Article

Driving the future: Leveraging digital transformation for sustainable transportation

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Abstract: The transportation sector is currently experiencing a significant transformation due to the influence of digital technologies, which are revolutionizing travel, goods transportation, and interactions with transportation systems. This study delves into the possibilities and obstacles presented by digital transformation in the realm of sustainable transportation. Moreover, it identifies the most effective methods for implementing digital transformation in this sector. Furthermore, our analysis sheds light on the potential impacts of digital transformation on sustainable development and environmental performance indicators within transportation systems. We discover that digital transformation can contribute to reduced greenhouse gas emissions, improved air quality, and increased resource efficiency, among other benefits. Nevertheless, we emphasize the potential risks and uncertainties associated with digital transformation, including concerns regarding data privacy, security, and ethics. Collectively, our research provides valuable insights into the opportunities and challenges presented by digital transformation in sustainable transportation. It also identifies best practices for successfully implementing digital transformation in this sector. The implications of our findings are significant for policymakers, businesses, and other stakeholders who aspire to drive the future of sustainable transportation through digital transformation.

Keywords: digital transformation; sustainable transportation; environmental performance indicators; implementation challenges

1. Introduction

Digital transformation is a process that involves the integration of digital technologies into various aspects of an organization or industry, fundamentally changing how business is conducted, processes are optimized, and value is created (Warner and Wäger, 2019). In the context of sustainable transportation, digital transformation entails leveraging technology and data-driven solutions to address the environmental, social, and economic challenges associated with transportation systems (Bibri and Krogstie, 2021). By adopting digital technologies, the transportation sector can enhance its efficiency, reduce its environmental footprint, and promote sustainable practices (Creutzig et al., 2019; Javaid et al., 2022).

The integration of digital technologies offers significant opportunities to improve transport efficiency, infrastructure development, energy requirements, and policy frameworks (Noussan and Tagliapietra, 2020; Inac and Oztemel, 2021). Through the use of digital platforms, real-time data collection, and advanced analytics, transportation organizations can optimize their operations by minimizing congestion, reducing travel times, and optimizing routes (Zhu et al., 2019).

Intelligent transportation systems powered by digital technologies can enable better traffic management, leading to smoother traffic flow and reduced emissions (Lv and Shang, 2023). Additionally, digital transformation can facilitate the integration of renewable energy sources into transportation networks, supporting the transition to a low-carbon future (Song et al., 2022).

One of the key benefits of digital transformation in transportation is the greater transparency and accountability it brings to the system (Baldini et al., 2019). Digitizing processes such as ticketing, booking, and payment systems enables stakeholders to access real-time information, empowering them to make informed decisions (Cruz and Sarmento, 2020). This transparency fosters trust among users and promotes accountability among transportation service providers. Moreover, digital platforms can facilitate the tracking and monitoring of transportation operations, ensuring compliance with sustainability standards and regulations (Ebinger and Omondi, 2020). This increased transparency and accountability contribute to a more sustainable and reliable transportation ecosystem.

Digital transformation also plays a crucial role in promoting the shift towards shared and sustainable mobility models (Paiva et al., 2021). Through the use of digital platforms and mobile applications, users can access various shared transportation options such as ride-sharing, bike-sharing, and car-sharing services (Mckinsey.com, 2023; Lee et al., 2021). These shared mobility solutions not only reduce the number of private vehicles on the road but also promote efficient resource utilization and congestion reduction. Digital technologies also enable the integration of different modes of transportation, allowing users to plan and combine various modes seamlessly (Shaheen and Cohen, 2020). This shift towards shared and sustainable mobility is essential for reducing greenhouse gas emissions, improving air quality, and creating more livable cities.
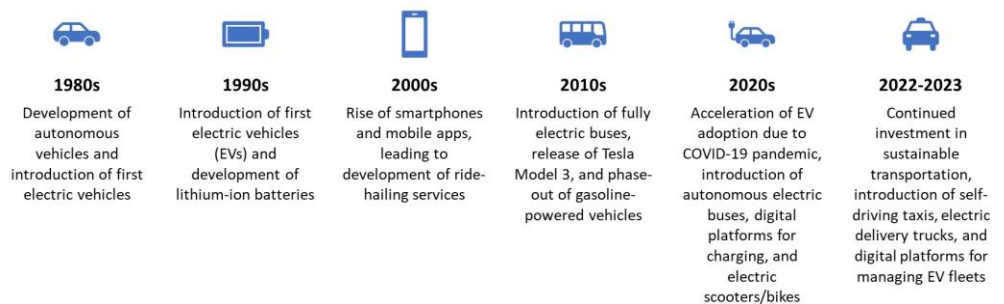
Figure 1. The evolution of transportation technology over the past four decades.

Figure 1 showcases the evolution of transportation technology over the past four decades, with a focus on electric vehicles (EVs) and autonomous vehicles (AVs). The timeline highlights significant milestones, such as the development of the first autonomous vehicles in the 1980s and the introduction of electric vehicles like the General Motors EV1 and the Toyota Prius hybrid in the 1990s. The rise of smartphones and mobile apps in the 2000s led to the development of ride-hailing services like Uber and Lyft. The 2010s witnessed the introduction of fully electric buses and the success of the Tesla Model 3 as the best-selling EV of all time. In the 2020s, there has been a surge in the adoption of EVs, as well as advancements in

autonomous electric buses, digital platforms for charging, and electric scooters and bikes. Furthermore, continued investment in sustainable transportation in 2022 and 2023 has brought the introduction of self-driving taxis, electric delivery trucks, and digital platforms for managing EV fleets.

