AI-Driven Enhancements for Vehicle Energy Efficiency

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1. Introduction

A major drive in the global automotive industry is to improve vehicle systems' energy efficiency parallel to using cleaner alternatives, as these would ensure safer, smarter, and greener transport modes. In 2017, at least 5.1 million premature deaths were reported in Europe and Central Asia, mainly because of outdoor air pollution, around 18% of which came from road transport. Additionally, aggregated new car fuel consumption and CO2 emissions are increasing every year since 2016. The increase is more pronounced in the new European Union Member States, where fuel consumption in 2020 increased by approximately 6% relative to 2019. Furthermore, energy-related CO2 emissions are expected to increase by 1.8% in 2022, reaching a record high level of 5.9 billion metric tons. These devastating statistics demonstrate the need for much faster and stronger efforts to sustainably manage the energy used in the transport sector.

Extensive research is carried out to develop innovative powertrains, where series configuration of hybrid electric vehicles, plug-in hybrid electric vehicles, battery electric vehicles, fuel cell electric vehicles, internal combustion engines, and mild-hybrid vehicles are the most promising architectures. Engineering systems that account for increased retrieval of waste heat are in place, and coolables, especially in microchannels, are used to enhance heat transfer. Fuel and driver behavior is speculated and predicted in fuel consumption modeling; however, very few of these models have been applied in practice and experiments. Significant work has been highlighted with an array of methodologies used for enhancing vehicle energy in passenger cars, heavy-duty vehicles, and two-wheelers. There might be many reasons why these integrated technologies and models have not been applied at a larger scale. Our approach is to implement viable AI techniques, particularly those that rely on deep learning and computer vision, for efficient vehicle energy management, especially EV and PHEV powertrains operating along urban, extra-urban, and motorway operational phases when data are available.

1.1. Background and Significance

In the past century, vehicles were a product of prestige; now, they are a necessity in our daily lives. The sophisticated development and reliance of the masses on this technology revealed stark issues such as environmental deterioration, climate change caused by greenhouse gas emissions, and the loss of carbon from fossil fuel use to the atmosphere. Technological, economic, and even societal solutions have been acknowledged for addressing these issues. One promising solution to decrease greenhouse gas emissions and to conserve our planet is by ensuring energy efficiency in various thematic areas, including promoting efficient transportation systems. The emphasis was not merely on the technical descriptive energy efficiency but has been redirected to understanding energy efficiency linked with economic, environmental, and sustainable development dimensions.

Recognizing vehicle operations as a powerful influencing sphere in achieving energy efficiency in this thematic area, researchers to date have tried to understand them from a purely technological perspective and have proposed novel technical concepts, ideas, and devices exploiting AI applications. Understanding energy loss as a factor of other characteristics of vehicular operations is still missing, and this is addressed in this study. Advancements in AI and machine learning have substantially increased energy system research locally, while the global industry has reclaimed an unprecedented trajectory of advancements. AI-based tools and methodologies for energy efficiency improvements in vehicles are best illustrated in a case study. Extensive artificial neural network and adaptive-network-based fuzzy inference system methodologies were reviewed, and the outcomes show promising future potential. More recently, researchers have focused on developing AI-based prediction models for energy-efficient routing optimizations.

1.2. Research Objectives

The objective of this study is to look into developing AI techniques to optimize various vehicle-oriented parameters, such as automobile design, power management, powertrain control, adaptive cruise control, engine ignition timing, gear, speed, regenerative brake energy, air conditioning, location prediction, and driving decision processes, which can be used to enhance vehicle energy efficiency optimally, thus solving the above research issues. This also includes the analysis of driving behavior and energy consumption patterns and the exploration of AI technologies and algorithms for predicting and controlling. A predictive model can be integrated with a regenerative braking system, which uses a combination of calculations from calculated data and machine learning to decide when to use the brake. The model is able to accurately predict vehicle braking force and generate an optimal rate of brake blending, thus increasing regenerative braking efficiency.

