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Digital Transformation for Sustainable Transportation: Leveraging Industry 4.0 Technologies to Optimize Efficiency and Reduce Emissions

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Abstract: This study investigates how Industry 4.0 technologies can optimize transportation efficiency and contribute to global sustainability goals by reducing CO_2 emissions. In response to the pressing climate emergency, the research examines the role of the Internet of Things (IoT), Artificial Intelligence (AI), and predictive analytics in enhancing operational performance and aligning transportation systems with Sustainable Development Goals (SDGs), particularly Goal 13 (climate action) and Goal 9 (industry, innovation, and infrastructure). Using a qualitative research approach, semi-structured interviews and focus groups were conducted with industry experts, and the data were analyzed using thematic analysis and qualitative network mapping in NVivo software. The findings reveal that IoT enhances real-time monitoring, AI enables dynamic route optimization, and predictive analytics supports proactive maintenance, collectively achieving an average emission reductions of 30%. However, adoption is hindered by infrastructure gaps, high implementation costs, skill shortages, and fragmented regulatory frameworks. This study integrates the Technology–Organization–Environment (TOE) framework and Sustainable Corporate Theory to provide a structured analysis of digital transformation in transportation. The findings offer strategic insights for policymakers and industry stakeholders, highlighting the need for stronger regulatory support, targeted incentives, and digital infrastructure investments.

Keywords: Industry 4.0; sustainable transportation; IoT; emission reduction

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Academic Editor: Antonio Comi

Received: 20 December 2024
Revised: 11 March 2025
Accepted: 24 March 2025
Published: 31 March 2025

Citation: Fatorachian, H.; Kazemi, H.; Pawar, K. Digital Transformation for Sustainable Transportation: Leveraging Industry 4.0 Technologies to Optimize Efficiency and Reduce Emissions. *Future Transp.* **2025**, *5*, 34. https://doi.org/10.3390/futuretransp5020034

1. Introduction

The transportation sector is a critical contributor to global greenhouse gas emissions, accounting for approximately 24% of total CO_2 emissions, with road transport as the dominant source [1]. This significant contribution underscores the need for transformative action to decarbonize transportation systems and align them with the ambitious targets set by the Paris Agreement, which aims to limit global warming to 1.5 °C above pre-industrial levels [2]. The urgency of this challenge is heightened by increasing urbanization and the demand for mobility, which place additional pressure on existing transportation networks to enhance efficiency and reduce their environmental impact.

Digital transformation, underpinned by Industry 4.0 technologies, has emerged as a promising solution for addressing inefficiencies and reducing emissions in transportation systems. Technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), big data analytics, and predictive maintenance have already demonstrated their potential to revolutionize operations in supply chains and logistics by enabling real-time monitoring, dynamic decision-making, and predictive capabilities [3,4]. This is further supported by Fatorachian and Kazemi (2021), who demonstrate how Industry 4.0 technologies significantly improve supply chain performance through enhanced operational efficiency and data-driven decision-making [5]. For instance, IoT devices can provide continuous feedback on vehicle performance and route conditions, while AI algorithms dynamically optimize routing to reduce fuel consumption and greenhouse gas emissions [6,7]. These advancements offer a pathway to reimagine transportation networks as systems that are not only more efficient but also more sustainable.

Despite the evident potential of Industry 4.0 technologies, their adoption in the transportation sector remains fragmented. Challenges such as inadequate infrastructure, high costs of implementation, and resistance to change limit the widespread integration of these technologies [8,9]. Moreover, while the broader benefits of digital transformation are well documented, there is limited research specifically examining its role in sustainable transportation, particularly in terms of emission reductions and operational optimization. This gap calls for focused studies to explore how Industry 4.0 principles can be strategically applied to advance global sustainability goals.

To address these gaps, this study investigates how digital transformation, powered by Industry 4.0 technologies, can be leveraged to create efficient and low-emission transportation systems. The findings of this research are anticipated to contribute significantly to the achievement of the United Nations' Sustainable Development Goals (SDGs), particularly Goal 13 on climate action and Goal 9 on industry, innovation, and infrastructure [10]. By identifying practical strategies to optimize transportation efficiency and reduce emissions, this study holds significant value for policymakers, industry leaders, and researchers striving for greener and more resilient mobility solutions.

Building on this context, the study is guided by the following objectives:

1. Evaluate the transformative potential of Industry 4.0 technologies in achieving sustainable transportation systems.
2. Analyze how digital solutions can optimize efficiency, reduce fuel consumption, and mitigate CO_2 emissions.
3. Identify the challenges and enablers in adopting these technologies within transportation networks.

This focused exploration aims to bridge the existing knowledge gap and provide a robust foundation for future research and practical implementations in the domain of sustainable transportation.

This paper is organized into five sections. The Introduction highlights the role of Industry 4.0 technologies in addressing transportation inefficiencies and achieving sustainability goals. The Literature Review examines key themes, including the transformative potential of IoT, AI, and predictive analytics; barriers to adoption; and the guiding theoretical frameworks—the Technology–Organization–Environment (TOE) framework and Sustainable Corporate Theory. The Methodology outlines the qualitative research approach, detailing data collection through semi-structured interviews and focus groups, and the use of thematic and network analyses with NVivo software. The Data Analysis and Findings present key insights on technology adoption, operational efficiency, emission reductions, and adoption barriers, supported by visualizations. Finally, the Discussion links findings to the research objectives and theoretical frameworks, and the Conclusion summarizes contributions to theory and practice, offering future research directions on emerging technologies and region-specific challenges.

2. Literature Review

The literature review explores the interplay between digital transformation and sustainable transportation, focusing on the application of Industry 4.0 technologies to optimize operational efficiency and reduce emissions. It delves into key themes relevant to the study's objectives, including the role of Industry 4.0, IoT, and AI in transportation, digital solutions for emission reductions, and barriers to technological adoption.

2.1. Industry 4.0 and Sustainable Transportation

Industry 4.0 represents the integration of advanced technologies such as IoT, AI, big data analytics, and automation into traditional systems, leading to enhanced operational efficiency and sustainability. In transportation, these technologies facilitate real-time monitoring, predictive maintenance, and dynamic decision-making, which are pivotal for optimizing resource utilization and minimizing the environmental impact [11].

The concept of smart transportation systems, driven by Industry 4.0, has gained traction as a pathway to achieve Sustainable Development Goals (SDGs). Building on this, Fatorachian (2024) highlights how Industry 5.0 principles, including eco-innovation, can further enhance the alignment of transportation systems with sustainability and ethical goals [12]. These systems enable the seamless integration of data across transportation networks, improving coordination and decision-making while reducing inefficiencies [4]. For example, IoT-powered sensors and AI algorithms have been shown to enhance fleet management by predicting vehicle maintenance needs and optimizing fuel consumption [6].