This paper aims to explore the opportunities, challenges, best practices, and potential impact of using digital transformation to achieve sustainable transportation. The research approach employed a quantitative method to gather data and analyze the opinions and perspectives of stakeholders in the transportation industry regarding the impact of digital transformation on sustainability, efficiency, and society. A survey was designed to collect responses from participants, with the goal of understanding their perceived importance of digital transformation, the main barriers to implementation, and the potential benefits it can bring to the transportation sector and society as a whole.

2. Materials and methods

This research aims to investigate the role of digital transformation in sustainable transportation, focusing on opportunities, challenges, best practices, and potential impacts. We will rely on available data, statistics, and figures from credible sources to achieve this. This research aims to provide a comprehensive analysis of the role of digital transformation in sustainable transportation, highlighting opportunities, challenges, best practices, and potential impacts. By leveraging available data, statistics, and figures, we hope to contribute to the existing body of knowledge and provide insights that can inform decision-making and policy-making in the transportation sector.

The work answers the following research questions which are shown in **Figure 2**:
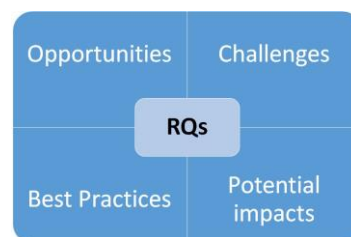
Figure 2. Research questions.

- RQ1: What are the key opportunities offered by digital transformation in sustainable transportation?

  This question explores the potential benefits and opportunities that arise from the application of digital technologies in the realm of sustainable transportation. By analyzing case studies, industry reports, and academic literature, we aim to identify and evaluate the advantages that digital transformation brings, such as improved operational efficiency, enhanced mobility services, and optimized resource allocation.

- RQ2: What are the challenges and uncertainties associated with digital transformation in sustainable transportation?

  Understanding the challenges and uncertainties is crucial for successful

implementation of digital transformation in sustainable transportation. This question investigates the barriers, risks, and potential drawbacks that may hinder the adoption and integration of digital technologies. Factors such as cybersecurity, data privacy, infrastructure requirements, and workforce readiness will be examined to provide a comprehensive view of the challenges involved.

- RQ3: What are the best practices for implementing digital transformation in sustainable transportation?

This question focuses on identifying and analyzing the best practices for effectively implementing digital transformation initiatives in the context of sustainable transportation. By studying successful case studies, industry guidelines, and expert opinions, we aim to extract valuable insights and strategies that can guide organizations, policymakers, and stakeholders in their digital transformation journeys. The examination of factors like stakeholder engagement, change management, and collaboration will be integral to capturing the essential elements of successful implementation.

- RQ4: What are the potential impacts of digital transformation on sustainable development and environmental performance indicators in transportation systems?

This question explores the broader impacts that digital transformation can have on sustainable development and environmental performance indicators within transportation systems. By analyzing empirical data, studies, and environmental assessments, we aim to quantify and evaluate the potential positive and negative impacts of digital transformation on factors such as greenhouse gas emissions, energy efficiency, air quality, and overall sustainability. Understanding these impacts is crucial for ensuring that digital transformation efforts align with the goals of sustainable development.

3. Opportunities

This section is dedicated to answering RQ1: What are the key opportunities offered by digital transformation in sustainable transportation? Digital transformation in the transportation industry offers numerous opportunities to enhance sustainability. By leveraging digital technologies, transportation systems can reduce emissions, improve energy efficiency, promote sustainable mobility options, enable data-driven decision-making, foster collaboration, and create new job opportunities.

3.1. Reduction of emissions

One key opportunity provided by digital transformation is the reduction of emissions. Digital technologies enable the adoption of electric vehicles (EVs), which are more fuel-efficient and produce fewer emissions than traditional gasoline-powered vehicles (Zhang et al., 2023). Moreover, digital tools can optimize traffic flow, reduce congestion, and minimize idle time, leading to reduced emissions (Toulni et al., 2023). Public transportation and ride-sharing services also play a crucial role in reducing emissions by decreasing the number of vehicles on the road (Yin, 2018). According to the International Energy Agency, electric vehicles could

reduce global CO_2 emissions from transportation by 60% by 2050 (electric vehicles, 2017). Additionally, autonomous vehicles have the potential to reduce fuel consumption by 15%–20% (Mckinsey.com, 2023).

3.2. Improvement of energy efficiency

Another opportunity lies in improving energy efficiency through digital transformation. Transportation systems can leverage intelligent transportation systems (ITS) to optimize traffic flow, reducing fuel consumption and improving overall energy efficiency (Sen, 2021; PricewaterhouseCoopers, 2022). Digital technologies can also enhance the efficiency of vehicles and transportation infrastructure, contributing to sustainable practices (Noussan and Tagliapietra, 2020). For example, intelligent transportation systems have the potential to reduce traffic congestion by up to 20% (Worldbank.org, 2018). In 2021, traffic congestion cost the US economy $742 billion, highlighting the need for energy-efficient solutions (Txdot.gov, 2021).

