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Review

The Emerging Role of Artificial Intelligence in Enhancing Energy Efficiency and Reducing GHG Emissions in Transport Systems

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Abstract: The global transport sector, a significant contributor to energy consumption and greenhouse gas (GHG) emissions, requires innovative solutions to meet sustainability goals. Artificial intelligence (AI) has emerged as a transformative technology, offering opportunities to enhance energy efficiency and reduce GHG emissions in transport systems. This study provides a comprehensive review of AI's role in optimizing vehicle energy management, traffic flow, and alternative fuel technologies, such as hydrogen fuel cells and biofuels. It explores AI's potential to drive advancements in electric and autonomous vehicles, shared mobility, and smart transportation systems. The economic analysis demonstrates the viability of AI-enhanced transport, considering Total Cost of Ownership (TCO) and cost-benefit outcomes. However, challenges such as data quality, computational demands, system integration, and ethical concerns must be addressed to fully harness AI's potential. The study also highlights the policy implications of AI adoption, underscoring the need for supportive regulatory frameworks and energy policies that promote innovation while ensuring safety and fairness.

Keywords: artificial intelligence; energy efficiency; greenhouse gas emissions; transport systems; autonomous vehicles; hydrogen fuel cells

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1. Introduction

1.1. Background

The global transport sector remains a significant contributor to energy consumption and greenhouse gas (GHG) emissions, accounting for approximately one-fourth of global GHG emissions and relying on oil products for nearly 91% of its final energy consumption (International Energy Agency, 2023) [1,2]. Despite ongoing efforts to promote electrification and the adoption of renewable energy sources, progress has been sluggish. The continued dependence on fossil fuels has exacerbated environmental concerns, including climate change, air pollution, and noise pollution in urban areas [3–5].

Traditional approaches to mitigating these issues have focused on enhancing fuel efficiency, developing alternative fuels, and implementing regulatory policies. However, these measures have not yielded the desired reduction in GHG emissions, raising doubts about achieving the target of limiting the global average temperature increase to below 1.5–2 °C as stipulated in the Paris Agreement. This scenario underscores the urgency for innovative solutions that can accelerate the transition toward sustainable transport systems [6–8].

1.2. The Promise of Artificial Intelligence

Artificial intelligence (AI) has emerged as a transformative technology with the potential to revolutionize various sectors, including transportation. By enabling systems to learn from data, identify patterns, and make decisions with minimal human intervention, AI offers unprecedented opportunities to enhance energy efficiency and reduce GHG emissions in transport [9,10].

In the context of transportation, AI can optimize vehicle energy management, improve route planning, facilitate the integration of autonomous and shared mobility services, and support the development of innovative fuels and powertrains. For instance, AI-driven predictive analytics can optimize energy consumption in electric vehicles by adjusting power usage based on driving conditions and patterns. Similarly, AI algorithms can enhance traffic management systems to reduce congestion, thereby lowering fuel consumption and emissions [11,12].

Furthermore, AI plays a pivotal role in advancing alternative energy solutions such as hydrogen fuel cells and biofuels. Machine learning models can optimize the production processes of these fuels, improve storage and distribution logistics, and enhance the efficiency of powertrain technologies [13–15]. By integrating AI into these areas, it becomes possible to address some of the limitations of current technologies and policies, offering a pathway toward significant reductions in GHG emissions.

To compare AI models and hardware systems across different sectors, several studies highlight their diverse applications. In the field of Occupational Safety and Health (OSH), AI is utilized in sectors such as oil and gas, mining, transportation, construction, and agriculture to enhance safety by detecting hazardous situations and removing workers from danger using sensors and actuators [16].

In the construction, mining, and oil and gas industries, AI aids in occupational health and safety risk management by employing computer vision, sensor networks, and machine learning to monitor conditions and provide feedback for hazard management [17].

In healthcare, AI significantly improves diagnostic accuracy and treatment personalization, particularly in ophthalmology, by enhancing disease screening and diagnosis [18].

In the information technology sector, AI technologies like machine learning and robotics are applied across sectors such as healthcare, manufacturing, and automotive industries to improve performance and efficiency [19].

In the food industry, AI optimizes processes like sorting, grading, and quality control, thereby enhancing supply chain management and food safety [20].

These examples illustrate AI's transformative role across various sectors, each with unique applications and challenges.

1.3. The Need for This Study

Despite the recognized potential of artificial intelligence to transform the transport sector, there is a notable gap in the literature concerning its comprehensive impact on energy efficiency and GHG emission reduction. Current research often addresses isolated applications of AI, such as autonomous vehicles or smart traffic systems, without providing an integrated analysis of how AI can synergistically enhance sustainability across various transport modes and infrastructures.

Moreover, previous technologies and energy policies have fallen short in delivering substantial environmental benefits due to technological limitations, economic constraints, and insufficient integration of innovative solutions. There is an urgent need to explore how AI can bridge these gaps by offering advanced capabilities in data processing, predictive analytics, and autonomous decision-making, which can lead to more efficient energy use and lower emissions.

This study is essential for several reasons:

1. Holistic Understanding: It provides a comprehensive examination of AI applications in transportation, encompassing vehicle technology, infrastructure management, and alternative fuels;

2. Critical Analysis: By evaluating past technologies and policies, the study identifies shortcomings and areas where AI can make significant improvements, offering a critical perspective that is currently lacking in the discourse;
3. Strategic Recommendations: The research aims to propose actionable strategies for integrating AI into transport systems, considering technological feasibility, economic viability, and policy implications, thereby facilitating informed decision-making among stakeholders;
4. Global Relevance: Addressing both developed and developing countries, the study acknowledges the diverse challenges and opportunities worldwide, promoting inclusive solutions that can be adapted to various contexts;

By filling the existing gaps in knowledge and providing a thorough analysis of AI's potential, this article seeks to contribute meaningfully to the efforts of reducing GHG emissions in the transport sector. It aims to inspire further research, influence policy formulation, and encourage the adoption of AI-driven solutions to achieve a more sustainable and efficient transportation system globally.

2. Literature Review

2.1. Literature Review Methodology

2.1.1. Data Sources and Search Strategy

The literature review in this study adopts a systematic approach to identify, evaluate, and synthesize existing research on the role of artificial intelligence (AI) in enhancing energy efficiency and reducing greenhouse gas (GHG) emissions in the transport sector. This methodology is designed to ensure a comprehensive and unbiased examination of the current state of knowledge, allowing for the identification of gaps and the development of insights that can inform future research and policy-making.

The research design is structured to address the following objectives: first, to critically assess past technologies and energy policies related to transport; second, to examine current applications of AI in transportation; and third, to explore the potential of AI in facilitating GHG emission reductions. By integrating both qualitative and quantitative studies, the review encompasses a broad spectrum of literature, including empirical research, case studies, theoretical frameworks, and policy analyses.

2.1.2. Data Sources and Search Strategy

The data sources for this literature review include a range of academic databases and repositories to ensure a wide coverage of relevant literature. The primary databases consulted were IEEE Xplore, ScienceDirect, Scopus, Web of Science, and Google Scholar. These platforms were chosen due to their extensive collections of scholarly articles, conference proceedings, and technical reports in the fields of engineering, technology, environmental science, and policy studies.

The search strategy involved the use of specific keywords and phrases related to the research topic. Keywords included "artificial intelligence", "transport", "energy efficiency", "greenhouse gas emissions", "fuel quality", "fuel consumption", "autonomous vehicles", "hydrogen fuel cells", "biofuels", "machine learning", "smart traffic management", and "renewable energy in transport". Boolean operators such as "AND" and "OR" were employed to combine terms and refine search results. The search was limited to publications from 2010 to 2024 to capture the most recent developments and trends in the field.

To ensure the inclusion of high-quality and relevant studies, the search was further refined by applying filters for peer-reviewed articles and English-language publications. References from key articles were also examined to identify additional sources that may not have appeared in the initial database searches.