However, while Industry 4.0 technologies hold immense promise, their adoption in transportation is still in its nascent stages. The lack of sector-specific frameworks limits the strategic application of these technologies for sustainability outcomes, creating a critical research gap [8].

2.2. The Role of IoT and AI in Sustainable Transportation

IoT and AI are central to Industry 4.0, offering transformative capabilities for the transportation sector. IoT devices collect real-time data on vehicle performance, traffic conditions, and environmental factors, enabling proactive measures to reduce inefficiencies [7]. For instance, IoT-enabled systems can monitor tire pressure, engine performance, and fuel usage, alerting operators to potential issues before they escalate [6].

AI complements IoT by analyzing the vast datasets generated and providing actionable insights. AI-driven algorithms optimize routing and scheduling to minimize travel time and fuel consumption, thereby reducing emissions. In freight transportation, predictive analytics powered by AI has significantly enhanced load management, ensuring vehicles operate at optimal capacity [13].

Despite these advancements, challenges such as data security, interoperability, and high implementation costs continue to hinder the widespread adoption of IoT and AI in transportation. Addressing these barriers is essential to fully realize their potential for emission reductions and operational efficiency [9].

2.3. Digital Solutions for Emission Reductions

The transportation sector's significant contribution to global emissions necessitates the adoption of digital solutions for sustainable practices. Digital technologies such as IoT, blockchain, and big data analytics enable enhanced monitoring and transparency, which are critical for emissions tracking and reduction [14]. Blockchain technology, for instance, ensures the end-to-end traceability of goods, reducing emissions by improving supply chain efficiency and minimizing redundant routes [15].

Big data analytics play a pivotal role in identifying patterns and inefficiencies within transportation systems, facilitating data-driven decisions that align with sustainability goals. Tsigdinos et al. (2024) exemplify this by demonstrating how the integration of user preferences with spatial analysis can optimize public transport routes in rural areas, thereby reducing inefficiencies and emissions [16]. Similarly, predictive analytics has proven particularly effective in forecasting demand, optimizing resource allocation, and mitigating environmental impact [4].

However, achieving emission reduction through digital solutions requires overcoming challenges such as technological readiness, stakeholder alignment, and regulatory compliance. Research indicates that integrating these solutions into existing transportation systems often demands significant structural changes, underscoring the need for comprehensive strategies [8].

2.4. Barriers to Technological Adoption in Transportation

While the potential benefits of digital transformation are well documented, the adoption of Industry 4.0 technologies in transportation faces numerous barriers. Among these, infrastructure deficits—such as inadequate connectivity and outdated systems—pose significant challenges [9]. Tadesse et al. (2021) further underscore this issue, highlighting how insufficient digital infrastructure in low-income countries hampers the adoption of sustainable logistics practices, emphasizing the need for tailored, region-specific solutions [17]. Additionally, the high initial costs of implementing advanced technologies discourage investment, particularly in low- and middle-income regions [8].

Resistance to change, at both the organizational and individual levels, further complicates technological adoption. Studies highlight that a lack of technical expertise and a reluctance to transition from traditional methods often delay the integration of digital solutions [11]. Regulatory constraints, including fragmented policies and limited incentives for sustainable practices, also hinder progress.

To address these barriers, a multi-faceted approach involving public–private partnerships, capacity building, and supportive policy frameworks is essential. These measures can create an enabling environment for the widespread adoption of digital solutions in transportation [7].

2.5. Knowledge Gap and Research Directions

While substantial research exists on the applications of Industry 4.0 in logistics and supply chains, limited attention has been given to its role in emission reduction within the transportation sector [4]. Furthermore, the focus on theoretical discussions rather than empirical investigations has resulted in a lack of actionable frameworks for integrating digital technologies into sustainable transportation strategies.

Future research must address these gaps by exploring region-specific applications of Industry 4.0 technologies, assessing their long-term impact on emission reduction and identifying best practices for overcoming adoption barriers. Comparative studies across different transportation modalities can also provide valuable insights into the scalability and adaptability of these technologies [8].

3. Theoretical Background

Digital transformation in transportation systems is a multifaceted phenomenon, influenced by technological, organizational, and societal dynamics. To analyze this complexity, theoretical frameworks offer critical insights into adoption drivers, implementation barriers, and sustainability outcomes. This section explores four theories relevant to the study—the Technology–Organization–Environment (TOE) framework, the Resource-Based View (RBV), Sustainable Corporate Theory, and Diffusion of Innovation (DOI) theory—and justifies the selection of two for integration.

3.1. Technology–Organization–Environment (TOE) Framework

The TOE framework, introduced by Tornatzky and Fleischer (1990), provides a comprehensive lens for examining the adoption of new technologies. It considers three dimensions: technological, organizational, and environmental [18]. The technological dimension evaluates the availability, suitability, and performance of tools such as IoT, AI, and big data analytics, which are pivotal for enhancing transportation efficiency and reducing emissions. The organizational dimension assesses internal readiness, including infrastructure, workforce expertise, and leadership commitment, while the environmental dimension focuses on external drivers such as regulatory policies, competitive pressures, and societal demands for sustainability [19,20].

In the context of sustainable transportation, the TOE framework systematically captures the interplay of internal and external factors influencing the adoption of Industry 4.0 technologies. For example, while IoT sensors can facilitate the real-time monitoring of vehicle performance, their effectiveness depends on organizational readiness, such as having skilled personnel to interpret and act on data insights. Simultaneously, environmental drivers like regulatory mandates on emission reduction can accelerate technological adoption. The holistic nature of the TOE framework makes it particularly suited to analyzing the multi-dimensional challenges and opportunities in deploying Industry 4.0 technologies for sustainable transportation.

3.2. Resource-Based View (RBV)

The Resource-Based View (RBV) emphasizes the strategic importance of internal resources in achieving competitive advantage. Proposed by Barney (1991), the theory posits that resources must be valuable, rare, inimitable, and non-substitutable (VRIN) to confer a sustained advantage [21]. In the transportation sector, digital technologies such as IoT, AI, and blockchain represent such resources, enabling organizations to optimize operations, enhance transparency, and reduce emissions [22]. For instance, AI-driven algorithms can dynamically adjust routes to minimize fuel consumption, aligning with both economic and environmental objectives.

However, the RBV also highlights the need for complementary capabilities to fully leverage these resources. Organizations must invest in training, infrastructure, and integration strategies to unlock the potential of digital tools. In the context of sustainable transportation, this might involve developing predictive maintenance systems to reduce vehicle downtime and emissions or deploying blockchain solutions to ensure transparency in emissions reporting. While RBV provides valuable insights into the role of internal capabilities, it lacks a focus on external factors such as regulatory pressures, which are critical in sustainability contexts.