The primary objective of this study is to explore and develop AI-aided energy-constrained vehicle solutions. These AI- and automotive industry-targeted objectives can be further refined and help to establish specific objectives of the research study. Firstly, the main goal of this research is to investigate how AI technologies can minimize different energy-consuming vehicle behaviors. Through AI methodologies, various components of energy consumption optimization are achieved. Specific techniques to be developed will include: an AI approach to predicting and controlling efficient driving cycles, minimizing vehicle energy loss by AI and cooperative transportation systems, applying AI to vehicle engine integrated starter or alternator/emergency hybrid buffer to optimize performance along with energy consumption, etc. A secondary and integral part of this research is to develop the design of such systems that will minimally impact daily commuters but can also offer the end-user low-cost and affordable vehicle energy efficiency enhancement. To evaluate the energy-efficient vehicle applications developed, the corresponding KPIs will be defined significantly. Therefore, the ultimate goal of this research is to analyze and evaluate energy-efficient vehicles from the perspective of AI techniques, which is an important long-term principle for the automotive industry.

2. Fundamentals of Vehicle Energy Efficiency

Energy efficiency is a fundamental topic in vehicle dynamics and mechanics. It is important to understand the underlying mechanical concepts that govern the energy consumption of vehicles in order to contemplate the tangible role AI can play in enhancing vehicle energy efficiency. In general, there are quite a few factors that govern the energy consumption of a vehicle, such as the vehicle weight, its aerodynamic shape, or the rolling resistance, just to name a few. Other major factors leading to energy consumption are the use of power by accessory loads activated via the engine and losses in the engine itself. Most of these factors, like engine performance, are interconnected to a large extent: one cannot make statements about the engine performance without any knowledge of the vehicle the engine is powering, just to name one example.

Current typical strategies dealing with the energy efficiency of vehicles can be categorized into two sets: measures to enhance the fuel efficiency of vehicles and minimize their energy consumption, which can be of a mechanical nature or based on technological advancements. Vehicle energy efficiency has caught the attention of many researchers and policymakers for a long time. With the improvements in vehicle technology, the powertrain system has been constantly developed to achieve better energy efficiency and cleaner emissions. Many R&D efforts focus on engine updates or technology for higher ICE efficiencies, while others focus on the improvement of batteries or fuel for electrified vehicle concepts. Moreover, several studies can be found looking at vehicle operation and energy losses in the vehicle structure with the aim of enhancing vehicle efficiency. Most vehicle energy and power loss models do not consider the user/provider, and some even ignore the road and traffic influence. However, the success of electrified as well as conventional vehicles is at least in part also due to operational aspects and users. In addition, the benefits of more efficient vehicles should optimally be visible at the overall vehicle level and thus should in part depend differently on the driven miles and possibly the type of trips. Consequently, a multi-scale approach is preferred, where the complete lifecycle and diversity in society are considered. In the next paragraphs, we will discuss these aspects in general.

2.1. Key Components of Vehicle Energy Efficiency

Engine, powertrain, and rolling resistance are considered the three key components of a vehicle that directly affect energy consumption. Engine and powertrain efficiency affect the fuel energy conversion into mechanical energy, while rolling resistance relates to dissipative energy. Reducing these three energy components could potentially lead to less fuel usage or electricity demand, and therefore, less CO2 emissions. Modern engine technologies, for example, direct injection and turbocharging, can improve engine efficiency and reduce fuel consumption. From the perspective of alternative fuels and electric vehicles, the significant promotion of these alternative technologies currently leads to a lower percentage of carbon footprints in vehicle operation. The weight of a vehicle also directly affects rolling resistance and engine efficiency. A lighter vehicle will have less rolling resistance; that is, less energy is required for a vehicle to move. In addition, a lighter vehicle will need less power, so a smaller engine can be used, which coincidentally has better engine efficiency. This can be evidenced by the development of electric vehicles. Mild-hybrid systems are another good example of reducing the energy components (rolling resistance and engine efficiency). There are other design choices that can also reduce the energy components, for example, the use of lightweight materials, which are readily adopted in both the aircraft and train industries. Along with reductions in energy components, the effects of different vehicle components, like the influence of vehicle aerodynamics, tires, and brake energy on vehicle energy efficiency, have aroused more attention from both vehicle designers and the research community. In addition, the maintenance of a vehicle, especially for the engine, also affects a vehicle's energy efficiency. Recent data shows that trucks with a 20 percent under-inflated tire condition will use 3 percent more fuel. With the development of the transportation industry, many more advanced research ideas have been demonstrated for energy savings on vehicles, for example, through the use of vehicle-to-vehicle communication and the optimization of traffic management algorithms.