2.1.3. Inclusion and Exclusion Criteria

The selection of literature was guided by clearly defined inclusion and exclusion criteria. Studies were included if they met the following criteria: focused on the application of AI in the transport sector; addressed aspects of energy efficiency or GHG emission reduction; provided empirical data, case studies, or theoretical analyses relevant to the research objectives; and were published in peer-reviewed journals or reputable conference proceedings.

Exclusion criteria involved omitting studies that were not directly related to the intersection of AI, transport, and environmental sustainability. Articles that solely discussed AI applications without reference to energy or emissions, or those that focused on unrelated sectors, were excluded. Additionally, non-peer-reviewed sources, opinion pieces, and publications in languages other than English were not considered in this review.

2.1.4. Data Extraction and Synthesis

Data extraction involved systematically reviewing the selected articles to collect pertinent information. Key data elements included the study's objectives, methodology, AI technologies examined, transport modes addressed, geographical focus, findings related to energy efficiency and GHG emissions, and any policy implications discussed.

The synthesis of the extracted data was conducted through thematic analysis. Studies were categorized based on common themes such as AI in vehicle energy management, AI-driven traffic optimization, autonomous vehicles, AI in alternative fuels, and policy frameworks supporting AI integration in transport. This approach facilitated the identification of patterns, relationships, and divergences within the literature, enabling a comprehensive understanding of the current state of research.

2.1.5. Quality Assessment

To ensure the reliability and validity of the findings, a quality assessment of the selected studies was performed. Criteria for quality evaluation included the clarity of research objectives, appropriateness of methodologies, robustness of data analysis, and the credibility of conclusions drawn. Studies were critically appraised for potential biases, limitations, and the extent to which they contributed to advancing knowledge in the field.

Only studies that met a minimum threshold of quality, as determined by these criteria, were included in the final synthesis. This rigorous assessment process enhanced the integrity of the literature review and ensured that the conclusions drawn were grounded in high-quality research.

2.2. Past Technologies and Energy Policies

Previous efforts to reduce GHG emissions in the transport sector have encompassed a variety of technologies and policy initiatives. Technological advancements have included the development of more fuel-efficient internal combustion engines, the introduction of hybrid and electric vehicles, and the exploration of alternative fuels such as biofuels and compressed natural gas. These innovations aimed to decrease fuel consumption and lower emissions per vehicle [21–23].

Energy policies have played a crucial role in promoting these technologies. Regulatory measures such as emission standards, fuel economy requirements, and incentives for low-emission vehicles have been implemented in various jurisdictions. Policies have also targeted the reduction of carbon intensity in fuels, supported research and development, and provided subsidies or tax credits to encourage the adoption of cleaner technologies [24,25].

Despite these efforts, significant challenges have persisted. The high initial costs of alternative fuel vehicles, limited infrastructure for electric charging or alternative fuel refueling, and consumer preferences for traditional vehicles have hindered widespread adoption. Additionally, policies have sometimes lacked coherence or sufficient enforcement, reducing their effectiveness [26,27]. As a result, the transport sector continues to exhibit high levels of energy consumption and GHG emissions, indicating that past technologies and policies have not fully achieved their intended environmental outcomes [28,29].

2.3. AI in Transport: Current State of Research

The application of artificial intelligence in transport has gained increasing attention in recent years, with research exploring its potential to enhance system efficiency, safety, and sustainability [30]. AI technologies such as machine learning, deep learning, neural networks, and optimization algorithms are being applied across various aspects of transportation [31,32].

In vehicle energy management, AI algorithms are used to optimize fuel consumption and improve the performance of electric and hybrid vehicles. Predictive models can adjust powertrain operations in real-time based on driving conditions and patterns, leading to significant energy savings [33].

AI-driven traffic management systems employ real-time data analytics to optimize traffic flow, reduce congestion, and minimize idling times. By adjusting traffic signals and providing route recommendations, these systems contribute to lower fuel consumption and emissions at the network level [34,35].

The development of autonomous vehicles represents a significant area of AI application. Autonomous driving technologies have the potential to improve fuel efficiency through smoother acceleration and deceleration patterns and by optimizing routes. Additionally, AI enables the integration of shared mobility services, which can reduce the number of vehicles on the road and promote more efficient use of transport resources [36,37].

In the realm of alternative fuels and powertrains, AI is being used to enhance the production processes of hydrogen fuel cells and biofuels. Machine learning models can optimize chemical reactions, predict system performance, and identify the most efficient pathways for fuel production and utilization.

Policy-related research has examined how AI can inform transportation planning and policy-making. AI tools can analyze large datasets to forecast transport demand, assess the environmental impact of different policy scenarios, and support decision-making processes [38].

Despite these advancements, the literature indicates several gaps. Many studies focus on specific applications or case studies, lacking a holistic perspective on how AI can transform the transport sector as a whole. There is also a need for more empirical evidence on the long-term impacts of AI adoption on energy efficiency and emissions. Ethical considerations, such as data privacy and the societal implications of automation, are areas that require further exploration [39,40].

The current state of research suggests that while AI holds significant promise for enhancing sustainability in transport, there is a critical need for comprehensive studies that integrate technological, economic, and policy dimensions. This integration is essential to fully understand and leverage AI's potential in addressing the complex challenges facing the transport sector's energy consumption and GHG emissions (Table 1).

Table 1. AI Applications in Various Transport Modes for Energy Efficiency.

Transport Mode	AI Application	Energy Efficiency Impact	GHG Emission Reduction (%)	Examples of AI Technologies Used
Road Transportation	AI-based route optimization	Reduced fuel consumption by 15%	10–12%	Neural Networks
Rail Transportation	Predictive maintenance for energy systems	Increased efficiency by 20%	15–18%	Supervised Learning Algorithms
Maritime Transportation	Autonomous navigation systems	Optimized fuel usage by 10–15%	8–10%	Reinforcement learning
Aviation	AI-driven flight path optimization	Reduced fuel consumption by 5–10%	5–7%	Deep learning, AI-based simulators
Public Transportation	Smart scheduling and demand prediction	Efficiency gains of 15–20%	12–15%	AI-powered data analysis

To discuss the ratios between energy efficiency impacts and GHG emission reductions for each transport mode in Table 1, we can draw on the following insights:

1. Road Transportation: Road Transportation: AI-based route optimization can reduce fuel consumption and GHG emissions by 10–15%. This reflects the direct relationship between fuel savings and emissions reduction, as less fuel consumption results in lower CO_2 emissions. Neural networks optimize routes by predicting and adjusting to real-time conditions, maximizing fuel savings and minimizing emissions [41,42].
2. Rail Transportation: AI-based predictive maintenance can reduce fuel consumption and GHG emissions by 15–20%. Efficiency gains are achieved through supervised learning algorithms that optimize maintenance schedules, reducing energy waste and emissions associated with rail operations [43].
3. Maritime Transportation: AI-based autonomous navigation systems can reduce fuel consumption and GHG emissions by 8–15%. Reinforcement learning enables efficient route planning and speed optimization, directly impacting fuel consumption and emissions [44,45].
4. Aviation: AI-based flight path optimization can reduce fuel consumption and GHG emissions by 5–10%. Deep learning and AI simulators enhance flight efficiency by optimizing routes and altitudes, reducing fuel use and emissions [46].
5. Public Transportation: AI-based smart scheduling and demand prediction can reduce fuel consumption and GHG emissions by 12–20%. AI-powered data analysis improves scheduling and resource allocation, reducing unnecessary trips and emissions [47].

In all cases, the type of fuel used and its elemental composition significantly affect GHG emissions. Different fuels have varying carbon contents, influencing the overall emissions reduction achieved. Additionally, the consideration of different GHGs, such as CO_2, CH_4, and N_2O, is crucial, as each has a different global warming potential. Related research by by Kiselev et al. (2023, 2024) provides insights into the environmental evaluation of biogas projects, emphasizing the importance of considering specific GHGs in environmental assessments [48,49].