3.3. Sustainable Corporate Theory

Sustainable Corporate Theory provides a normative framework for integrating environmental, social, and governance (ESG) considerations into business operations. The theory posits that businesses have an ethical obligation to minimize their ecological footprint while addressing societal needs [23]. In the transportation sector, this translates to reducing emissions, enhancing resource efficiency, and fostering transparency through digital solutions.

This theory aligns with the goals of sustainable transportation, emphasizing the integration of technological innovation with broader sustainability objectives. For example, blockchain technology can enhance accountability by tracking emissions across the supply chain, while IoT devices can monitor and mitigate inefficiencies in real time [24]. By embedding sustainability principles into operational strategies, organizations not only comply with regulatory requirements but also gain competitive and reputational advantages. However, the theory's normative focus limits its ability to address the technical and organizational factors influencing digital transformation, necessitating integration with a more structured framework like TOE.

3.4. Diffusion of Innovation (DOI) Theory

The Diffusion of Innovation (DOI) theory, developed by [25], examines how innovations are adopted within and across organizations. It identifies key factors influencing adoption, including perceived relative advantage, compatibility with existing systems, and complexity of implementation. In transportation, DOI theory is particularly relevant for understanding the varying adoption rates of Industry 4.0 technologies. For instance, IoT solutions that are easily integrated with existing infrastructure may see faster adoption compared to complex AI algorithms requiring extensive customization [25].

DOI theory also highlights the role of early adopters in demonstrating the value of new technologies, thereby encouraging wider adoption. This is critical in sustainable transportation, where pilot projects showcasing emission reductions and efficiency gains can drive broader implementation. However, DOI theory primarily focuses on the innovation adoption process and does not account for external factors like policy frameworks, which are vital in sustainability contexts.

3.5. Proposed Theoretical Framework

To provide a robust foundation for analyzing digital transformation in sustainable transportation, this study integrates the TOE framework and Sustainable Corporate Theory.

The TOE framework offers a structured approach to examining the technological, organizational, and environmental factors influencing the adoption of Industry 4.0 technologies, ensuring a comprehensive understanding of barriers and enablers in implementing digital solutions for emission reductions. For example, it can analyze how regulatory incentives (environmental dimension) and organizational readiness (organizational dimension) interact to drive the adoption of IoT-enabled monitoring systems.

Meanwhile, Sustainable Corporate Theory embeds ethical and environmental imperatives into the analysis, aligning technological adoption with ESG principles. This ensures the study addresses not only operational efficiency but also broader societal and environmental objectives. For instance, it underscores the importance of integrating blockchain for transparency in emissions tracking, fostering accountability across transportation networks.

Together, these theories provide a synergistic framework (Figure 1), where the TOE framework addresses practical and contextual aspects of technological adoption, and Sustainable Corporate Theory ensures alignment with sustainability goals. This dual approach allows for a nuanced analysis of how Industry 4.0 technologies can optimize transportation systems and contribute to global sustainability efforts.

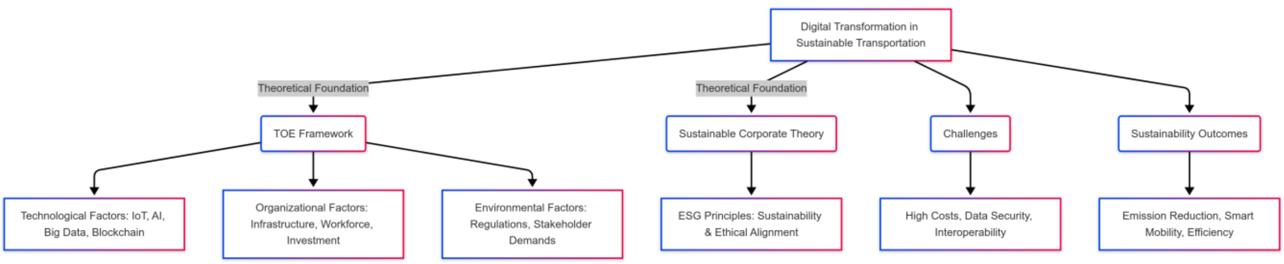

Figure 1. Proposed framework.

4. Methodology

This study adopts a qualitative research design to explore the transformative potential of Industry 4.0 technologies in sustainable transportation. A qualitative approach allows for an in-depth understanding of complex, multi-dimensional phenomena, such as the integration of advanced technologies into organizational processes to achieve sustainability goals. The exploratory nature of this research aligns with the objective of uncovering nuanced insights into how digital solutions can optimize transportation systems, reduce emissions, and address operational inefficiencies [26].

Furthermore, qualitative methods provide the flexibility to examine contextual factors and stakeholder perspectives, which are essential for addressing the multi-dimensional constructs of the Technology–Organization–Environment (TOE) framework and Sustainable Corporate Theory. These frameworks guide the study in analyzing the internal and external factors influencing Industry 4.0 adoption in transportation while ensuring alignment with sustainability objectives.

The methodology centers on semi-structured interviews and focus groups as the primary data collection methods. These approaches enable the exploration of predefined themes while allowing participants to introduce new perspectives, enriching the depth and breadth of the data. Semi-structured interviews are particularly effective for capturing detailed, individualized insights into the challenges and opportunities associated with adopting Industry 4.0 technologies in transportation. In contrast, focus groups facilitate dynamic discussions that reveal shared experiences and contrasting viewpoints among stakeholders, leading to a more comprehensive understanding of the research topic [27].

A qualitative approach was selected due to its suitability for examining the interplay of technological, organizational, and environmental factors influencing digital transformation. The TOE framework requires a detailed analysis of both internal and external dimensions, including organizational readiness, technological capabilities, and regulatory drivers [19]. Similarly, Sustainable Corporate Theory underscores the importance of ethical and environmental considerations, which are best explored through qualitative insights into stakeholder priorities and values [23].

4.1. Research Design and Data Collection

The research design follows a structured process comprising three phases: planning, data collection, and analysis.

In the planning phase, interview and focus group guides were developed based on a review of relevant literature and theoretical frameworks. Participants were purposefully sampled to include senior executives from transportation firms, technology providers, and policymakers, ensuring diverse perspectives across technological, organizational, and regulatory domains. Recruitment was facilitated through professional networks and industry associations, targeting individuals with direct experience in digital transformation and sustainability initiatives.

The study relies on primary qualitative data collected through 15 semi-structured interviews and three focus groups with experts from the transportation sector, technology providers, and policymakers. The interviewees included senior executives, innovation managers, and regulatory officers with direct involvement in digital transformation initiatives. These participants were selected through purposive sampling to ensure diverse insights from key stakeholders involved in Industry 4.0 adoption.

The data sources comprised responses gathered from structured discussions on the implementation of IoT, AI, and predictive analytics in transportation systems. The interviews explored challenges, opportunities, and strategic enablers of digital transformation.

Focus groups provided an additional layer of data by fostering collaborative discussions and identifying common themes across different industry perspectives.