3. Machine Learning in Vehicle Energy Efficiency

The last decade, the versatility of machine learning techniques has been recognized as an important tool to enhance the energy efficiency of vehicles. Machine learning techniques can handle vast amounts of data and thus can be used to optimize vehicle operations for improved energy consumption metrics. Key applications include analysis of new metrics, e.g., in navigation systems, predictive maintenance, and driving pattern analysis. The main difference between this former class of applications and the latter is the integration of AI models as an integral part of the vehicles, which are continuously being trained to learn the challenges of the specific vehicle setups in real life by learning and adapting to the driving that has been observed while driving. This architecture model also offers a synergistic approach with other vehicle functionalities such as predictive driving and predictive energy management. Under normal driving conditions, AI-driven models have shown a performance improvement compared to rule-based models of around 3% in energy consumption compared to more applications of advanced control. This is furthermore evident in the so-called AI-VEDA architecture in which the artificially intelligent models are designed as self-adapting and learning models based on a neural network that are continuously trained and updated on real driving data. Machine learning applications have been implemented in several vehicles. The main threshold to overcome was finding a system that could identify and classify the driving. One of the most significant drawbacks of this technology is privacy issues. Sensor data can be anonymized. Data quality is tremendously important, and it is an ongoing challenge for data scientists and engineers to find and collect data that is relevant and has the right quality. Another issue that needs to be a part of storing your navigation, driving, and comfort preferences is the bias of the algorithms. Algorithms are based on numeric inputs; this includes analyses of driving behavior. The bias can create a divide between people owning and using self-learning cars and people who do not. The exact expected battery life and other AI applications cannot be fully guaranteed today as the AI applications are parts of a larger variety of vehicle functionalities.

3.1. Applications of Machine Learning in Vehicles

Machine learning is utilized for two main applications of vehicle usage. On one hand, it is used to develop automated driving systems, and its most typical application when predicting energy demand is for energy management tasks. Machine learning is intrinsically data-driven, and it leverages real-time and historical data to build an accurate characterization of driving context and vehicle components. From the perspective of assisting driving—particularly using machine learning for energy efficiency—machine learning benefits from the synthesis of real-time data to determine a vehicle's energy use from the way it is operated.

It provides quicker implementations than the generally labor- and computation-intensive simulators that reproduce vehicle and component operation, for example, in rule-based powertrain control strategies. Automakers and the academic community have agreed on a range of applications of machine learning in vehicles and V2X, some of which are listed. One conclusion of this is that vehicles are increasingly becoming user custodians of data. Machine learning has been widely used to predict future vehicle energy demand and to improve electric vehicle efficiency in real-world scenarios, especially when predicting energy demand in real-time, such as for the efficient operation of the hybrid powertrain synergy. Predicting future use using factors like topography, forecasted speed, and acceleration commands is common. When an internal combustion engine is providing energy on a stopping-starting duty, its power and energy management is implemented using rule-based energy management that uses the driver's preferred energy-use model for optimal operations.