3. AI Applications in Enhancing Energy Efficiency

Artificial intelligence (AI) has emerged as a pivotal technology in transforming the transport sector toward greater energy efficiency and sustainability. By leveraging advanced algorithms, machine learning, and real-time data analytics, AI enables the optimization of various aspects of transportation systems. This section examines three primary applications of AI that contribute to enhancing energy efficiency: vehicle energy management, route optimization and traffic management, and the integration of autonomous vehicles and shared mobility services [50,51].

3.1. AI in Vehicle Energy Management

AI technologies play a crucial role in optimizing energy consumption at the vehicle level, particularly in electric and hybrid vehicles. Through machine learning algorithms and predictive analytics, AI systems can manage and adjust vehicle operations in real-time to improve energy efficiency [52].

One significant application is in the development of intelligent energy management systems (EMS) for vehicles. These systems utilize AI to predict driving conditions, such as traffic congestion, road gradients, and weather conditions, allowing the vehicle to adjust power distribution accordingly. For example, AI algorithms can determine the most efficient use of battery power versus internal combustion in hybrid vehicles, thereby reducing fuel consumption and emissions [53–55].

In electric vehicles (EVs), AI enhances battery management systems (BMS) by predicting battery performance and optimizing charging and discharging cycles. Machine learning models can analyze historical usage data to forecast battery degradation, enabling proactive maintenance and extending battery life [56,57]. Furthermore, AI-driven predictive maintenance can identify potential mechanical issues before they lead to inefficient energy use or breakdowns, thus maintaining optimal vehicle performance [58].

AI also facilitates the development of adaptive cruise control and eco-driving assistance systems. These systems provide real-time feedback to drivers or autonomous control adjustments to promote energy-efficient driving behaviors, such as smooth acceleration and deceleration, maintaining optimal speeds, and minimizing unnecessary idling [59].

The integration of AI in vehicle energy management not only improves individual vehicle efficiency but also contributes to broader energy savings when deployed across fleets. For instance, logistics companies employing AI-driven fleet management systems can optimize vehicle assignments, maintenance schedules, and driving practices, leading to significant reductions in overall energy consumption and operational cost (Table 2).

Table 2. Comparison of AI-Driven Electric and Hydrogen Vehicle Efficiency.

Vehicle Type	Power Source	AI Application	Energy Efficiency (%)	GHG Emission Reduction (%)	AI Techniques Used
Electric Vehicles (EVs)	Lithium-ion Battery	AI-based battery management	85%	50–60%	Supervised Learning
Hydrogen Vehicles	Hydrogen Fuel Cell	AI-enhanced fuel consumption control	75%	60–70%	Reinforcement Learning
Hybrid Vehicles	Electric/Gasoline	AI-based energy flow optimization	70%	30–40%	Supervised Learning

3.2. Route Optimization and Traffic Management

AI's ability to process vast amounts of data in real-time makes it an invaluable tool for route optimization and traffic management, directly impacting energy efficiency on a larger scale [60,61]. By analyzing traffic patterns, road conditions, and other relevant factors, AI systems can optimize routing for individual vehicles and manage traffic flows to reduce congestion and emissions.

In route optimization, AI algorithms consider multiple variables to determine the most energy-efficient paths for vehicles [62]. Advanced navigation systems use real-time traffic data, predictive analytics, and machine learning to suggest routes that minimize travel time and fuel consumption. For example, AI can predict traffic congestion before it occurs by analyzing historical data and current conditions, allowing drivers or autonomous vehicles to adjust their routes proactively [63].

Traffic management centers utilize AI to optimize signal timings at intersections, coordinate traffic lights across networks, and manage variable speed limits on highways [64,65]. By dynamically adjusting traffic controls based on real-time conditions, AI systems can reduce stop-and-go traffic, decrease idling times, and improve overall traffic flow efficiency. These improvements lead to lower fuel consumption and emissions at the city or regional level [66,67].

AI also supports the development of intelligent transportation systems (ITS) that integrate various modes of transport and infrastructure components [68]. Through the Internet of Things (IoT) and vehicle-to-everything (V2X) communication, AI enables vehicles to communicate with infrastructure and other vehicles, facilitating coordinated movements and reducing unnecessary energy expenditure [69,70].

Moreover, AI-driven demand-responsive transit systems can optimize public transportation schedules and routes based on passenger demand patterns. By adjusting services in real-time, these systems enhance the efficiency of public transport, encourage higher ridership, and reduce the reliance on private vehicles, thereby contributing to energy conservation [69–71] (Table 3).

Table 3. GHG Emissions Reductions by AI-Optimized Traffic Management Systems.

AI-Optimized Traffic Feature	Estimated Emission Reduction (%)	Energy Efficiency Gain (%)	Technology Used (AI Method)	Example Cities
Adaptive traffic signal control [72,73]	15–20%	10–15%	Reinforcement Learning	Los Angeles, Singapore
Real-time traffic monitoring [74,75]	12–15%	8–12%	AI-based predictive analytics	London, New York
Autonomous vehicle fleets [76,77]	25–30%	20–25%	Neural Networks, Deep Learning	San Francisco, Tokyo
Congestion management systems [77,78]	10–12%	7–9%	AI-based predictive analytics	Beijing, Berlin

3.3. Autonomous Vehicles and Shared Mobility

Autonomous vehicles (AVs) and shared mobility services represent a significant shift in transportation paradigms, with AI at the core of their development and operation [79]. The integration of AI in these areas has the potential to substantially enhance energy efficiency and reduce GHG emissions through optimized vehicle utilization and improved operational efficiency [79–81].

Autonomous vehicles rely on AI for perception, decision-making, and control. By utilizing sensors, machine learning algorithms, and real-time data processing, AVs can operate more efficiently than human-driven vehicles [60]. AI enables AVs to maintain optimal speeds, execute smooth acceleration and deceleration, and reduce unnecessary idling, all of which contribute to lower energy consumption. Additionally, AVs can be programmed to follow eco-driving strategies consistently, further enhancing energy efficiency [82].

Shared mobility services, such as ride-sharing and car-sharing platforms, utilize AI to match supply and demand effectively [77]. AI algorithms analyze user data, traffic conditions, and vehicle availability to optimize ride matching and routing, reducing the total number of vehicles needed to meet transportation needs [83]. By increasing vehicle occupancy rates and decreasing vehicle miles traveled per passenger, shared mobility can lead to significant energy savings and emission reductions [84].

The combination of autonomous and shared mobility offers synergistic benefits. Autonomous shared vehicles can operate continuously with minimal downtime, maximizing vehicle utilization and reducing the need for personal vehicle ownership [85]. AI manages fleet operations, including vehicle dispatching, routing, and charging schedules for electric AVs, ensuring efficient energy use across the entire system [86,87].

However, the impact of AVs and shared mobility on energy efficiency is not unilaterally positive. The convenience of these services may lead to increased travel demand or shifts from more energy-efficient modes like public transit. Therefore, the implementation of AI-driven autonomous and shared mobility systems must be accompanied by supportive policies and planning to realize their potential benefits fully.

Shared mobility faces several challenges and handicaps that hinder its widespread adoption. One significant issue is the low integration with public transport systems, which limits the seamless transition between different modes of transportation. Additionally, there is a lack of necessary infrastructure, such as charging stations for electric shared vehicles, which further complicates the adoption process. Regulatory barriers also pose a significant challenge, as existing laws and regulations may not adequately support the new models of shared mobility. Public nuisance, such as increased traffic congestion and noise, can also deter communities from embracing shared mobility solutions. These challenges are highlighted in the study by Coenegrachts (2021), which examines the potential of shared mobility hubs to overcome these barriers by integrating sustainable transportation modes into a coherent network [88] and policy uncertainties are also significant barriers to the adoption of autonomous vehicles in shared mobility. Safety concerns, high initial costs, and inadequate public communication infrastructure further complicate the situation. The absence of standardized regulations can hinder the widespread adoption of autonomous vehicles, as highlighted in the study by Tu (2024). This study emphasizes the need for clear policies and communication strategies to promote the use of autonomous vehicles in shared mobility markets [89].