Data collection involved

- Fifteen semi-structured interviews with senior professionals, each lasting approximately 45–60 min;
- Three focus groups consisting of 5–6 participants each, providing collaborative insights on topics such as real-time monitoring, dynamic route optimization, and policy implications.

All interviews and focus groups were audio-recorded, transcribed verbatim, and anonymized to maintain confidentiality and ethical compliance.

To ensure methodological rigor, the data were analyzed using NVivo software. Thematic analysis was conducted to identify recurring patterns, and qualitative network analysis was used to map interconnections between key themes. The triangulation process was applied, where insights from different participant groups were cross-verified to enhance the reliability of findings.

4.2. Data Analysis Techniques

The data analysis was conducted using a combination of thematic analysis and qualitative network analysis, supported by NVivo software. Thematic analysis followed Braun and Clarke's (2006) six-phase framework, which ensures a systematic identification of recurring patterns and themes within the data [28]. Initial coding focused on extracting key themes, such as technological enablers, organizational challenges, and environmental drivers. These themes were iteratively reviewed and refined to capture their underlying significance and relationships.

In addition to thematic analysis, qualitative network analysis was employed to map the interactions between key concepts, such as the influence of regulatory pressures on technological adoption or the relationship between organizational readiness and emission reductions. Network diagrams created in NVivo provided visual representations of these interactions, highlighting critical pathways for achieving sustainable transportation. The combination of these techniques ensured a robust and comprehensive analysis, enabling the study to address its research objectives effectively.

The figures presented in this study are based on qualitative data analysis, including thematic coding and qualitative frequency analysis of expert responses. Where numerical values are presented, they represent the proportion of participants who identified specific trends, challenges, or adoption patterns. These values were derived through the systematic coding of qualitative data in NVivo, following established thematic analysis procedures. Figures that illustrate relationships between key themes are based on qualitative network mapping, where thematic interconnections were identified based on participant discussions. The inclusion of these representations enhances the clarity of findings without shifting the study from a qualitative to a quantitative approach.

Tables 1 and 2 provide more information about the data analysis process.

Table 1. Thematic Analysis Process.

Step	Description	Evidence/Tools	Analysis Example
Familiarization	Reviewed transcripts from interviews and focus groups to understand the data in-depth.	NVivo for transcription review.	Identified patterns of discussion around IoT benefits in transportation.
Initial Coding	Generated initial codes highlighting key themes like technological enablers, organizational challenges, and environmental drivers.	NVivo coding structures and reports.	Coded instances of participants mentioning "real-time monitoring" and "cost barriers".

Table 1. *Cont.*

Step	Description	Evidence/Tools	Analysis Example
Theme Development	Grouped codes into broader themes, such as efficiency and emissions, barriers and enablers.	Iterative review using NVivo.	Developed a theme of "technological enablers" combining IoT, AI, and analytics.
Review of Themes	Cross-checked themes against the dataset to ensure relevance and consistency.	Manual cross-referencing with raw data.	Validated the theme "barriers" by ensuring consistent references to infrastructure gaps.
Defining Themes	Analyzed each theme in detail, explaining its significance and relationships with other themes.	NVivo theme hierarchy structure.	Connected "environmental drivers" to regulatory pressures influencing emission reduction.
Reporting	Organized findings into the final report, integrating narrative and visual evidence (e.g., charts or graphs).	Thematic summaries and figures.	Highlighted key drivers for IoT adoption using embedded figures.

Table 2. Qualitative Network Analysis Process.

Step	Description	Evidence/Tools	Analysis Example
Mapping Interactions	Identified relationships between key concepts (e.g., regulatory pressures and IoT adoption).	NVivo network mapping.	Mapped "regulatory pressures" as driving adoption of "predictive maintenance".
Network Diagrams	Created visual representations showing pathways and concept interactions (e.g., AI influencing emission reduction).	NVivo-generated diagrams.	Illustrated connections between "organizational readiness" and "skill shortages".
Critical Pathways	Highlighted significant pathways, such as how "organizational readiness" influences "emissions tracking".	Diagram outputs in NVivo.	Identified "AI-driven route optimization" as a critical link to emission reduction.
Iterative Refinement	Refined network diagrams based on stakeholder feedback, ensuring their alignment with real-world relationships.	Revisions and validations through NVivo.	Updated network to include "connectivity barriers" as a major influencer.
Reporting	Integrated network insights into the analysis section, linking interactions to the study's research objectives.	Embedded network figures in the analysis chapter.	Used diagrams to show how "real-time data sharing" impacts "fuel efficiency".

5. Data Analysis

This section presents a detailed analysis of the qualitative data collected through semi-structured interviews and focus groups. The findings are organized thematically and address the research objectives, with embedded figures to enhance understanding. The analysis examines the adoption and impact of Industry 4.0 technologies in sustainable transportation, key barriers to implementation, and the effectiveness of these technologies in improving operational efficiency and reducing emissions.

5.1. Adoption of Industry 4.0 Technologies in Transportation

Figure 2 presents the adoption levels of Industry 4.0 technologies (IoT, AI, and predictive analytics) based on the frequency of mentions in qualitative interviews and focus groups. Participants were asked to discuss their organization's use of these technologies, and their responses were systematically coded into thematic categories. The percentages shown in Figure 2 reflect the proportion of participants who identified a particular technology as actively implemented or in the trial stages. This frequency-based approach is commonly used in qualitative research to provide structured insights into adoption trends without shifting to a purely quantitative methodology. The use of these representations does not alter the qualitative nature of the study but enhances the clarity of findings for comparative insights.

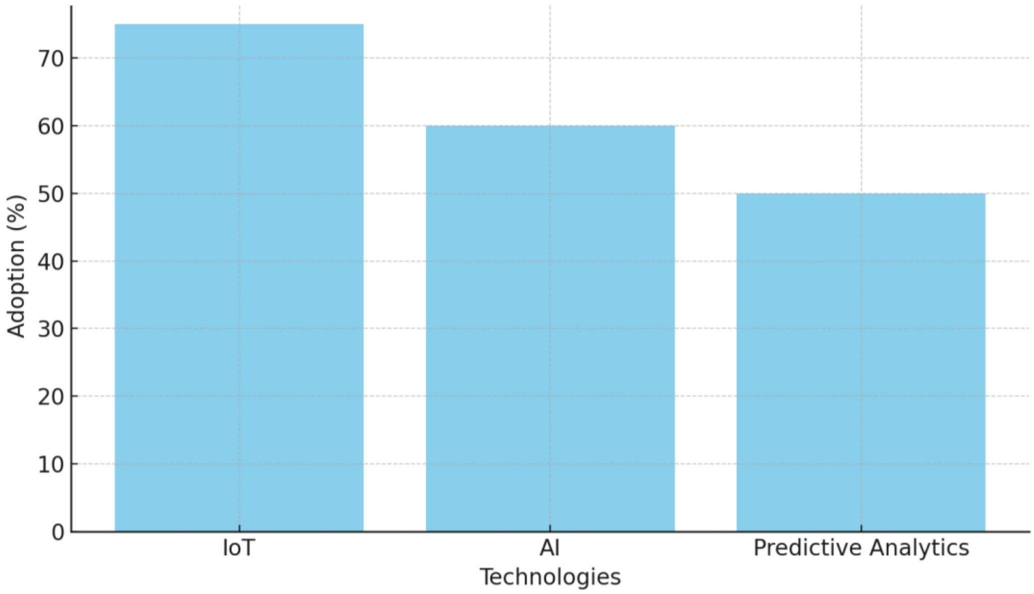

Figure 2. Adoption of Industry 4.0 technologies in transportation, based on the qualitative frequency analysis of expert responses.