3.3. Enhancement of safety

Digital transformation can help improve safety in transportation. Autonomous vehicles equipped with sensors and cameras can detect and avoid accidents. The National Highway Traffic Safety Administration found that self-driving cars could potentially reduce traffic fatalities by up to 94% (Warpnews.org, 2023). Similarly, the Insurance Institute for Highway Safety reported that self-driving cars could reduce traffic crashes by up to 80% (Iihs.org, 2020). By incorporating digital technologies, transportation systems can significantly enhance safety on the roads.

3.4. Promotion of sustainable mobility options

Digital technologies enable the promotion of sustainable mobility options. Mobile applications provide real-time information on traffic conditions, public transportation schedules, and the availability of ride-sharing services, making it easier for individuals to choose more sustainable modes of transportation (Angelaki et al., 2020). Successful implementations, such as Oslo's congestion pricing systems and London's "Boris bike" initiative, have encouraged sustainable practices like reduced private vehicle usage and increased cycling, leading to decreased traffic congestion and improved air quality (Aasness, 2014; Chapman, 2016).

3.5. Data-driven decision-making

Digital transformation supports data-driven decision-making in transportation. Vast amounts of data generated through digital technologies can be analyzed to gain insights into transportation patterns, customer preferences, and operational efficiency (Zhu et al., 2019). This data-driven approach enables more informed and targeted policies, facilitating sustainable transportation planning and resource allocation. By utilizing data analytics, transportation stakeholders can optimize routes, predict demand, and allocate resources more efficiently, resulting in improved sustainability outcomes.

3.6. Collaboration and coordination

Digital platforms facilitate collaboration and coordination among different stakeholders in the transportation ecosystem (Carvalho et al., 2020). These platforms connect transportation providers, shippers, and customers, optimizing freight management and reducing empty trips. By fostering collaboration, digital transformation improves overall coordination and responsiveness in the transportation industry. Sharing data and information through digital platforms enables stakeholders to make more informed decisions, leading to increased efficiency and sustainability.

3.7. Creation of new job opportunities

Digital transformation is expected to create new jobs in the transportation sector. With the emergence of new technologies such as electric vehicles and autonomous vehicles, new industries will develop to develop, maintain, and operate these technologies. A study by the McKinsey Global Institute found that digital transformation could create up to 10 million new jobs in the transportation sector by 2030 (Mckinsey.com, 2023). Similarly, the World Economic Forum predicted that the self-driving car industry alone could create up to 10 million new jobs by 2030 (Weforum.org, 2017). These new job opportunities will contribute to economic growth while driving sustainable practices in the transportation industry.

Despite the numerous opportunities, it is important to address the challenges associated with digital transformation. These challenges include ensuring data privacy and security, promoting equitable access to digital technologies, and mitigating potential rebound effects. By addressing these challenges, the transportation industry can fully harness the potential of digital transformation to create a more sustainable and efficient transportation system for the future.

4. Challenges

This section is dedicated to answering RQ2: What are the challenges and uncertainties associated with digital transformation in sustainable transportation? Challenges and uncertainties associated with digital transformation in sustainable transportation are multifaceted and require careful consideration.

4.1. Integration of digital technology

One of the key challenges is the integration of digital technology into traditional transportation systems. Ensuring that different systems can communicate with each other and that data is standardized and interoperable is essential (Ezgeta et al., 2022). This challenge is particularly relevant when dealing with legacy systems and coordinating efforts across various stakeholders. Integration issues can arise due to fragmented data sources, lack of interoperability standards, and resistance to change from existing stakeholders. Overcoming these challenges requires collaboration and coordination among all parties involved.

4.2. Data privacy and security

Data privacy and security concerns arise with the increased amount of data

generated by digital transportation systems. Protecting sensitive information and mitigating cybersecurity risks are crucial aspects of digital transformation (Saeed et al., 2023). Transportation systems collect vast amounts of personal and operational data, including location information and travel patterns. Establishing robust data privacy and security measures helps maintain public trust and prevents potential misuse of personal information. It requires implementing encryption, access controls, and secure data storage practices to safeguard data from unauthorized access.

4.3. Infrastructure investment

Significant investment is required in infrastructure to support digital transformation in sustainable transportation (Anthony Jnr, 2020). This includes IT systems, data analytics tools, smart transportation systems, and other related infrastructure. The cost of these investments can be substantial and may necessitate government support and funding. Upgrading existing infrastructure and deploying new technologies require financial resources and long-term planning. Securing funding and allocating resources effectively is a critical challenge that transportation authorities and organizations need to address.

4.4. Public acceptance

Public acceptance is another challenge that can hinder the adoption of digital transportation systems (Fauzi et al., 2022). Concerns about privacy, security, and job displacement can lead to resistance from the public. People may be skeptical about sharing their personal data or relying on autonomous vehicles. Addressing these concerns through public education and outreach efforts is crucial for fostering acceptance and understanding (Cantilina et al., 2021). Building trust and transparency in the use of digital technologies can help alleviate public concerns and encourage wider adoption.

4.5. Regulatory frameworks

The existing regulatory frameworks may need to be adapted to accommodate the changes brought about by digital transformation in sustainable transportation. Flexibility in regulations is necessary to address emerging technologies and business models effectively (Bludyan, 2021). Adapting regulatory frameworks ensures that they remain relevant and supportive of sustainable transportation goals. A study by the Brookings Institution found that the regulatory environment for autonomous vehicles is still evolving, and there is a need for clear and consistent regulations (Brookings.edu, 2016). Regulatory bodies need to collaborate with industry stakeholders to develop appropriate guidelines and standards.