Trust and acceptance issues, particularly across generational groups, also hinder the adoption of connected and autonomous vehicles. A study by Mutzenich (2024) [90] reveals that low trust and acceptance, especially among older generations, slow the transition to shared autonomy. The preference for private vehicle ownership remains a significant barrier to embracing shared mobility solutions. The study introduces the SASS Model, which categorizes individuals based on their inclinations towards connected and autonomous vehicles, suggesting tailored communication strategies to address these challenges. Furthermore, research by Fitschen et al. (2024) [91] highlights that shared mobility providers often fail to attract car drivers due to a lack of understanding of urban mobility challenges, emphasizing the need for strategies that address the specific preferences and concerns of car users.

Uncertainty regarding the acceptance and environmental impact of shared mobility remains a significant concern. The environmental impacts of shared mobility are mixed, as highlighted by Qi (2018) [92], who notes that while shared mobility can reduce the number of vehicles on the road, it may also lead to potential increases in emissions due to prolonged trip distances and increased vehicle miles traveled.

This complexity underscores the need for careful planning and implementation to ensure that shared mobility contributes positively to environmental goals.

Furthermore, the environmental benefits of shared mobility are not guaranteed and largely depend on factors such as travel behavior, local context, and the specific design of shared mobility systems. Vélez (2023) [93] emphasizes that the effectiveness of shared mobility in reducing emissions and energy consumption is contingent upon these variables, suggesting that a one-size-fits-all approach may not be effective.

The true environmental impact of shared e-scooters is still under investigation. Bozzi (2021) [94] raises concerns about the production and maintenance impacts of e-scooters, which may offset some of their environmental benefits. The lifecycle analysis of these devices is crucial to understanding their overall sustainability.

4. AI in Innovative Fuels and Powertrains

The advancement of innovative fuels and powertrains is critical for reducing the transport sector's reliance on fossil fuels and mitigating greenhouse gas (GHG) emissions. Artificial intelligence (AI) plays a transformative role in enhancing the efficiency, performance, and feasibility of alternative fuel technologies. This section explores how AI contributes to the development and optimization of hydrogen fuel cells and biofuels, offering potential pathways toward sustainable transport energy solutions [95,96] (Table 4).

Table 4. Comparative Analysis of AI-Enhanced Alternative Fuel Systems.

Alternative Fuel Type	AI Application	Energy Efficiency Improvement	GHG Emission Reduction (%)	Region
Hydrogen Fuel Cells	AI-based fuel optimization systems	20–25%	40–45%	Germany (H2 Mobility Initiative) [97,98]
Biofuels	AI for blending optimization	15–20%	30–35%	Brazil (Ethanol Program) [99,100]
Solar-Powered Vehicles	AI for solar panel efficiency	25–30%	50–60%	USA (Tesla Solar) [101]
Electric Vehicles	AI for battery life optimization	10–15%	20–25%	China (BYD EV) [102,103]

4.1. Hydrogen Fuel Cells

Hydrogen fuel cells represent a promising alternative to traditional internal combustion engines, offering zero tailpipe emissions and high energy efficiency. However, challenges such as high production costs, storage difficulties, and limited infrastructure have hindered their widespread adoption [104,105]. AI technologies address these challenges by optimizing various aspects of hydrogen fuel cell systems, from production and storage to system performance and lifecycle management [106,107].

4.1.1. Hydrogen Production Optimization

AI enhances hydrogen production processes by improving the efficiency of methods such as electrolysis, steam methane reforming, and biomass gasification. Machine learning algorithms analyze operational data to optimize reaction conditions, catalyst performance, and energy inputs, leading to higher hydrogen yields and lower energy consumption [108,109]. For instance, AI models can predict the optimal temperature and pressure settings for electrolysis processes, reducing operational costs and improving scalability [110,111].

4.1.2. Fuel Cell Performance and Durability

The performance and longevity of hydrogen fuel cells are critical for their commercial viability. AI contributes to the design and control of fuel cell systems by modeling complex electrochemical reactions and predicting system behavior under various conditions. Deep learning models can identify patterns in degradation mechanisms, enabling predictive maintenance and extending fuel cell lifespan. Additionally, AI-driven control systems adjust operating parameters in real-time to maintain optimal performance and efficiency [108,109].

4.1.3. Hydrogen Storage and Distribution

Effective hydrogen storage and distribution are essential for supporting fuel cell vehicles. AI assists in developing advanced storage materials and systems by predicting the properties of novel hydrogen storage alloys and composites through computational modeling. Furthermore, AI optimizes logistics for hydrogen distribution networks, analyzing demand patterns, transportation routes, and storage capacities to minimize costs and enhance reliability [110,111].

4.1.4. System Integration and Optimization

Integrating hydrogen fuel cells into vehicles requires careful system-level optimization. AI techniques, such as genetic algorithms and multi-objective optimization, help design fuel cell powertrains that balance performance, efficiency, and cost. AI models simulate vehicle dynamics and energy flows, enabling engineers to evaluate different configurations and control strategies without extensive physical prototyping [112–114].

4.1.5. Case Studies and Applications

Several real-world applications demonstrate AI's impact on hydrogen fuel cell technologies. For example, automotive manufacturers are utilizing AI to optimize fuel cell stack designs, reducing material usage and improving power density. In public transportation, AI-managed hydrogen buses are being deployed with optimized routing and refueling schedules, enhancing operational efficiency and reducing emissions in urban areas [115–117].

4.2. Biofuels and Alternative Fuels

Biofuels and other alternative fuels offer renewable and potentially carbon-neutral options for powering transport vehicles, especially in sectors where electrification is challenging, such as aviation and maritime transport. AI contributes to the advancement of these fuels by improving production processes, enhancing fuel properties, and optimizing engine performance [118–120].

4.2.1. Biofuel Production Enhancement

AI algorithms optimize biofuel production by modeling and controlling biochemical processes involved in converting biomass into fuels like bioethanol, biodiesel, and biogas. Machine learning models predict the optimal conditions for fermentation, enzymatic reactions, and microbial growth, increasing yield and reducing processing time. AI also aids in selecting suitable feedstocks and pretreatment methods, considering factors like availability, cost, and environmental impact [121,122].

4.2.2. Fuel Property Prediction and Improvement

The performance of biofuels depends on their chemical and physical properties. AI techniques, such as artificial neural networks and support vector machines, predict fuel properties based on molecular structures and processing parameters. This capability allows researchers to tailor biofuels with desired characteristics, such as higher energy density or better cold-flow properties, enhancing their suitability for various applications [117–119].

4.2.3. Engine Optimization for Alternative Fuels

Integrating alternative fuels into existing engines requires adjustments to engine design and operation. AI assists in optimizing combustion processes, injection timing, and air-fuel mixtures to accommodate biofuels and synthetic fuels. Computational models simulate engine performance with different fuel blends, enabling engineers to identify configurations that maximize efficiency and minimize emissions [123,124].

4.2.4. Waste-to-Fuel Technologies

AI supports the development of waste-to-fuel technologies by optimizing processes that convert waste materials into usable fuels. Machine learning models analyze the composition of waste streams and predict the outcomes of pyrolysis, gasification, and anaerobic digestion processes. This approach enhances the efficiency of converting municipal solid waste, agricultural residues, and industrial byproducts into renewable fuels, contributing to circular economy principles [125–127].

4.2.5. Policy and Sustainability Assessments

AI tools facilitate the assessment of biofuels' environmental and economic sustainability. Life cycle assessment (LCA) models integrated with AI analyze the energy inputs, GHG emissions, and resource usage associated with biofuel production and use. These analyses inform policy decisions by highlighting the trade-offs and benefits of different biofuel pathways, guiding investments and regulatory support [128,129].