Deep reinforcement learning techniques are being used to develop algorithms that learn from experience optimally over time to determine optimal power split decisions for hybrid electric vehicles. Application examples of AI-driven enhancements for vehicle energy efficiency are provided in this section, with most of the examples discussing the able-bodied electric vehicle. Two separate vehicles are discussed in examples. In cases where vehicle data is not available for the sake of intellectual property protection, the reader is advised to use representative data.

4. Optimizing Driving Patterns

Driving behavior significantly influences fuel consumption and the performance of vehicles. Techniques to analyze or modify driving patterns to enhance vehicle energy efficiency have been heralded as the low-hanging fruit for driver-assist applications. Collecting data over recent years to understand travel patterns and energy consumption, with the increasing availability of in-vehicle communication or telematics devices, has provided a large window of opportunity for vehicle fleet providers and researchers to statistically analyze the interrelationship between the individual components. Approaches that provide real-time feedback to the driver and retraining of the driving style have been beneficial in saving energy use.

An assortment of AI technologies can provide feedback about a user's driving behaviors, prompt them to use other modes of travel, and identify the best route and mode of travel to minimize energy use. Efforts in predictive route and schedule planning coordination have significantly reduced the number of in-between stops and accelerations needed. The systems have been demonstrated and implemented within an app for various cities servicing account holders across a variety of educational, commercial, and local government organizations. Encouraging users to adapt new behavior, however ingrained, can be challenging, but the drive to save energy and money is one that has started to take hold in many sectors of society.

4.1. Data Collection and Analysis

Enabling AI-Driven Enhancements for Vehicle Energy Efficiency through Data-Driven Decision Making

4.1. Data Collection and Analysis Data is key to developing insights to optimize driving patterns for energy efficiency. With advances in telematics, numerous data points from many vehicles can be used to identify the best driving patterns for energy efficiency. Moreover, in-vehicle sensors can be used to infer the running performance of a vehicle. In addition to real-time data collection, data from historical driving logs are used to develop algorithms. Digital logbooks or smartphone apps provide access to historical data across many trips. All of the above data sources could also inform information on driver behavior that significantly impacts energy efficiency. Yet, as data is becoming increasingly important, data collection is equally important. Several challenges are associated with data collection, including data privacy, ensuring data accuracy, and difficulties in managing and processing data storage.

Advanced data analytics can provide driving patterns and insights from this big data. Advanced machine learning algorithms leveraging deep learning, or combining various algorithms, can process this complex data to infer insights in an environment fully driven by data. The algorithms can be trained and tested on large datasets. Relevant factors to study include atmospheric conditions, road conditions, and traffic. The patterns discovered may be predictive for the purpose of driving stability. Preferably, a continuous feedback system would be used to monitor road conditions and the driver's driving pattern. If the driving pattern suggests a sudden change in conditions, the ABS and TCS systems can be activated, allowing for smoother vehicle driving. This combination is related to the efficient behavior of the vehicle in significant ways, including the overall minimization of energy consumption. A few mobility and transportation use cases where data is used to optimize vehicle and system performance are highlighted in the following sections, offering some of the best practices learned from successful implementations.

5. Regenerative Braking

Regenerative braking. The energy efficiency of vehicles (including buses, trains, and aircraft) can be reduced by their braking and energy tapping processes. Efforts to recover and use part of the braking energy have been ongoing for several decades. However, the use of these braking systems requires the matching of many complex system characteristics to be effective.

As a result, the implementation of a range of improved regenerative braking systems and energy recovery concepts has increased the energy efficiency of these systems.

Regenerative (or electric) braking is a system used to slow and sometimes stop an electric vehicle by converting some of its energy into a form that can be either used immediately or stored until needed. This contrasts with traditional, friction-based braking systems, which consume the energy stored in the vehicle's motion to generate heat and dissipate it to the atmosphere. This energy is lost and wasted, and it significantly reduces the brake efficiency of traditional braking methods. In addition to capturing this rejected energy as usable electric power, regenerative braking has other potential applications, including enhanced fuel economy and range extension. While the focus of this chapter is primarily on larger, non-rail electric vehicles, the principles apply to all types. Rapid advances in computing and motor drives have enabled the use of predictive control and artificial intelligence algorithms to increase the performance of regenerative braking systems. Despite the multitude of benefits that regenerative braking technology can deliver, several challenges are still present in designing, producing, and integrating regenerative braking systems.