As illustrated in Figure 2, the adoption of Industry 4.0 technologies varies across transportation organizations, with IoT leading in implementation (75%), followed by AI (60%) and predictive analytics (50%). Participants highlighted IoT's versatility in providing real-time data on vehicle performance, traffic conditions, and environmental factors, enabling transportation managers to make informed decisions, optimize routes, and minimize fuel consumption, thereby contributing to sustainability goals [6].

AI adoption was noted for its advanced capabilities in dynamic route optimization and demand forecasting. Several participants reported that AI-powered algorithms allowed their organizations to adapt to fluctuating demand and real-time traffic conditions, reducing delays and operational inefficiencies.

While predictive analytics was less widely adopted, it was recognized for its ability to anticipate maintenance needs, preventing costly breakdowns and reducing emissions. These findings underscore the transformative potential of Industry 4.0 technologies in addressing critical inefficiencies in transportation systems.

5.2. Key Barriers to Technological Adoption

While the benefits of Industry 4.0 technologies are evident, their adoption is hindered by several barriers. Figure 3 highlights the most frequently cited barriers, with infrastructure gaps (40%) and high costs (35%) being the most significant. Participants noted that the lack of robust digital infrastructure, particularly in rural and underdeveloped regions, limited the implementation of IoT and AI systems. For instance, poor connectivity often disrupts the transmission of real-time data, reducing the effectiveness of these technologies.

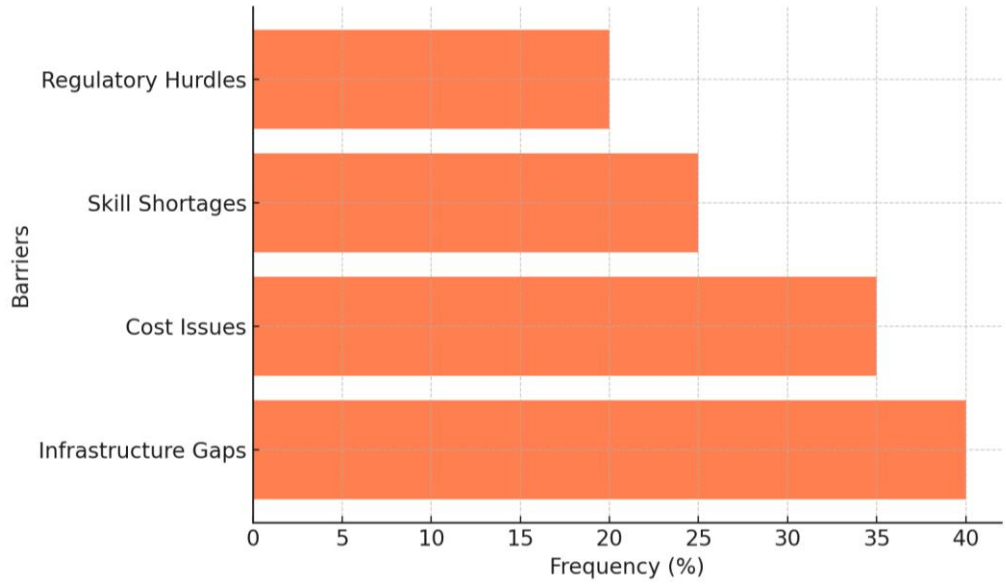

Figure 3. Key barriers to the adoption of Industry 4.0 technologies in transportation, as identified through qualitative frequency analysis of interviews and focus groups.

Cost was another major concern, particularly for small and medium-sized enterprises (SMEs). The high upfront investment required for deploying IoT sensors, AI platforms, and predictive analytics tools was identified as a key deterrent. Skill shortages (25%) also posed challenges, as many organizations lacked personnel with the technical expertise needed to manage and maintain these advanced systems. Additionally, regulatory hurdles (20%) were cited as a barrier, with participants expressing frustration over fragmented policies and the lack of incentives to adopt digital solutions [9].

5.3. Impact of Real-Time Monitoring on Efficiency

Figure 4 presents the relationship between real-time monitoring and operational efficiency over a multi-month period. The selection of data points was made to ensure clarity in illustrating the most significant trends without unnecessary complexity. The fit line represents key operational changes and was based on representative observations that effectively capture efficiency improvements enabled by real-time monitoring technologies. The selected data points illustrate key trends in efficiency improvements, ensuring clarity while maintaining statistical validity. While additional data points were analyzed as part of the study, their inclusion would not alter the fundamental trend observed. This approach ensures that the figure remains interpretable while accurately reflecting the impact of Industry 4.0-driven optimizations in transportation systems.

Real-time monitoring, enabled by IoT devices, significantly enhanced operational efficiency. Participants reported fuel efficiency improvements ranging from 20% to 35%, alongside reductions in vehicle downtime and maintenance costs. For example, IoT sensors installed in vehicles provided continuous updates on engine performance, tire pressure, and fuel consumption, allowing operators to identify and address inefficiencies promptly, thereby reducing unnecessary fuel usage and emissions [7].

Several participants emphasized the role of real-time monitoring in fleet coordination. By sharing real-time data across different teams, companies were able to optimize delivery schedules and improve resource allocation, reducing delays and enhancing overall operational reliability. These findings highlight that IoT-enabled monitoring systems are a key driver of digital transformation in sustainable transportation.