4.2.6. Applications in Hard-to-Electrify Sectors

In aviation and shipping, where battery technologies face limitations due to weight and energy density, AI-optimized biofuels and synthetic fuels offer viable alternatives. AI aids in developing sustainable aviation fuels (SAFs) by optimizing feedstock selection and refining processes to produce fuels compatible with existing aircraft engines. Similarly, AI models support the creation of marine biofuels that meet the stringent performance and environmental requirements of the maritime industry [22,45,54]

5. Economic Analysis

The integration of artificial intelligence (AI) technologies into the transport sector carries significant economic implications. While AI offers substantial benefits in enhancing energy efficiency and reducing greenhouse gas (GHG) emissions, it also entails costs related to technology adoption, infrastructure development, and maintenance. This section provides an economic analysis focusing on the Total Cost of Ownership (TCO) of AI-enhanced transport systems and conducts a cost-benefit analysis to evaluate the economic viability of AI implementation in transportation [28,95]

5.1. Total Cost of Ownership (TCO)

The Total Cost of Ownership (TCO) is a comprehensive assessment of all costs associated with the acquisition, operation, and maintenance of a product or system over its entire lifecycle. In the context of AI-enhanced transport vehicles and infrastructure, TCO analysis is crucial for understanding the economic feasibility and competitiveness of these technologies compared to conventional options [127,128].

5.1.1. Components of TCO for AI-Enhanced Transport

The TCO for AI-integrated vehicles and systems encompasses several key components. Firstly, acquisition costs include the purchase price of AI-equipped vehicles, sensors, hardware, and software licenses required for AI functionalities. AI-enabled vehicles, such as autonomous vehicles (AVs) or those with advanced driver-assistance systems (ADAS), often have higher upfront costs due to the integration of sophisticated technologies. These initial expenses can be a barrier to adoption for individual consumers and fleet operators [129].

Secondly, infrastructure costs are significant, as implementing AI in transportation may require investments in supportive infrastructure. This includes communication networks for vehicle-to-infrastructure (V2I) connectivity, data centers for processing and storage, and charging stations for electric vehicles (EVs) with AI [130,131]. The development of such infrastructure is essential to realize the full potential of AI technologies but adds to the overall cost.

Operational costs are another crucial component, including energy or fuel costs, maintenance, repairs, and insurance. AI can influence these costs positively by improving fuel efficiency, predicting maintenance needs, and potentially reducing insurance premiums due to enhanced safety features [132]. For instance, AI-driven predictive maintenance can anticipate component failures before they occur, thereby reducing downtime and repair costs.

Maintenance and update costs are ongoing expenses associated with AI systems. These technologies require regular updates to software algorithms, cybersecurity measures, and hardware components. The costs associated with technical support, software updates, and system upgrades are integral to the TCO [133,134]. Ensuring that AI systems remain up-to-date and secure is vital for their effective operation but contributes to the long-term costs.

Finally, end-of-life costs must be considered. At the end of the vehicle's lifecycle, there may be costs or residual values associated with disposal, recycling, or resale. AI components may have specific requirements for disposal due to proprietary technology or data security concerns [135]. Proper handling of these components can add to the overall TCO.

5.1.2. Comparative TCO Analysis

Comparing the TCO of AI-enhanced vehicles with conventional vehicles provides insights into their economic competitiveness. Studies have shown that while the upfront costs of AI-equipped electric vehicles (EVs) are higher, lower operational and maintenance costs can offset these expenses over time. AI-driven energy management systems contribute to reduced energy consumption and lower fuel costs [136]. For example, intelligent battery management systems can optimize charging cycles, extending battery life and reducing electricity costs.

In the case of autonomous vehicles, the TCO remains significantly higher due to expensive sensor suites and computing systems required for full autonomy. However, when these vehicles are utilized in shared mobility services with high utilization rates, the cost per mile can become competitive with traditional vehicles [137]. The ability to operate continuously and serve multiple users increases the economic efficiency of autonomous vehicles in shared fleets.

For commercial fleets, AI-enabled optimization can lead to substantial savings in fuel costs, maintenance, and operational efficiency. The TCO for fleets may favor AI adoption due to economies of scale and the ability to spread costs over a larger number of vehicles [138]. Fleet operators can benefit from AI-driven route optimization, load management, and predictive maintenance, enhancing overall profitability.

5.1.3. Factors Influencing TCO

Several factors affect the TCO of AI-enhanced transport systems. Technological advancements play a significant role; as AI technologies mature and production scales up, costs are expected to decrease. Economies of scale in manufacturing sensors and computing hardware contribute to lower acquisition costs [139,140]. Moreover, advancements in software development and machine learning algorithms can improve performance while reducing computational requirements.

Energy prices also influence operational costs. Fluctuations in energy prices impact the cost-effectiveness of AI-driven energy savings. AI's role in improving energy efficiency can mitigate the effects of rising fuel or electricity prices by reducing overall consumption [141,142]. In regions with high energy costs, the benefits of AI-enhanced efficiency are more pronounced.

Policy incentives are crucial in affecting the TCO. Government incentives, such as tax credits, subsidies, or regulatory support, can significantly reduce the TCO for AI-equipped vehicles, encouraging adoption [143,144]. Policies that support research and development, infrastructure development, and consumer adoption can lower barriers to entry.

Insurance and liability considerations also impact the TCO. AI's potential to enhance safety could lower insurance costs due to reduced accident rates. However, uncertainties regarding liability in autonomous systems may introduce additional costs or require new insurance models [57,145,146]. Establishing clear legal frameworks for autonomous vehicles is essential to address these concerns.

5.2. Cost-Benefit Analysis

A cost-benefit analysis (CBA) evaluates the economic worthiness of investing in AI technologies in the transport sector by comparing the total expected costs with the anticipated benefits. This analysis helps determine whether the net benefits justify the investments and can guide decision-making for stakeholders.

5.2.1. Benefits of AI in Transport

AI offers multiple benefits in the transport sector that can translate into economic gains. One of the primary benefits is energy savings. AI contributes to significant reductions in energy consumption through optimized vehicle operations, efficient routing, and improved traffic management. These savings result in lower operational costs for users and operators [147,148]. For example, AI-enabled route optimization can reduce fuel consumption by selecting the most efficient paths, avoiding congestion, and adjusting to real-time traffic conditions.

Another significant benefit is the reduction of GHG emissions. By enhancing energy efficiency and promoting alternative fuels, AI helps reduce emissions, contributing to environmental sustainability. The societal benefits of emission reductions include improved public health due to better air quality, reduced environmental degradation, and progress toward climate change mitigation goals [149,150]. These benefits, while not always directly monetizable, have substantial economic value in terms of healthcare cost savings and ecosystem services.

Safety improvements are also a critical benefit of AI technologies in transport. AI enhances vehicle safety through advanced driver-assistance systems and autonomous driving capabilities. Reduced accident rates lead to lower costs associated with healthcare, property damage, and traffic disruptions [151,152]. The economic impact of increased safety includes lower insurance premiums and reduced societal costs from accidents.

Operational efficiency is another area where AI provides economic benefits. For commercial operators, AI optimizes logistics, fleet management, and maintenance schedules, leading to cost savings and increased productivity [153,154]. By minimizing downtime and maximizing vehicle utilization, businesses can improve profitability.

Furthermore, the development and deployment of AI in transport stimulate economic growth and innovation. This includes job creation in technology development, data analysis, and infrastructure projects. Technological innovation enhances competitive advantages in global markets [154,155]. The spillover effects of investing in AI technologies can have a positive impact on the broader economy.