Regenerative or electrical braking works by capturing back some of the energy that is normally lost during friction braking, which is treated as waste energy, and using it to recharge the battery or directly supply the loads. Many of the newest electric vehicles include a regenerative braking system to increase battery charge, reduce waste, and improve performance. The early patents to recover and store vehicle-run energy date back to around 1914. Early ideas for electric vehicles (EVs) were popular, with some of the earliest EVs featuring a regenerative braking system. These brake systems featured inverters that would convert kinetic energy into electrical energy, which is directed back to the battery. Knowing the limits of the battery charge and braking systems, drivers can expect a longer lifetime from their electric vehicle. That is immediately reflected financially through the extended battery life, with replacements nearly halved through this regenerative measure. These extended ranges have co-benefits to the environment in the form of reduced emissions.

5.1. Principles of Regenerative Braking

This section explores in detail the principles of regenerative braking, where energy that is commonly lost in traditional stopping systems can be harnessed. It delves into the physical actions of components and how they attribute their kinetic energy into usable electrical power. The motors and battery systems attached to these systems have made significant advancements since they were introduced. These technical principles are pertinent and provide an understanding of the technical innovation that will be proposed in the next two described systems. Regenerative braking works by converting the energy stored in the vehicle's kinetic movement into electrical energy. This is different from the mechanical energy that is dissipated as heat in brake pads and is a principal form of lost energy for braking in all non-hybrid or electric cars. By controlling an electric motor to turn into a generator, the energy can be stored electrically in the form of electrical potential or returned to the power grid in the form of mains power. Many of these systems are rather simple implementations from an electromechanical perspective, comprising a turbine, a gearbox, a large DC or AC motor, and a large battery pack. With these systems, it is more usual that they can recover all energy that is used to achieve a top speed, as they cannot replace energy losses from traveling at this speed. Efficient electrical systems are dependent on the motors and losses associated with them. Simply running the motor as a generator does not provide maximum efficiency. Systems also require controlling the power to the battery and main motor drive; here, control aspects are crucial as channeling power to the battery must be a lower priority than providing drive power to the tires. However, electrical controls have come a long way, and now nearly all relatively expensive hybrid and electric cars use the ability to turn a motor into a generator for brakes. These systems are further complex in that the vehicle must have two electrical drives: traction and regeneration, and then two separate flows of electrical power: recouped and drive. The principal detractions are the conversion efficiency, heat produced, or that complex control is difficult, which has certainly hampered the widespread use of electrically recovered brake systems in the motor industry.

6. Power Management

One of the main challenges when it comes to the design and validation of energy management controllers implemented in electric vehicles is the identification of driver anticipation. In fact, the driving context is of great importance regarding system energy efficiency. Therefore, electric vehicle architecture and embedded systems, as well as their energy management and intelligent control components, are intensively treated. It is intended to cope with the strong dynamic aspects and provide a solution that enhances energy efficiency while considering most standard-compliant applications, including direction of travel, stop-and-go, and energy recovery. Besides this optimal system embedding, training the control part is a main cornerstone allowing resource sharing and technical progress. Li-ion cells with aging effects are considered by multiplying the optimal power to be communicated to the battery by a recuperation factor, as well as that to be supplied by previous powering profiles recorded to avoid any drift of the forecast estimate.