4.6. Skills gap

Addressing the skills gap is another challenge associated with digital transformation. The evolving nature of digital transportation systems requires workers with specialized skills such as data analytics, software development, and cybersecurity (Degtyareva et al., 2020). Implementing training and education programs to bridge the skills gap is essential. By equipping the workforce with the

necessary skills, they can actively participate in and contribute to the digital transformation of transportation. Collaboration between academia, industry, and government is crucial to develop educational programs that address the evolving skill requirements.

4.7. Scalability

Scalability is a vital consideration for digital transportation systems. These systems need to be scalable to accommodate growing demand and future integration with other systems. Scalability ensures that digital solutions can effectively meet the needs of a changing transportation landscape (Makeeva and Rychkova, 2023). As transportation systems expand and evolve, the underlying digital infrastructure must be capable of handling increased data volume, processing power, and connectivity. Planning for scalability from the outset can help avoid bottlenecks and ensure the long-term viability of digital transportation solutions.

4.8. Environmental impact

While digital transformation in sustainable transportation aims to reduce environmental impact, there are concerns about the environmental impact of the technology itself. Energy consumption and e-waste associated with digital infrastructures need to be carefully managed to ensure that the overall sustainability goals are not compromised. Energy-efficient design and operation of digital systems, use of renewable energy sources, and responsible waste management practices are essential to minimize the environmental footprint of digital transformation in transportation.

Digital transformation in sustainable transportation presents both challenges and uncertainties. Integration of digital technology, data privacy and security, infrastructure investment, public acceptance, regulatory frameworks, skills gap, scalability, and environmental impact are among the key challenges and uncertainties that need to be addressed. By proactively addressing these challenges, it is possible to maximize the benefits of digital transformation and achieve sustainable transportation goals.

5. Best practices

This section focuses on answering RQ3: What are the best practices for implementing digital transformation in sustainable transportation? Digital transformation plays a crucial role in driving sustainability in the transportation sector by leveraging digital technologies to optimize operations, reduce emissions, and improve overall efficiency. Implementing digital transformation in sustainable transportation requires a comprehensive approach and adherence to best practices.

5.1. Clear vision and strategy

A key best practice for implementing digital transformation in sustainable transportation is to have a clear vision and strategy. According to a study by McKinsey and Company, companies that have a clear vision and strategy for digital transformation are more likely to be successful (Mckinsey.com, 2018). Similarly, a

study by the World Economic Forum found that businesses with a clear digital transformation strategy are more likely to achieve their sustainability goals (Weforum.org, 2021). Having a well-defined vision and strategy helps transportation companies align their digital transformation initiatives with their sustainability objectives, guiding decision making and resource allocation.

5.2. Data-driven decision-making

Data-driven decision-making is another critical best practice for implementing digital transformation in sustainable transportation. By collecting and analyzing data from various sources, transportation companies can gain valuable insights into transportation patterns, energy consumption, and emissions (Gutierrez-Franco et al., 2021). This data can then be used to make informed decisions and optimize routes, schedules, and resource allocation. Intelligent transportation systems (ITS) that utilize technologies like sensors, GPS, and communication networks can also be implemented to improve traffic management, reduce congestion, and enhance safety (Chandra Shit, 2020). A study by the McKinsey Global Institute emphasizes the importance of data-driven decision-making for digital transformation (Mckinsey.com, 2018), while the International Energy Agency found that transportation companies that use data and analytics to make decisions are more likely to reduce emissions and improve efficiency (Iea.org, 2009).

5.3. Promoting electrification and alternative fuels

Promoting electrification and alternative fuels is a crucial best practice for achieving sustainability in transportation. By embracing electric vehicles (EVs) and exploring alternative fuels like hydrogen and biofuels, transportation companies can significantly reduce emissions (Ban et al., 2019). Developing charging infrastructure and incentivizing the adoption of EVs through subsidies and tax benefits can further accelerate the transition to sustainable transportation. By actively supporting the adoption of cleaner technologies and fuels, transportation companies can contribute to the overall decarbonization of the transportation sector.

5.4. Utilizing digital platforms for Mobility-as-a-Service (MaaS)

Digital platforms play a vital role in implementing Mobility-as-a-Service (MaaS) solutions, which integrate various modes of transportation into a seamless and sustainable mobility option (Wong et al., 2020; Cruz and Sarmento, 2020). These platforms provide users with access to different transport services, such as public transport, ride-sharing, car-sharing, bike-sharing, scooter-sharing, taxi, car rental, and ride-hailing, all in one single digital mobility offer (Mitropoulos et al., 2023). By offering easy booking, payment, and route planning capabilities, digital platforms encourage the use of public transit and other sustainable transportation options. Implementing MaaS solutions enhances convenience, reduces the reliance on private car ownership, and promotes the efficient utilization of transportation resources.

5.5. Collaboration and partnerships

To ensure the success of digital transformation initiatives in sustainable

transportation, collaboration and partnerships between transportation companies, technology providers, government agencies, and other stakeholders are crucial. By fostering collaborative efforts, innovative solutions can be developed, best practices can be shared, and policy support for sustainable transportation initiatives can be established. Collaboration enables the pooling of resources, expertise, and data, leading to more effective and impactful digital transformation projects.