5.2.2. Costs of AI Implementation

Implementing AI technologies in transportation involves various costs. Technological investment is substantial, encompassing expenses for research and development, acquisition of advanced hardware, and development of software systems. These initial costs can be significant barriers, especially for smaller operators or in developing regions.

Infrastructure upgrades are often necessary to support AI systems. This includes investments in connectivity infrastructure, such as 5G networks, data management systems, and energy supply upgrades like smart grids for EV charging [156]. The development of such infrastructure requires significant capital and coordination between public and private sectors [157].

Transition costs are associated with shifting from conventional systems to AI-enhanced systems. This includes retraining personnel to operate and maintain new technologies, managing legacy systems during the transition period, and potential disruptions to operations during the implementation phase.

Regulatory compliance introduces additional costs. Ensuring compliance with new regulations related to data privacy, cybersecurity, and safety standards may involve investments in legal counsel, compliance systems, and audits. Navigating the evolving regulatory landscape can be complex and resource-intensive.

5.2.3. Net Economic Impact

The net economic impact of AI adoption in transport depends on the balance between the quantified benefits and the associated costs. In scenarios where energy savings, operational efficiencies, and societal benefits outweigh the costs, AI implementation is economically justified. For example, AI-driven traffic management systems have demonstrated high benefit-cost ratios due to substantial reductions in congestion and emissions [158,159].

However, uncertainties and risks can affect the economic viability. Factors such as technology maturity, market acceptance, and policy changes can influence the outcomes. Sensitivity analyses are essential to assess how variations in key parameters impact the net benefits [160,161]. It is important to consider both optimistic and pessimistic scenarios to understand the range of possible outcomes.

Adopting a long-term perspective is crucial, as initial costs may be high, but benefits often accrue over the lifespan of the technology. Discounted cash flow analyses help evaluate the present value of future benefits relative to current investments [162]. Policymakers and investors need to consider the long-term horizon to fully appreciate the economic potential of AI in transport.

5.2.4. Policy Implications

Effective policies can enhance the cost-benefit outcomes of AI adoption. Financial incentives, such as subsidies or tax credits, can lower initial costs and accelerate market penetration of AI technologies. Regulatory support, including clear standards and guidelines, reduces uncertainties and encourages private investment.

Public-private partnerships can be instrumental in sharing risks and leveraging resources for infrastructure development. Collaboration between government and industry can facilitate large-scale projects that may be beyond the capacity of individual stakeholders.

6. Policy Implications

The integration of artificial intelligence (AI) into the transport sector holds significant promise for enhancing energy efficiency and reducing greenhouse gas (GHG) emissions [163]. However, realizing this potential requires supportive policy environments that address the unique challenges posed by AI technologies. This section examines the policy implications of AI adoption in transportation, focusing on regulatory frameworks and energy and fiscal policies that can facilitate or hinder the implementation of AI-driven solutions (Table 5).

Table 5. Policy Impacts of AI Adoption in Sustainable Transport.

Policy Type	AI Adoption Area	Potential Energy Savings (%)	GHG Reduction Potential (%)	Required Infrastructure Investments	Example Countries
Carbon Pricing Policies	AI for energy demand forecasting	15–20%	30–40%	Moderate	Germany, Sweden [164,165]
Emission Trading Schemes (ETS)	AI for fuel efficiency monitoring	20–25%	35–45%	High	EU, Canada [166,167]
Subsidies for Clean Technology	AI-driven autonomous transport	25–30%	40–50%	High	Norway, Netherlands [168,169]
Public Transport Development	AI-based traffic flow optimization	15–20%	20–30%	Moderate	Singapore, Japan [170]

6.1. Regulatory Frameworks

Regulatory frameworks play a critical role in shaping the development and deployment of AI technologies in transportation. Effective regulations can promote innovation, ensure safety, protect consumer interests, and encourage investment. Conversely, overly restrictive or unclear regulations may stifle technological advancement and delay the adoption of beneficial innovations.

6.1.1. Enabling Innovation While Ensuring Safety

One of the primary challenges in regulating AI in transport is balancing the promotion of innovation with the need to ensure safety and public trust. AI technologies, particularly in autonomous vehicles (AVs), introduce new operational paradigms that existing regulations may not adequately address. Traditional vehicle safety standards and traffic laws are based on human-driven vehicles and may not be applicable to AI-operated systems [171].

Regulators need to develop frameworks that accommodate the unique characteristics of AI technologies. This includes establishing performance-based standards that focus on outcomes rather than prescriptive technical requirements. For example, regulations could specify safety objectives for AVs without mandating specific technologies, allowing manufacturers the flexibility to innovate [172].

Furthermore, implementing rigorous testing and certification processes for AI systems is essential. Regulators can collaborate with industry stakeholders to develop standardized testing protocols that assess the safety and reliability of AI technologies under various conditions [173]. Transparent reporting and data sharing between companies and regulators can enhance oversight and build public confidence.

6.1.2. Addressing Liability and Legal Accountability

AI technologies in transport raise complex questions regarding liability and legal accountability in the event of accidents or malfunctions. Traditional liability frameworks assign responsibility to human drivers or vehicle owners, but AI systems introduce new actors such as software developers and data providers [174–176].

Regulatory frameworks need to clarify liability issues to ensure that victims have avenues for compensation and that responsible parties are held accountable. This may involve updating existing laws or creating new legislation that addresses the roles and responsibilities of manufacturers, operators, and users of AI systems [177].

Some jurisdictions are exploring concepts such as strict liability for manufacturers of AVs or establishing insurance models that account for AI-related risks [178]. Clear liability frameworks can reduce legal uncertainties, encourage investment, and promote responsible development of AI technologies.

6.1.3. Data Privacy and Security Regulations

AI systems rely heavily on data collection and processing, raising concerns about data privacy and cybersecurity. Regulations must address how data is collected, stored, used, and shared to protect individual privacy and prevent unauthorized access or misuse [178].

Data protection laws, such as the General Data Protection Regulation (GDPR) in the European Union, set strict guidelines for personal data handling. Transport-specific regulations may be needed to address the unique data flows associated with AI systems, including vehicle sensor data, user preferences, and operational information [179,180].

Cybersecurity is also a critical concern, as AI systems can be vulnerable to hacking and malicious attacks. Regulatory frameworks should mandate robust cybersecurity measures, regular vulnerability assessments, and incident reporting requirements to mitigate risks [181,182].

6.1.4. International Harmonization and Standardization

The global nature of the transport industry necessitates international harmonization of regulations and standards related to AI technologies. Divergent regulatory approaches across countries can create barriers to market entry, increase compliance costs, and hinder the scalability of AI solutions [183,184].

International bodies, such as the United Nations Economic Commission for Europe (UNECE) and the International Organization for Standardization (ISO), play vital roles in developing harmonized standards and facilitating cooperation among regulators [185,186]. Collaborative efforts can lead to the adoption of common safety standards, testing procedures, and certification processes, promoting consistency and interoperability.

6.1.5. Ethical Considerations and Public Engagement

Regulatory frameworks should also address the ethical implications of AI in transport. This includes considerations related to algorithmic transparency, fairness, and the avoidance of biased decision-making [187,188]. Engaging with the public and stakeholders is essential to understand societal values and expectations.

Policymakers can establish ethical guidelines for AI development and deployment, encouraging companies to adopt responsible practices. Mechanisms for public consultation and participation in policy development can enhance legitimacy and acceptance of AI technologies [189,190].

6.2. Energy and Fiscal Policies

Energy and fiscal policies are instrumental in influencing the adoption of AI technologies in the transport sector. These policies can provide incentives for investment, shape market conditions, and align economic interests with environmental objectives.

6.2.1. Engagement Incentives for Sustainable Transport Solutions

Fiscal policies, such as subsidies, tax credits, and grants, can encourage the adoption of AI-enhanced vehicles and infrastructure. Governments can offer financial incentives for purchasing AI-equipped electric vehicles (EVs), installing smart charging stations, or investing in AI-based fleet management systems [191].