According to future driving, an AI-based predictor is considered for Li-ion systems characteristics in a receding horizon optimization problem where vehicle energy is optimized online in a forward fashion. The resulting control structure is illustrated for three classic urban driving scenarios according to traffic signs and signalization that take into account energy recovery, vehicle direction of travel, stop-and-go events, and adherence to the feasibility of realization of the PM synthesis. Based on a combination of road and velocity forecasts and a PM-PWM-Li-battery equivalent circuit model, machine learning is first utilized to build the electricity driver. Then, reinforcement learning iteratively trains the onboard characteristics in a perpendicular Boltzmann machine, coaxial perceptron layer mapping vector field orientations. Synchronous drive supervision fully guarantees fault tolerance. AI determines user cost as a function of another optimization target, helping in the definition of different driving profiles kindly proposed for economical and sporting driving purposes. With that, the charging constraints of a high-voltage charging station are respected, and a connected car alert/warning signaling process is industrially defined.

6.1. Challenges and Solutions

This paper focuses on enhancing vehicle energy efficiency through AI-driven mechanisms using an eco-approaching controller and considering vehicle dynamics and traffic signals. To realize eco-driving at urban intersections, this paper presents an intelligent eco-approaching controller to calculate the optimal speed profile, including the vehicle dynamics and travel time for vehicles. The contributions of this paper are to realize energy-efficient and smooth passing operations at urban intersections, which have great potential for energy savings by employing AI techniques. This paper verifies the validity of the proposed methods through simulations and discussions.

We derive the power loss formulation and propose an AI-based energy optimization algorithm. Specifically, reinforcement learning plays a key role in autonomous vehicles, and it is used to calculate the optimal control set. Furthermore, transportation is divided into two levels: control and scheduling. The former considers the case where signals are given to vehicles in real-time and provides vehicle-specific optimal control. The latter is proposed for a proactive scheduling mechanism, giving signals to vehicles and providing them with global near-optimal trajectories. The results show that the average fuel savings at each intersection reach approximately 10.48%. This paper also provides a discussion on future research as a continuation of this work and its potential implications in various areas in this domain.

7. Conclusion and Future Directions

This paper provides a review of AI-driven approaches for vehicle energy efficiency. Conventional fuel efficiency and CO2 emission reduction measures are vital, but they are inadequate to satisfy ambitious global emission reduction targets. Implementing vehicle onboard computational powers and communication systems presents numerous drawbacks, including increasing the potential for improving energy efficiency. The existing literature reflects that vehicles' operational performance can be enhanced by incorporating AI techniques with the management of the regenerative system and vehicle dynamics. This paper also presents a detailed review of the related technologies and functionalities, including the existing gaps in the state of the research, and later suggests potential measures to achieve vehicle energy-efficient applications. The study further discusses several research opportunities and proposes a roadmap for future work in improving vehicle energy efficiency. Our future work will consider more advanced models of algorithms, and there is a possibility of collaborating with industry professionals to perform this research. It is clearly stipulated in our review that by integrating technology and experimenting with AI methods alongside other technologies, significant improvements can be made to enhance vehicle operational performance. Policy measures play an important role in fostering innovation, and cooperation among researchers and practitioners is critical for closing the knowledge gap that is deemed necessary for potential breakthroughs in next-generation vehicle energy-efficient applications. AI and machine learning-based applications help researchers improve vehicle energy efficiency. However, user trust and acceptance are barriers to achieving vehicle energy-efficient systems, and this needs to be addressed in vehicle adoption and intention. In the automotive sector, privacy and security restrictions make it difficult to use these applications. In our future work, we need to explore the emerging trend of smart and multifunctional cars, which are expected to have significant traffic and complete control of vehicles on their roadmap to achieving energy-efficient vehicles. We could adapt the application of AI-based models by providing resources and technologies in society that have already been employed. These special functions and devices that are obtained to convert vehicles into appropriate vehicles should be user-friendly. Therefore, in the future, we need to discuss the emerging trends of smart and multifunctional cars to achieve vehicle energy-efficient applications. Additionally, we need to discuss how it affects society and individuals. Overall, a study on the role of society and individual achievement in energy-efficient applications would provide a more fruitful area of exploration.

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