5.6. Continuous improvement and innovation

Continuous improvement and innovation should be encouraged as part of the digital transformation process in sustainable transportation. Staying updated with emerging technologies and industry trends enables transportation companies to identify new opportunities for sustainability in transportation. Experimentation and pilot projects can be conducted to test and scale innovative solutions, ensuring that digital transformation efforts remain effective and relevant. By fostering a culture of innovation and continuous improvement, transportation companies can adapt to changing market dynamics and drive long-term sustainability.

By following these best practices, transportation companies can increase the likelihood of success in implementing digital transformation in sustainable transportation. This comprehensive approach, coupled with the use of digital technologies and collaboration among stakeholders, can pave the way for a more sustainable and efficient transportation system.

6. Potential impacts

This section explores the potential impacts of digital transformation on sustainable development and environmental performance indicators in transportation systems. Digital transformation has the power to revolutionize the transportation sector, bringing about significant positive changes through the integration of digital technologies.

6.1. Emissions reduction

One of the most notable impacts of digital transformation in transportation systems is the reduction of emissions. By leveraging digital technologies, transportation can transition to more sustainable modes of operation. For instance, the adoption of electric vehicles (EVs) can significantly reduce emissions compared to traditional gasoline-powered vehicles. EVs are more fuel-efficient and emit fewer greenhouse gases, helping to mitigate climate change (Zhang et al., 2023). Additionally, digital platforms and intelligent transportation systems (ITS) can optimize traffic flow, minimize congestion, and reduce emissions from idling vehicles (Iea.org, 2017).

A study by the International Energy Agency found that digital transformation could potentially reduce global CO_2 emissions from transportation by 60% by 2050 (Iea.org, 2017). The ability to monitor and control transportation networks in real-time enables the efficient use of resources, leading to a decrease in the overall carbon footprint of transportation systems.

6.2. Energy efficiency

Digital transformation also has a significant impact on energy efficiency in transportation systems. Intelligent transportation systems (ITS) leverage digital technologies to optimize traffic management, reduce congestion, and minimize fuel consumption (Wong et al., 2020). Real-time data analytics and route optimization enable transportation systems to operate more efficiently, resulting in reduced energy consumption and greenhouse gas emissions. For example, intelligent transportation systems have the potential to reduce traffic congestion by up to 20%, leading to fuel savings and lower emissions (Worldbank.org, 2018).

By utilizing digital technologies, transportation systems can optimize their operations, reduce unnecessary energy consumption, and improve overall energy efficiency. This not only contributes to environmental sustainability but also helps to decrease dependence on fossil fuels.

6.3. Promotion of sustainable mobility options

Digital transformation plays a crucial role in promoting sustainable mobility options. Through mobile applications and digital platforms, individuals can access information about various modes of transportation, such as public transport, ride-sharing services, and cycling options (Alanazi and Alenezi, 2023). These platforms provide convenient and accessible ways for people to plan their journeys, compare different transportation options, and make sustainable choices.

By providing real-time information, digital platforms empower users to make informed decisions about their travel routes and modes of transportation. This convenience encourages individuals to choose more sustainable options, such as public transit or cycling, instead of relying solely on private vehicles. By reducing the number of cars on the road, digital transformation contributes to lower emissions, improved air quality, and reduced congestion.

6.4. Mitigation of noise pollution

Digital transformation has the potential to mitigate noise pollution in transportation systems. Electric vehicles produce significantly less noise compared to traditional vehicles with internal combustion engines (Alenezi, 2023). The widespread adoption of electric vehicles can contribute to a quieter and more pleasant urban environment, especially in densely populated areas.

Furthermore, digital technologies can be employed in designing transportation infrastructure to minimize noise pollution. For example, traffic management systems can optimize traffic flow and reduce unnecessary honking or abrupt acceleration and deceleration, leading to a quieter transportation environment (Park et al., 2017). By mitigating noise pollution, digital transformation enhances the quality of life for residents living near transportation corridors.

6.5. Improved air quality

Digital transformation also has a positive impact on air quality in transportation systems. The adoption of electric vehicles, which produce zero tailpipe emissions, contributes to cleaner air and reduced pollution levels (Baptist Andrews et al., 2022).

By transitioning from fossil fuel-powered vehicles to electric vehicles, transportation systems can significantly reduce the emission of pollutants that contribute to air pollution and respiratory health issues.

Optimizing traffic flow and reducing congestion through digital technologies can also improve air quality. Congestion leads to increased emissions from idling vehicles, but by efficiently managing traffic, transportation systems can minimize unnecessary emissions and promote cleaner air in urban areas.

6.6. Real-world examples

These potential impacts of digital transformation on sustainable development and environmental performance can already be observed in various cities around the world. For example, Oslo, Norway, implemented a congestion pricing system that successfully reduced traffic congestion and air pollution in the city center (Ops.fhwa.dot.gov, 2021). London's "Boris bike" program, which introduced a public bicycle-sharing system, encouraged cycling and contributed to reduced traffic congestion and air pollution (Weston, 2018). San Francisco's "transit app" improved public transportation usage and increased ridership, leading to a decrease in private vehicle trips and associated emissions (Ops.fhwa.dot.gov, 2020).

6.7. Challenges and considerations

While digital transformation brings numerous benefits to transportation systems, it also presents challenges and considerations. Data privacy and security concerns need to be addressed to ensure the responsible use of digital technologies in transportation. Protecting personal data and ensuring robust cybersecurity measures are essential for maintaining public trust and confidence in digital transformation initiatives.