For example, providing rebates or tax deductions for consumers who purchase AI-enabled EVs can offset higher upfront costs and stimulate market demand. Similarly, offering grants to companies that invest in AI technologies for energy efficiency can accelerate innovation and deployment.

6.2.2. Carbon Pricing and Emission Regulations

Implementing carbon pricing mechanisms, such as carbon taxes or cap-and-trade systems, internalizes the environmental costs of GHG emissions and creates economic incentives for low-emission technologies [191]. By increasing the cost of carbon-intensive fuels, these policies make energy-efficient and alternative fuel vehicles more competitive.

Emission regulations that set limits on GHG emissions from vehicles can drive manufacturers to adopt AI technologies that enhance efficiency and reduce emissions. Compliance with stringent emission standards may necessitate the integration of AI systems for optimized engine performance, energy management, and emission controls [191,192].

6.2.3. Investment in Infrastructure and Research

Government investment in infrastructure is crucial for supporting AI technologies in transport. Funding the development of communication networks, data management systems, and charging infrastructure enables the effective operation of AI systems [193,194].

Additionally, investing in research and development (R&D) through public funding or partnerships can advance AI innovations. Supporting universities, research institutions, and startups in developing AI applications for transport can lead to breakthroughs in efficiency and sustainability [192–194].

6.2.4. Addressing Socioeconomic Impacts

Energy and fiscal policies should consider the socioeconomic implications of AI adoption. This includes addressing potential job displacement due to automation and ensuring equitable access to AI-enhanced transport services [195].

Policymakers can implement retraining programs for workers affected by automation, helping them acquire new skills relevant to emerging industries. Ensuring that benefits of AI technologies, such as improved public transportation, are accessible to all segments of society promotes inclusivity and social equity [196].

6.2.5. International Cooperation on Energy Policies

Global challenges like climate change require coordinated international efforts. Collaborating on energy policies, sharing best practices, and aligning incentives can amplify the impact of national initiatives [197].

International agreements and partnerships can facilitate the diffusion of AI technologies by harmonizing standards, reducing trade barriers, and pooling resources for large-scale projects. Joint efforts can accelerate progress toward global emission reduction targets and sustainable development goals.

6.2.6. Monitoring and Evaluation of Policy Effectiveness

Regular monitoring and evaluation of energy and fiscal policies are essential to ensure their effectiveness. Data-driven assessments can inform policymakers about the impact of incentives, regulations, and investments on AI adoption and environmental outcomes [198].

Adjusting policies based on empirical evidence allows for continuous improvement and adaptation to changing technological landscapes. Transparency in reporting and stakeholder engagement enhances accountability and public trust.

7. Challenges and Future Directions

The integration of artificial intelligence (AI) into the transport sector presents significant opportunities for enhancing energy efficiency and reducing greenhouse gas (GHG) emissions. However, several challenges must be addressed to fully realize this potential. This section discusses the technological, economic, institutional, ethical, and social challenges associated with AI adoption in transportation and outlines future research directions to overcome these barriers.

7.1. Technological Challenges

Despite advancements in AI technologies, several technical obstacles hinder their widespread implementation in transportation systems.

7.1.1. Data Quality and Availability

AI systems rely heavily on large volumes of high-quality data for training and operation. In transportation, data may come from various sources, including sensors, vehicles, infrastructure, and users. Ensuring the accuracy, consistency, and completeness of this data is challenging [199,200]. Data silos and lack of standardization impede data sharing between stakeholders, limiting the effectiveness of AI applications.

7.1.2. Computational Requirements

AI algorithms, particularly deep learning models, demand substantial computational resources. Processing large datasets and running complex models in real-time for applications like autonomous driving or dynamic traffic management require high-performance computing infrastructure [201]. The cost and energy consumption associated with these computational needs can be prohibitive, especially in resource-constrained settings.

7.1.3. System Integration and Interoperability

Integrating AI technologies into existing transportation systems poses technical challenges. Compatibility issues between new AI components and legacy systems can result in operational inefficiencies or system failures [202,203]. Achieving interoperability among different AI applications, vehicles, and infrastructure requires standardized communication protocols and interfaces, which are still under development.

7.1.4. Reliability and Robustness

AI systems must perform reliably under diverse and unpredictable real-world conditions. Ensuring robustness against environmental factors, sensor failures, and unforeseen scenarios is critical for safety and efficiency [204]. Developing AI models that can generalize well and handle edge cases remains a significant technical hurdle.

7.1.5. Cybersecurity Threats

As AI systems become more connected and data-driven, they are increasingly vulnerable to cyberattacks. Unauthorized access, data breaches, and malicious interference can compromise the safety and functionality of AI-enhanced transportation [205,206]. Implementing robust cybersecurity measures is essential but adds complexity to system design and maintenance.

7.2. Economic and Institutional Barriers

Beyond technical challenges, economic and institutional factors can impede the adoption of AI technologies in transport.

7.2.1. Market Uncertainties

The evolving nature of AI technologies introduces market uncertainties. Rapid technological changes can render investments obsolete, discouraging stakeholders from committing resources [207,208]. Additionally, unclear market demand for AI-enhanced transport solutions can affect the scalability and profitability of such ventures.

7.2.2. Institutional Resistance to Change

Organizations may resist adopting AI technologies due to institutional inertia, risk aversion, or lack of understanding. Established procedures, regulations, and organizational cultures can hinder innovation and adaptation [209,210]. Overcoming institutional barriers requires leadership, education, and change management strategies.

7.2.3. Regulatory and Policy Gaps

Inadequate or outdated regulatory frameworks can slow down the implementation of AI in transportation. Ambiguities in legal responsibilities, safety standards, and compliance requirements create uncertainties that deter investment and development [210,211]. Aligning policies with technological advancements is necessary to facilitate progress.

7.2.4. Workforce Displacement and Skill Gaps

The introduction of AI technologies may displace certain job categories, leading to social and economic challenges. Simultaneously, there is a growing demand for skilled professionals capable of developing, managing, and maintaining AI systems [212,213]. Addressing workforce transitions and education is essential to mitigate negative impacts.

7.3. Ethical and Social Considerations

The deployment of AI in transportation raises important ethical and social issues that must be carefully considered.

7.3.1. Privacy Concerns

AI systems often collect and process vast amounts of personal data, raising concerns about privacy and data protection. Ensuring that data collection practices comply with legal and ethical standards is crucial to maintain public trust [214].

7.3.2. Bias and Fairness

AI algorithms can inadvertently perpetuate or amplify existing biases present in training data, leading to unfair outcomes [215,216]. In transportation, biased AI systems could result in unequal service provision, discrimination, or safety risks for certain groups.

7.3.3. Transparency and Accountability

The complexity of AI models, particularly deep learning networks, can make it difficult to understand their decision-making processes. This "black box" nature poses challenges for transparency and accountability, especially in critical applications like autonomous vehicles [216,217]. Developing explainable AI is necessary to address these concerns.

7.3.4. Ethical Decision-Making in Autonomous Systems

Autonomous vehicles may face ethical dilemmas requiring decisions that have moral implications, such as unavoidable accident scenarios. Programming ethical decision-making into AI systems raises complex philosophical and practical questions [37,134,187]. Societal consensus on ethical frameworks is needed to guide developers.

7.3.5. Social Acceptance and Trust

Public acceptance of AI technologies in transportation is essential for their successful adoption. Concerns about safety, job losses, and loss of control can lead to resistance [186]. Building trust through transparent communication, demonstrations of safety, and engagement with communities is vital.

7.4. Future Research Opportunities

Addressing the challenges outlined above presents numerous opportunities for future research and development.

7.4.1. Advancing AI Algorithms and Models

Research into more efficient, robust, and explainable AI algorithms can overcome technological barriers. Developing models that require less data and computational power while maintaining performance can enhance accessibility [218,219]. Developing hybrid models that integrate AI algorithms—such as machine learning or neural networks—with traditional control systems like proportional-integral-derivative (PID) controllers can enhance reliability by combining AI's adaptability with the stability and predictability of conventional methods.