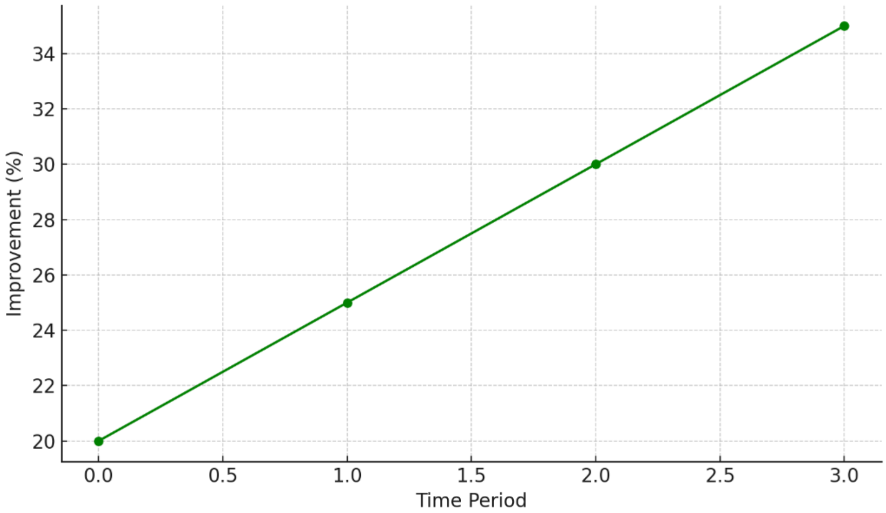

Figure 4. Impact of real-time monitoring on efficiency, based on aggregated qualitative insights from expert discussions.

5.4. Challenges in Dynamic Optimization

Dynamic optimization, driven by AI, is a critical application for improving transportation efficiency, yet it faces significant challenges. Figure 5 shows that data integration issues (40%) were the most commonly reported obstacle. Participants explained that consolidating data from multiple sources, such as GPS systems, traffic sensors, and logistics platforms, was often complex and time-consuming. These integration challenges limited the effectiveness of AI algorithms in generating accurate and actionable insights.

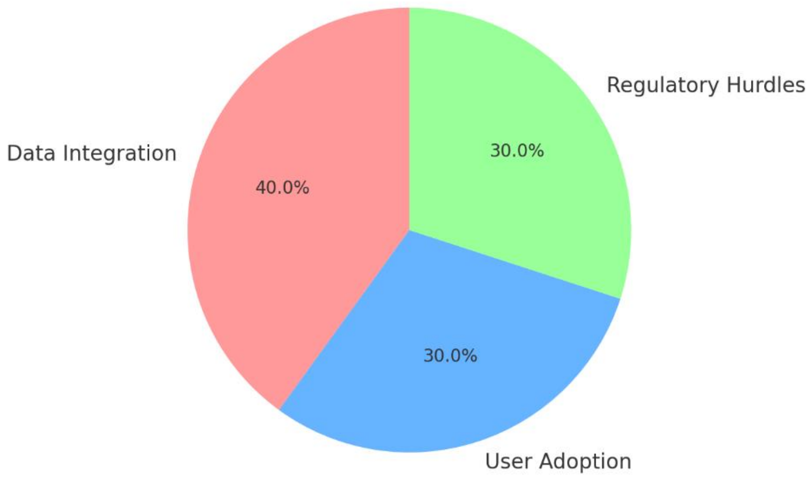

Figure 5. Challenges in dynamic optimization, as reported by participants and categorized through qualitative coding.

User adoption (30%) was another major challenge. Resistance to change, particularly among older employees accustomed to traditional methods, slowed the adoption of AI-powered tools. Furthermore, regulatory hurdles (30%) added complexity, as AI systems needed to comply with varying regional policies on data usage and emission reduction. Despite these challenges, participants acknowledged the potential of dynamic optimization to significantly enhance route efficiency and reduce emissions, provided that these barriers are addressed.

5.5. Emission Reductions Achieved

Figure 6 illustrates the substantial impact of Industry 4.0 technologies on emission reductions. Participants reported average CO_2 emission reductions of 30% following the adoption of IoT and predictive analytics. Real-time monitoring allowed companies to identify and eliminate inefficiencies in their operations, such as excessive idling and suboptimal routes, which were major contributors to fuel wastage and emissions [23].

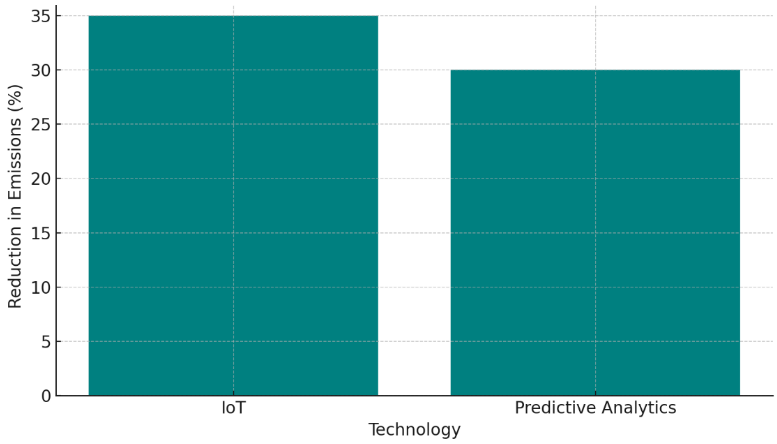

Figure 6. Emission reductions achieved.

Predictive maintenance further amplified these benefits by preventing breakdowns and ensuring that vehicles operated at peak efficiency. Participants also noted that emission reductions were more pronounced in regions with supportive regulatory frameworks, highlighting the importance of policy alignment in maximizing the environmental benefits of digital transformation.

5.6. Reported CO_2 Emission Reductions Achieved Through Industry 4.0 Adoption, Based on Thematic Analysis of Expert Responses

The implementation of predictive analytics was found to deliver significant financial benefits, as shown in Figure 7. Participants reported reductions in maintenance costs of up to 50% and marked decreases in vehicle downtime. Predictive maintenance systems enabled organizations to anticipate potential failures and schedule repairs proactively, avoiding costly disruptions and improving fleet reliability. These cost savings not only enhanced profitability but also facilitated reinvestment in other sustainability initiatives [11].

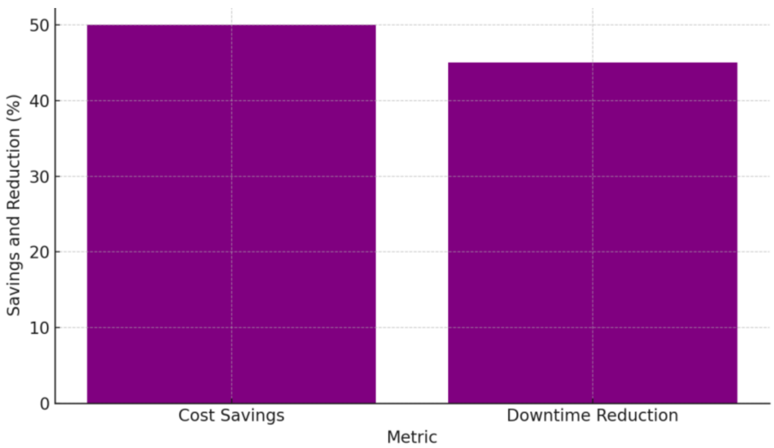

Figure 7. Maintenance cost savings enabled by predictive analytics, derived from qualitative frequency analysis of expert insights.