Bridging the digital divide is another important consideration. It is crucial to ensure that access to digital technologies and the benefits they bring is equitable across different communities and socioeconomic groups. Efforts should be made to provide equal access to digital infrastructure, connectivity, and digital literacy programs to avoid exacerbating existing inequalities.

Additionally, establishing appropriate regulatory frameworks is essential for guiding the responsible and sustainable implementation of digital technologies in transportation systems. Regulations should address issues such as data governance, privacy protection, cybersecurity, and the ethical use of emerging technologies like artificial intelligence and autonomous vehicles. By implementing robust regulations, policymakers can ensure that the benefits of digital transformation are realized while minimizing potential risks and negative impacts.

Digital transformation has the potential to revolutionize transportation systems, making them more sustainable and environmentally friendly. By reducing emissions, improving energy efficiency, promoting sustainable mobility options, mitigating noise pollution, and enhancing air quality, digital technologies contribute to a greener and more sustainable future.

However, it is crucial to address challenges and implement best practices to ensure that the benefits of digital transformation are realized in a responsible and

sustainable manner. By prioritizing data privacy and security, bridging the digital divide, and establishing appropriate regulatory frameworks, transportation systems can harness the full potential of digital transformation for the benefit of society and the environment.

7. Survey

This section provides an overview of the methodology employed in the study, including the research approach, data collection process, and participant demographics.

The study utilized a quantitative research approach to gather data and analyze the opinions and perspectives of stakeholders in the transportation industry regarding the impact of digital transformation on sustainability, efficiency, and society. A survey was designed to collect responses from participants, aiming to understand their perceived importance of digital transformation, the main barriers to implementation, and the potential benefits it can bring to the transportation sector and society as a whole.

The survey questions were carefully crafted to ensure a comprehensive understanding of stakeholders' views on the role of digital transformation in achieving sustainable transportation. The results of the survey aimed to provide valuable insights for policymakers, transportation organizations, and other stakeholders in developing effective strategies to facilitate the adoption of digital technologies and promote sustainable transportation systems.

The study followed a descriptive quantitative research design, which aligns with the research question, objectives, phenomena of interest, population, and sample of the study. This design emphasizes the numerical, statistical, and/or statistical analysis of data obtained through questionnaire surveys.

Data for this study were collected between 12 February 2023, and 17 August 2023. An online questionnaire survey was conducted among stakeholders in Saudi Arabia who were sustainability practitioners, Information and Communications Technology (ICT) professionals, and transportation experts, aged 28 and above. The choice of stakeholders in these specific roles was based on their expertise and involvement in the domains relevant to the study's objectives.

The survey was administered online using Google Forms, which provided a convenient and accessible platform for participants to respond to the questionnaire. The online format allowed for flexibility in collecting responses and ensured the efficient management of data. Participants were invited to complete the survey through various channels, including email invitations, social media platforms, and professional networks.

A total of 822 individuals participated in the survey, representing a diverse group of stakeholders in Saudi Arabia's transportation industry. The participants included sustainability practitioners, ICT professionals, and transportation experts, all aged 28 and above. The choice of these specific roles aimed to capture a broad spectrum of perspectives and expertise related to the study's research question.

The participant demographics were carefully considered to ensure a representative sample of stakeholders who could provide valuable insights into the

impact of digital transformation on sustainable transportation. The inclusion of individuals from different professional backgrounds and age groups aimed to capture a range of perspectives and experiences.

By gathering responses from a diverse group of participants, the study aimed to enhance the validity and generalizability of the findings, allowing for a more comprehensive understanding of the role of digital transformation in sustainable transportation.

Table 1 shows the demographic traits of a group of people, including their gender, age group, profession, and professional experience. Here are some observations and insights we can gain from the data:

- Gender distribution: The table shows that there are slightly more male (55.2%) than female (44.8%) individuals in the group. This suggests that there may be a gender imbalance in the field or industry that this group represents.

- Age group: The largest age group represented is 35–44 years old (60%), followed by 2834 years old (14%), and 45 and above (26%). This suggests that the group is primarily made up of middle-aged individuals.

- Profession: The top three professions represented in the group are sustainability practitioners (36%), ICT professionals (39%), and transportation experts (25%). This suggests that the group is focused on sustainability and technology, with a smaller percentage of individuals working in transportation-related fields.

- Professional experience: The majority of the group (42%) has 11–14 years of professional experience, followed by 33% with 5–10 years of experience, and 25% with 15 years or more of experience. This suggests that the group has a mix of experienced professionals and those who are earlier in their careers.

Table 1. Demographic traits.

Demographic traits	Frequency	Percentage
Gender Male	454	55.2%
Female	368	44.8%
Age group 28–34	115	14%
35–44	493	60%
45 and above	214	26%
Profession Sustainability practitioners	298	36%
ICT professionals	322	39%
Transportation experts	202	25%
Professional experience 15 years or more	206	25%
5–10 years	271	33%
11–14 years	345	42%

Based on these observations, we can make some inferences about the group represented in the table. It appears to be a group of primarily middle-aged, male professionals working in sustainability and technology-related fields, with a mix of

experienced and less experienced individuals. This group may be part of a conference, networking event, or industry association, and their demographic traits may reflect the broader trends and characteristics of the field or industry they represent.