7.4.2. Enhancing Data Management and Sharing

Innovations in data management, including the use of distributed ledger technologies like blockchain, can improve data quality, security, and sharing among stakeholders [189]. Establishing data standards and interoperable platforms facilitates collaboration and accelerates AI development.

7.4.3. Interdisciplinary Approaches

Integrating insights from engineering, economics, sociology, ethics, and other disciplines is essential to address the multifaceted challenges of AI in transportation. Interdisciplinary research can inform holistic solutions that consider technical feasibility, economic viability, and societal impact [217,220].

7.4.4. Policy and Governance Studies

Research into effective policy frameworks and governance models can support the responsible deployment of AI technologies. Comparative studies of regulatory approaches, impact assessments, and stakeholder analyses can guide policymakers in crafting supportive environments [212,221].

7.4.5. Human-AI Interaction and Interface Design

Improving the interaction between humans and AI systems enhances usability and safety. Research into user-centered design, intuitive interfaces, and collaborative control mechanisms can facilitate acceptance and effectiveness [23,175]. Understanding human factors and ergonomics is crucial in applications like driver-assistance systems.

7.4.6. Socioeconomic Impact Analysis

Evaluating the long-term socioeconomic impacts of AI adoption in transportation informs strategies to manage transitions. Studies on employment effects, equity considerations, and regional development can guide interventions to maximize benefits and minimize adverse outcomes [211].

7.4.7. Sustainability Assessments

Assessing the environmental impacts of AI technologies themselves, including energy consumption and resource use, ensures that solutions contribute positively to sustainability goals. Life cycle analyses and eco-design principles can inform the development of greener AI systems [215,220,221].

7.5. Estimation Limitations and Future AI Advancements

We acknowledge that some of the percentage figures presented in this paper are based on estimations derived from current data and technological capabilities. These estimations, while grounded in the best available research, may not fully capture the future potential of AI technologies in the transport sector. As computing capacities expand and AI algorithms become more sophisticated, the effectiveness of AI applications in enhancing energy efficiency and reducing GHG emissions is likely to increase significantly [222,223]. Future advancements may lead to more accurate models, real-time data processing, and adaptive systems that can further optimize transport operations beyond current expectations [224]. Therefore, the actual improvements in energy efficiency and emission reductions could surpass the estimates provided in this study. We emphasize the importance of ongoing research and the need for adaptive strategies that can accommodate rapid technological advancements in AI and computing power.

7.6. Patent Analysis

The analysis of patent trends in AI for energy efficiency and GHG emissions reduction in transport reveals several insights. A study on the Visegrád [225] countries found that an increase in patents led to a reduction in GHG emissions, indicating a positive impact of innovation on emissions reduction. However, another study focusing on 12 OECD countries found no direct evidence that the number of patents affected GHG emissions in the transport sector, suggesting that patents alone may not be sufficient to drive significant emissions reductions [226]. Additionally, the historical trends in patents for climate change mitigation technology show a relationship between international agreements like the Kyoto Protocol and technological innovation, highlighting the role of policy in fostering innovation [227].

These findings suggest that while patents and technological innovation are crucial, their effectiveness in reducing emissions may depend on complementary factors such as policy support and broader technological integration.

8. Conclusions

This paper has explored the emerging role of artificial intelligence (AI) in enhancing energy efficiency and reducing greenhouse gas (GHG) emissions within the transport sector. Through a comprehensive literature review and analysis of current applications, we have identified several key areas where AI is making significant contributions.

Firstly, AI technologies are optimizing vehicle energy management by enabling intelligent control systems, predictive maintenance, and adaptive driving strategies. These advancements lead to reduced fuel consumption and extended vehicle lifespans. Secondly, AI-driven route optimization and traffic management systems are improving traffic flow, decreasing congestion, and minimizing unnecessary idling, thereby lowering overall energy use and emissions at the systemic level.

The integration of autonomous vehicles and shared mobility services represents a transformative shift, with AI at the core of these developments. Autonomous electric vehicles, when combined with shared mobility models, have the potential to significantly reduce the number of vehicles on the road, enhance utilization rates, and decrease per-mile emissions.

AI is also playing a critical role in the advancement of innovative fuels and powertrains. In hydrogen fuel cell technology, AI optimizes production processes, enhances fuel cell performance, and improves storage and distribution logistics. For biofuels and alternative fuels, AI aids in production efficiency, fuel property enhancement, and engine optimization, facilitating the adoption of these sustainable energy sources in transport.

Economic analyses indicate that while the initial costs of AI implementation can be high, the long-term benefits—such as energy savings, operational efficiencies, and emission reductions—can outweigh these expenses. Total Cost of Ownership (TCO) and cost-benefit analyses support the economic viability of AI-enhanced transportation solutions, especially when supported by appropriate policies and incentives.

Policy implications highlight the need for adaptive regulatory frameworks that balance innovation with safety and ethical considerations. Energy and fiscal policies are instrumental in incentivizing AI adoption, investing in necessary infrastructure, and managing socioeconomic impacts.

Case studies from both developed and developing countries demonstrate the practical applications and benefits of AI in transportation. These examples showcase reductions in energy consumption and emissions, improved service efficiency, and the scalability of AI solutions across diverse contexts.

However, challenges remain in technological, economic, institutional, ethical, and social domains. Addressing data quality, computational demands, system integration, and cybersecurity is essential. Economic and institutional barriers, such as high initial investments and regulatory gaps, require strategic interventions. Ethical and social considerations, including privacy, bias, transparency, and public trust, must be carefully managed.

8.1. Implications for Stakeholders

The findings of this study have significant implications for various stakeholders involved in the transport sector:

- Policymakers: There is a clear need for supportive policies and regulatory frameworks that facilitate AI adoption while ensuring safety, ethical standards, and public trust. Policymakers should consider incentives, investments in infrastructure, and collaboration with international bodies to harmonize standards and regulations.
- Industry Players: Automotive manufacturers, technology companies, and transport service providers can leverage AI to enhance competitiveness, improve efficiency, and contribute to sustainability goals. Strategic investments in AI technologies, partnerships, and innovation are crucial.
- Researchers and Academics: The challenges identified highlight opportunities for further research in AI algorithm development, data management, interdisciplinary approaches, policy analysis, and human-AI interaction. Collaborative efforts can drive advancements that address existing barriers.
- Consumers and the Public: Increased awareness of the benefits and implications of AI in transport can influence acceptance and adoption. Engaging with communities, addressing concerns, and demonstrating the tangible benefits of AI-enhanced transportation are essential for building trust.
- Environmental Organizations: The potential of AI to contribute to emission reductions aligns with environmental objectives. Advocacy and collaboration with stakeholders can promote sustainable practices and technologies.

8.2. Final Thoughts

Artificial intelligence stands at the forefront of transforming the transport sector toward greater energy efficiency and environmental sustainability. The convergence of AI with transportation offers unprecedented opportunities to address some of the most pressing challenges of our time, including climate change and resource depletion.

While the potential benefits are substantial, realizing them requires concerted efforts to overcome technological hurdles, economic constraints, institutional inertia, and ethical dilemmas. It necessitates a holistic approach that integrates technological innovation with supportive policies, economic incentives, and societal engagement.

The journey toward AI-enhanced sustainable transportation is complex and multifaceted. However, the examples and analyses presented in this paper demonstrate that progress is not only possible but already underway in various parts of the world. By learning from these experiences and addressing the challenges collaboratively, stakeholders can accelerate the transition to a more efficient, clean, and intelligent transport system.

In conclusion, AI has the capacity to revolutionize transportation, delivering significant energy savings and emission reductions. Embracing this potential is imperative for achieving global sustainability targets and fostering a more resilient and equitable future.

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