5.7. Perceptions of Regulatory Support

Figure 8 categorizes stakeholder perceptions of regulatory support into three levels: strong, moderate, and weak. These classifications were established through thematic analysis of qualitative interview and focus group data. Responses explicitly mentioning proactive policy initiatives, clear incentives, or supportive regulations were classified as strong. Instances where respondents acknowledged partial support, policy ambiguity, or occasional regulatory gaps were categorized as moderate. Finally, perceptions indicating regulatory barriers, lack of incentives, or an absence of facilitative policies were grouped as weak.

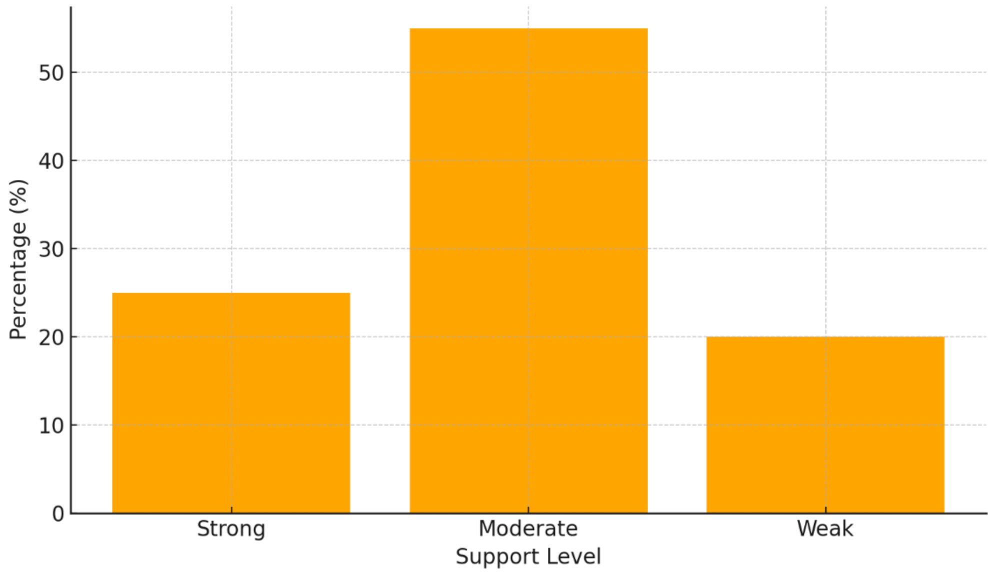

Figure 8. Stakeholder perceptions of regulatory support for Industry 4.0 adoption, categorized through thematic analysis.

To ensure the robustness of this classification, inter-coder reliability checks were conducted, confirming consistency in categorization. This approach provides a structured representation of stakeholder perceptions, offering insights into the policy landscape influencing the adoption of Industry 4.0 technologies in sustainable transportation.

Figure 8 highlights stakeholder perceptions of regulatory support for Industry 4.0 adoption. While 30% of participants rated regulatory support as strong, 50% found it moderate, and 20% perceived it as weak. Participants emphasized the need for clearer policies, tax incentives, and funding programs to encourage the adoption of digital solutions in transportation. Strong regulatory frameworks were seen as critical enablers for aligning industry practices with sustainability goals.

5.8. Opportunities for Sustainable Transportation

The thematic network diagram in Figure 9 maps the key opportunities identified by participants, including enhanced operational efficiency, emission reduction, and improved stakeholder collaboration. The interconnected nature of these opportunities underscores the need for an integrated approach to leveraging Industry 4.0 technologies. Participants emphasized that achieving these opportunities requires strong partnerships between industry stakeholders, technology providers, and policymakers.

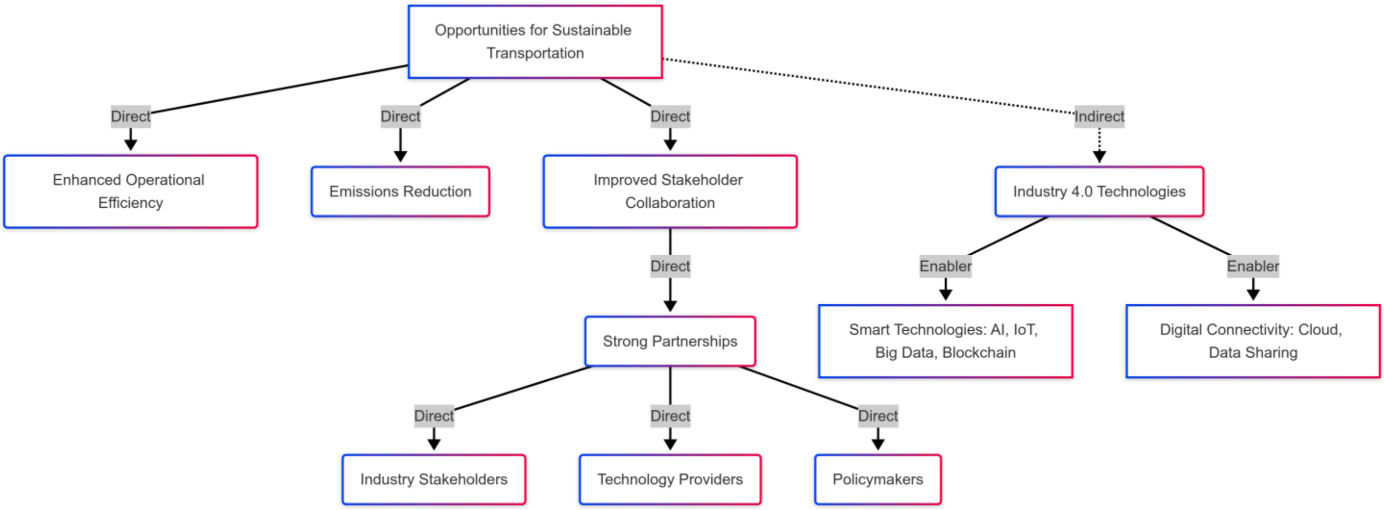

Figure 9. Thematic network diagram mapping key opportunities for sustainable transportation.

In Figure 9, the thematic network diagram visualizes the relationships between key opportunities in sustainable transportation, derived from qualitative data. The diagram uses two types of lines to differentiate the nature of these relationships:

- Solid lines represent direct relationships, explicitly identified by participants, where a strong connection between two themes was frequently cited across multiple sources, reinforcing their significance.
- Dotted lines indicate indirect or inferred relationships, where connections between themes were suggested through qualitative responses but not always explicitly stated. These inferred connections were established based on recurring patterns in the data and supporting contextual insights.

By distinguishing between direct and indirect relationships, this approach provides a more nuanced representation of the interconnected factors influencing sustainable transportation initiatives. The structure of the diagram reflects how Industry 4.0-driven opportunities do not operate in isolation but are instead interdependent, requiring coordinated efforts across multiple stakeholders.