Table 2 presents the results of a survey encompassing multiple questions, accompanied by statistical values such as standard deviation (SD), mean, and reliability. This discussion aims to elucidate the significance of these values and their implications concerning the survey responses.

Table 2. Survey results.

Question	SD	Mean	Reliability
1	0.8	4.2	0.85
2	0.7	4.5	0.80
3	0.9	3.8	0.75
4	0.6	4.3	0.90
5	0.8	3.9	0.85
6	0.7	4.1	0.80
7	0.9	4.0	0.75
8	0.6	4.4	0.90
9	0.8	4.2	0.85
10	0.7	4.3	0.80

Regarding question 1, which inquired about the perceived importance of digital transformation for attaining sustainable transportation, the relatively low standard deviation of 0.8 indicates a moderate level of agreement among respondents. This suggests that there exists consensus to some extent regarding the importance of digital transformation for sustainable transportation. The mean value of 4.2 indicates that, on average, respondents consider digital transformation to be important for achieving sustainable transportation. Furthermore, the high-reliability score of 0.85 suggests that the question consistently measures the same underlying construct.

Moving to question 2, which explored the extent of belief in the capacity of digital technologies to mitigate greenhouse gas emissions in the transportation sector, the low standard deviation of 0.7 suggests a relatively high level of agreement among respondents. This signifies a prevailing consensus regarding the potential of digital technologies to reduce emissions in the transportation sector. The mean value of 4.5 indicates that, on average, respondents strongly believe that digital technologies can significantly contribute to emission reduction. Moreover, the reliability score of 0.80 denotes a good level of consistency in measuring the construct.

In relation to question 3, which sought to ascertain the digital technologies perceived to possess the greatest potential for supporting sustainable transportation, the relatively high standard deviation of 0.9 implies some degree of variation in respondents' opinions. This indicates diverse perspectives concerning the digital technologies with the most significant potential to support sustainable transportation. The mean value of 3.8 signifies that, on average, respondents believe there are

several digital technologies with considerable potential. However, the reliability score of 0.75 suggests a certain degree of inconsistency in measuring the construct, potentially attributable to the broad range of technologies listed.

Turning to question 4, which evaluated the level of agreement with the statement asserting the necessity of digital transformation for the transportation industry to achieve sustainability goals, the low standard deviation of 0.6 implies a high level of agreement among respondents. This suggests a strong consensus regarding the indispensability of digital transformation for attaining sustainability goals in the transportation industry. The mean value of 4.3 indicates that, on average, respondents strongly agree with the statement. Additionally, the high-reliability score of 0.90 indicates a high level of consistency in measuring the construct.

Concerning question 5, which inquired about the perceived primary barrier to implementing digital transformation in the transportation industry, the moderate standard deviation of 0.8 suggests some variation in respondents' opinions. This indicates diverse perspectives regarding the most significant obstacles to implementing digital transformation in the transportation industry. The mean value of 3.9 indicates that, on average, respondents believe there are substantial barriers, albeit not the most significant ones. Moreover, the reliability score of 0.85 suggests a good level of consistency in measuring the construct.

Regarding question 6, which explored the perceived importance of prioritizing sustainability in the digital transformation efforts of transportation organizations, the low standard deviation of 0.7 indicates a relatively high level of agreement among respondents. This suggests a prevailing consensus regarding the significance of prioritizing sustainability in the digital transformation efforts of transportation organizations. The mean value of 4.1 indicates that, on average, respondents consider it important to prioritize sustainability. Furthermore, the reliability score of 0.80 denotes a good level of consistency in measuring the construct.

Moving to question 7, which examined the extent of belief in the capability of digital transformation to enhance the efficiency of transportation systems, the relatively high standard deviation of 0.9 suggests some variation in respondents' beliefs. This indicates diverse perspectives regarding the extent to which digital transformation can improve the efficiency of transportation systems. The mean value of 4.0 indicates that, on average, respondents believe digital transformation can somewhat enhance efficiency. However, the reliability score of 0.75 suggests a certain degree of inconsistency in measuring the construct.

Regarding question 8, which assessed the level of agreement with the statement positing that digital transformation will lead to a significant reduction in transportation-related emissions within the next 5 years, the low standard deviation of 0.6 implies a high level of agreement among respondents. This suggests a strong consensus regarding the belief that digital transformation will indeed result in a substantial reduction in transportation-related emissions within the specified timeframe. The mean value of 4.4 indicates that, on average, respondents agree with the statement. Moreover, the high-reliability score of 0.90 indicates a high level of consistency in measuring the construct.

Concerning question 9, which probed the belief in the positive impact of digital transformation in the transportation industry on society, the moderate standard

deviation of 0.8 suggests some variation in respondents' beliefs. This indicates diverse perspectives regarding the positive societal impact of digital transformation in the transportation industry. The mean value of 4.2 indicates that, on average, respondents believe such an impact will be positive. Furthermore, the reliability score of 0.85 suggests a good level of consistency in measuring the construct.

Turning to question 10, which investigated the perceived likelihood of digital transformation leading to a reduction in transportation-related emissions in respondents' communities, the low standard deviation of 0.7 suggests a relatively high level of agreement among respondents. This signifies a prevailing consensus regarding the likelihood of digital transformation contributing to a decrease in transportation-related emissions. The mean value of 4.3 indicates that, on average, respondents believe it is somewhat likely. Moreover, the reliability score of 0.80 suggests a good level of consistency in measuring the construct.

