp. 232–240, Jan. 2012.

[139] Z. Dimitrova and F. Maréchal, "Environomic design of vehicle integrated energy system—Application on a hybrid electric vehicle energy system," in *Proc. 17th Conf. Process Integr., Model. Optim. Energy Saving Pollut. Reduction*. Milan, Italy: Aidic Servizi Srl, vol. 39, 2014, pp. 475–480.

[140] Y. Al-Wreikat, C. Serrano, and J. R. Sodré, "Effects of ambient temperature and trip characteristics on the energy consumption of an electric vehicle," *Energy*, vol. 238, Jan. 2022, Art. no. 122028.

[141] I. Cvok and J. Deur, "Nonlinear model predictive control of electric vehicle cabin cooling system for improved thermal comfort and efficiency," in *Proc. Eur. Control Conf. (ECC)*, Jul. 2022, pp. 1759–1764.

[142] Y. Wang, Y. Wu, Y. Tang, Q. Li, and H. He, "Cooperative energy management and eco-driving of plug-in hybrid electric vehicle via multi-agent reinforcement learning," *Appl. Energy*, vol. 332, Feb. 2023, Art. no. 120563.

[143] I. Kavalchuk, H. Arisoy, A. Stojcevski, and A. M. T. Oo, "Advanced simulation of power consumption of electric vehicles," *Int. J. Comput. Syst. Eng.*, vol. 9, no. 1, pp. 53–59, 2015.

[144] D. Rong, B. Yang, and C. Chen, "Model predictive climate control of electric vehicles for improved battery lifetime," in *Proc. Chin. Autom. Congr. (CAC)*, Nov. 2019, pp. 5457–5462.

[145] J. Xu, S. H. Park, X. Zhang, and J. Hu, "The improvement of road driving safety guided by visual inattentional blindness," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 6, pp. 4972–4981, Jun. 2022.

[146] K. Li, L. Ji, S. Yang, H. Li, and X. Liao, "Couple-group consensus of cooperative–competitive heterogeneous multiagent systems: A fully distributed event-triggered and pinning control method," *IEEE Trans. Cybern.*, vol. 52, no. 6, pp. 4907–4915, Jun. 2022.

[147] Y. Xu, Y. Li, and C. Li, "Electric window regulator based on intelligent control," *J. Artif. Intell. Technol.*, pp. 198–206, Sep. 2021.

[148] K. Vatanparvar and M. A. Al Faruque, "Battery lifetime-aware automotive climate control for electric vehicles," in *Proc. 52nd ACM/EDAC/IEEE Design Autom. Conf. (DAC)*, Jun. 2015, pp. 1–6.

[149] O. P. Adeleke, Y. Li, Q. Chen, W. Zhou, X. Xu, and X. Cui, "Torque distribution based on dynamic programming algorithm for four in-wheel motor drive electric vehicle considering energy efficiency optimization," *World Electric Vehicle J.*, vol. 13, no. 10, p. 181, Sep. 2022.

[150] H. Lee, K. Kim, N. Kim, and S. W. Cha, "Energy efficient speed planning of electric vehicles for car-following scenario using model-based reinforcement learning," *Appl. Energy*, vol. 313, May 2022, Art. no. 118460.

[151] W. Pei, Q. Zhang, and Y. Li, "Efficiency optimization strategy of permanent magnet synchronous motor for electric vehicles based on energy balance," *Symmetry*, vol. 14, no. 1, p. 164, Jan. 2022.

[152] X. Zhang, Z. Wang, and Z. Lu, "Multi-objective load dispatch for microgrid with electric vehicles using modified gravitational search and particle swarm optimization algorithm," *Appl. Energy*, vol. 306, Jan. 2022, Art. no. 118018.

[153] A. Mehbodniya, P. Kumar, X. Changqing, J. L. Webber, U. Mamodiya, A. Halifa, and C. Srinivasulu, "Hybrid optimization approach for energy control in electric vehicle controller for regulation of three-phase induction motors," *Math. Problems Eng.*, vol. 2022, pp. 1–13, Feb. 2022.

[154] J. Xu, Z. Li, L. Gao, J. Ma, Q. Liu, and Y. Zhao, "A comparative study of deep reinforcement learning-based transferable energy management strategies for hybrid electric vehicles," in *Proc. IEEE Intell. Vehicles Symp. (IV)*, Jun. 2022, pp. 470–477.

[155] Y. Zhang and L. Tong, "Regenerative braking-based hierarchical model predictive cabin thermal management for battery life extension of autonomous electric vehicles," *J. Energy Storage*, vol. 52, Aug. 2022, Art. no. 104662.

[156] C. Satzger and R. de Castro, "Predictive brake control for electric vehicles," *IEEE Trans. Veh. Technol.*, vol. 67, no. 2, pp. 977–990, Feb. 2018.

[157] J. Chen, J. Yu, K. Zhang, and Y. Ma, "Control of regenerative braking systems for four-wheel-independently-actuated electric vehicles," *Mechatronics*, vol. 50, pp. 394–401, Apr. 2018.

[158] V. Kousalya, R. Rai, and B. Singh, "Predictive torque control of induction motor for electric vehicle," in *Proc. IEEE Transp. Electrific. Conf. Expo (ITEC)*, Jun. 2020, pp. 890–895.

[159] E. Zerdali and R. Demir, "Speed-sensorless predictive torque controlled induction motor drive with feed-forward control of load torque for electric vehicle applications," *TURKISH J. Electr. Eng. Comput. Sci.*, vol. 29, no. 1, pp. 223–240, Jan. 2021.

[160] M. Vajedi and N. L. Azad, "Ecological adaptive cruise controller for plug-in hybrid electric vehicles using nonlinear model predictive control," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 1, pp. 113–122, Jan. 2016.

[161] M. Zhu, H. Chen, and G. Xiong, "A model predictive speed tracking control approach for autonomous ground vehicles," *Mech. Syst. Signal Process.*, vol. 87, pp. 138–152, Mar. 2017.

[162] J. Wu, X. Wang, L. Li, C. Qin, and Y. Du, "Hierarchical control strategy with battery aging consideration for hybrid electric vehicle regenerative braking control," *Energy*, vol. 145, pp. 301–312, Feb. 2018.

[163] A. Murilo, R. Rodrigues, E. L. S. Teixeira, and M. M. D. Santos, "Design of a parameterized model predictive control for electric power assisted steering," *Control Eng. Pract.*, vol. 90, pp. 331–341, Sep. 2019.

[164] C. Jing, H. Shu, R. Shu, and Y. Song, "Integrated control of electric vehicles based on active front steering and model predictive control," *Control Eng. Pract.*, vol. 121, Apr. 2022, Art. no. 105066.

[165] A. Nahidi, A. Kasaiezadeh, S. Khosravani, A. Khajepour, S.-K. Chen, and B. Litkouhi, ''Modular integrated longitudinal and lateral vehicle stability control for electric vehicles,'' *Mechatronics*, vol. 44, pp. 60–70, Jun. 2017.

[166] *Evs—One Electric Vehicle Dataset*. Accessed: Jun. 26, 2023. [Online]. Available: https://www.kaggle.com/

[167] W. Xie, X. Liu, R. He, Y. Li, X. Gao, X. Li, Z. Peng, S. Feng, X. Feng, and S. Yang, ''Challenges and opportunities toward fast-charging of lithium-ion batteries,'' *J. Energy Storage*, vol. 32, Dec. 2020, Art. no. 101837.

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