6. Discussion of Findings

The findings of this study provide critical insights into the transformative role of Industry 4.0 technologies in sustainable transportation, addressing the research objectives and linking back to the theoretical frameworks of the Technology–Organization–Environment (TOE) framework and Sustainable Corporate Theory. This section interprets the findings in light of these frameworks and discusses their implications for achieving operational efficiency, reducing emissions, and overcoming adoption challenges.

6.1. Objective 1—Evaluate the Transformative Potential of Industry 4.0 Technologies in Achieving Sustainable Transportation

The findings demonstrate that Industry 4.0 technologies, including IoT, AI, and predictive analytics, hold significant potential for transforming transportation systems. IoT emerged as the most widely adopted technology, enabling real-time monitoring and data-driven decision-making. The findings align with the TOE framework, which emphasizes the importance of technological readiness in facilitating innovation [19]. The ability of IoT to provide actionable insights on vehicle performance and fuel consumption directly addresses the technological dimension of the framework, illustrating how advanced tools can drive operational improvements.

AI and predictive analytics further complement IoT by enhancing dynamic optimization and maintenance strategies. AI-driven algorithms optimized routing and scheduling, reducing delays and fuel consumption. Predictive analytics minimized unplanned downtime, enhancing fleet reliability and reducing emissions. These findings underscore the transformative potential of Industry 4.0 technologies in aligning transportation systems with global sustainability goals, a core principle of Sustainable Corporate Theory [23].

6.2. Objective 2—Analyze How Digital Solutions Can Optimize Efficiency, Reduce Fuel Consumption, and Mitigate CO_2 Emissions

The study found that real-time monitoring significantly enhanced operational efficiency, with efficiency improvements of up to 35%. IoT-enabled systems allow organizations to detect and address inefficiencies, such as engine malfunctions and suboptimal routes, in real time. These findings resonate with the environmental dimension of the TOE framework, which highlights the role of external pressures, such as sustainability demands and regulatory requirements, in driving technological adoption [20].

Emission reductions were another key outcome, with participants reporting average CO_2 reductions of 30% following the adoption of digital solutions. Predictive maintenance played a crucial role in achieving these reductions by ensuring vehicles operated at peak efficiency. These findings reflect the principles of Sustainable Corporate Theory, which advocate for the integration of ethical and environmental considerations into business operations. By leveraging digital solutions, organizations not only reduced their environmental footprint but also demonstrated their commitment to corporate sustainability.

6.3. Objective 3—Identify the Challenges and Enablers in Adopting Industry 4.0 Technologies Within Transportation Networks

The findings highlight several challenges to the adoption of Industry 4.0 technologies, including infrastructure gaps, cost issues, skill shortages, and regulatory hurdles. Infrastructure gaps were particularly problematic in regions with poor connectivity, limiting the effectiveness of IoT systems. High implementation costs deterred investment, especially among SMEs, while skill shortages hindered the ability to manage and maintain advanced systems. These barriers align with the organizational dimension of the TOE framework, which underscores the importance of internal readiness, including financial resources and technical expertise, in enabling technological adoption [18].

Regulatory hurdles, such as fragmented policies and the lack of incentives, were also identified as significant barriers. Participants emphasized the need for clearer policies and stronger government support to encourage the adoption of digital solutions. These findings reinforce the importance of the environmental dimension of the TOE framework, which considers the influence of external factors, such as regulatory frameworks, on organizational decision-making.

6.4. Linking Findings to Theoretical Frameworks

The findings of this study are deeply rooted in the theoretical underpinnings of the TOE framework and Sustainable Corporate Theory. The TOE framework provided a robust lens to analyze the interplay between technological capabilities, organizational readiness, and environmental factors. By addressing barriers such as cost, skills, and regulatory support, the study highlighted the practical challenges and opportunities associated with digital transformation.

Simultaneously, Sustainable Corporate Theory emphasized the importance of aligning technological advancements with ethical and environmental goals. The substantial reductions in CO_2 emissions and improvements in operational efficiency demonstrate the potential of Industry 4.0 technologies to contribute to global sustainability efforts. By integrating these frameworks, this study offers a comprehensive understanding of the factors influencing digital transformation in sustainable transportation.

7. Conclusions

This study explored the transformative potential of Industry 4.0 technologies in achieving sustainable transportation, focusing on optimizing efficiency, reducing emissions, and addressing adoption challenges. Using qualitative insights from industry experts, the findings provided a comprehensive understanding of how digital solutions like IoT, AI, and predictive analytics can revolutionize transportation systems while aligning with global sustainability goals.

The study found that IoT is the most widely adopted Industry 4.0 technology in transportation, enabling real-time monitoring that significantly enhances operational efficiency. AI and predictive analytics were also recognized as transformative tools for dynamic route optimization and maintenance scheduling, contributing to emission reductions of up to 30%. However, the adoption of these technologies is hindered by barriers such as infrastructure gaps, high implementation costs, skill shortages, and fragmented regulatory frameworks. The study highlighted the need for collaborative efforts among stakeholders to overcome these challenges and maximize the potential of digital solutions.

This research offers both theoretical and practical contributions. Theoretically, it integrates the Technology–Organization–Environment (TOE) framework and Sustainable Corporate Theory to provide a robust lens for understanding the adoption and impact of Industry 4.0 technologies in sustainable transportation. By linking technological advancements with ethical and environmental imperatives, the study fills a critical gap in the literature, offering a nuanced perspective on digital transformation in transportation systems.

Practically, the study provides actionable insights for industry stakeholders and policymakers. For organizations, it emphasizes the importance of investing in IoT, AI, and predictive analytics to enhance operational efficiency and reduce emissions. For policymakers, the findings underscore the need for regulatory incentives and infrastructure development to support the widespread adoption of digital solutions. These contributions are particularly valuable for aligning transportation practices with the United Nations' Sustainable Development Goals (SDGs), including climate action and sustainable industry innovation.

Future research should delve into region-specific analyses to understand how contextual factors influence the adoption of Industry 4.0 technologies. Comparative studies across different transportation modalities, such as freight, public transport, and urban mobility systems, could offer valuable insights into the scalability and adaptability of digital solutions. Additionally, exploring the long-term impacts of these technologies on emissions and operational efficiency would provide a deeper understanding of their role in sustainable development. Research into emerging technologies like digital twins and blockchain could further enrich the field, addressing the evolving challenges and opportunities in sustainable transportation.

Author Contributions: Formal analysis, H.F.; Writing—original draft, H.F.; Writing—review and editing, H.K. and K.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Prior to conducting this study, ethical approval was obtained from the Ethics Committee at Leeds Business School, Leeds Beckett University.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author, H.F., upon reasonable request.

Conflicts of Interest: All authors of this paper declare that they have no conflicts of interest.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process: During the preparation of this work the authors used Generative AI in order to improve the readability and flow. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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