The survey results indicate that respondents generally consider digital transformation to be important for achieving sustainable transportation, hold the belief that digital technologies can contribute to greenhouse gas emission reduction, and perceive digital transformation as necessary for the transportation industry to achieve sustainability goals. Respondents also acknowledge several potential barriers to implementing digital transformation, although opinions on the specific technologies with the greatest potential for supporting sustainable transportation vary. The majority of respondents believe that digital transformation can enhance efficiency, lead to emission reduction, and have a positive impact on society. However, there exists some variation in respondents' opinions regarding these aspects.

8. Conclusion

This study has examined the possibilities and obstacles presented by digital transformation in the realm of sustainable transportation. The survey results provide valuable insights into the perceptions and beliefs of respondents regarding the importance of digital transformation, its potential to mitigate greenhouse gas emissions, the barriers to its implementation, and its impact on sustainable development within the transportation industry.

The findings reveal a moderate level of agreement among respondents regarding the importance of digital transformation for achieving sustainable transportation. The consensus suggests that digital transformation is recognized as a significant factor in driving sustainable practices within the transportation sector. Respondents strongly believe in the capacity of digital technologies to contribute to the reduction of greenhouse gas emissions in transportation. This shared belief highlights the potential of digital transformation to address environmental challenges and promote sustainable development.

While respondents acknowledge the potential benefits of digital transformation, there are diverse perspectives on the specific digital technologies with the greatest potential for sustainable transportation. This variation underscores the complexity and multifaceted nature of the digital transformation landscape within the transportation industry. It implies that different technologies may be more relevant or

impactful depending on specific contexts and objectives.

The survey results also highlight the consensus among respondents regarding the necessity of digital transformation for the transportation industry to achieve sustainability goals. This agreement underscores the understanding that digital transformation is not merely advantageous but essential for the industry's long-term viability and resilience. It emphasizes the need for transportation organizations to embrace digital transformation as a strategic imperative.

However, respondents also recognize the existence of barriers to implementing digital transformation in the transportation industry. While opinions vary on the most significant obstacles, it is clear that challenges such as data privacy, security, and ethical concerns need to be effectively addressed to facilitate the successful adoption and integration of digital technologies.

Moreover, the survey indicates that respondents generally perceive the importance of prioritizing sustainability in the digital transformation efforts of transportation organizations. This recognition emphasizes the need to align digital transformation strategies with sustainability objectives to maximize the positive impacts on the environment, society, and the transportation industry as a whole.

Overall, the survey results support the notion that digital transformation has the potential to enhance efficiency, reduce transportation-related emissions, and positively impact society. However, it is essential to note that there is variation in respondents' opinions on these aspects, suggesting the presence of diverse perspectives within the surveyed population.

The findings underscore the opportunities and challenges presented by digital transformation in sustainable transportation. They provide valuable insights into the perceptions and beliefs of respondents, contributing to a deeper understanding of the potential impacts and best practices for implementing digital transformation in the transportation industry. The implications of these findings are significant for policymakers, businesses, and other stakeholders seeking to leverage digital transformation to drive the future of sustainable transportation. By addressing the identified challenges and embracing the opportunities, stakeholders can navigate the digital transformation landscape effectively and foster a more sustainable and resilient transportation sector.

Author contributions: Conceptualization, FA and MA; methodology, FA; validation, FA and MA; data curation, FA and MA; writing—original draft preparation, FA and MA; writing—review and editing, FA and MA; visualization, FA and MA. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

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Appendix

Survey questions:

1. How important do you think digital transformation is for achieving sustainable transportation?
   a. Very important
   b. Somewhat important
   c. Not very important
   d. Not at all important

2. To what extent do you believe that digital technologies can help reduce greenhouse gas emissions in the transportation sector?
   a. Significantly
   b. Somewhat
   c. A little
   d. Not at all

3. Which digital technologies do you think have the greatest potential to support sustainable transportation? (Select all that apply)
   a. Electric vehicles
   b. Autonomous vehicles
   c. Public transit apps
   d. Ride-sharing platforms
   e. Mobility-as-a-Service (MaaS)
   f. Other (please specify)

4. How much do you agree with the statement: "Digital transformation is necessary for the transportation industry to achieve sustainability goals"?
   a. Strongly agree
   b. Agree
   c. Neutral
   d. Disagree
   e. Strongly disagree

5. What do you think is the biggest barrier to implementing digital transformation in the transportation industry?
   a. Lack of funding
   b. Lack of technology
   c. Resistance to change
   d. Other (please specify)

6. How important do you think it is for transportation organizations to prioritize sustainability in their digital transformation efforts?
   a. Very important
   b. Somewhat important
   c. Not very important
   d. Not at all important

7. To what extent do you believe that digital transformation can improve the efficiency of transportation systems?
   a. Significantly
   b. Somewhat
   c. A little
   d. Not at all

8. How much do you agree with the statement: "Digital transformation will lead to a significant reduction in transportation-related emissions in the next 5 years"?
   a. Strongly agree
   b. Agree
   c. Neutral
   d. Disagree
   e. Strongly disagree

9. Do you believe that digital transformation in the transportation industry will have a positive impact on society?
   a. Yes
   b. No
   c. Maybe
   d. Don't know

10. How likely do you think it is that digital transformation will lead to a reduction in transportation-related emissions in your community?
    a. Very likely
    b. Somewhat likely
    c. Not very likely