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THE ASSESSMENT OF THE IMPACT OF ARTIFICIAL INTELLIGENCE ON TRANSPORTATION SUSTAINABILITY

Summary. Assessing the impact of artificial intelligence (AI) on transportation sustainability is important for companies' internal and external benchmarking and improving technology and sustainability policies. This article focuses on developing and using the Transportation Technology Sustainability Index (TTSI) to assess the impact of AI on transportation sustainability. The authors did literature research to formulate dimensions and define sustainability indicators (SIs) and conducted interviews with experts from Dutch road freight transportation companies to validate the dimensions and SIs that can be used for calculating TTSI. The same TTSI-based assessment with some necessary adjustments can be applied to other modern technologies and transportation modes such as air, rail, sea, and multi-modal. Literature and qualitative research confirmed that AI applications foster sustainable performance, so more emphasis should be placed on increasing the use of AI in transportation. The TTSI-based assessment developed by the authors would allow transportation companies to measure the impact of AI or other advanced technologies on sustainability.

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Keywords: artificial intelligence, sustainability indicators, transportation sustainability, Transportation Technology Sustainability Index, company benchmarking, AI skills

1. INTRODUCTION

Technological development has tremendously accelerated, and fast-paced change can happen within a brief time. Roser [15] states that this fast-paced change driven by AI could speed up even more, and AI is already changing our world.

New technologies such as AI, blockchain, Internet of Things, virtual reality, big data or robotics transform business activities and working environments and can improve the performance of companies. These technologies are also reshaping the transportation landscape and hold the potential for sustainability [19].

The Dutch economy relies heavily on the transportation and logistics sectors. However, challenges related to emissions, safety, and increasing demand for public and business properties lie ahead. Numerous trucks transport goods across various routes in the Netherlands. These activities are good for the economy, but they are also causing problems like traffic jams, accidents, and pollution [7].

The Dutch government wants to use artificial intelligence (AI) technology in transportation to help the country's economy and remain a major hub for moving goods around. At the end of 2019, the Netherlands AI Coalition (NL AIC) was established to catch up to world leaders in AI like China and the USA and provide an effective platform and favorable business environment for Dutch AI initiatives [7, 13]. AI in transportation is critical for optimizing processes, planning, and forecasting and fosters better management, decision-making, and sustainability.

The assessment of the impact of AI on transportation sustainability would allow transportation companies to understand sustainable performance gaps related to AI and to improve companies' technology and sustainability policies.

The research objective is to develop the Transportation Technology Sustainability Index (TTSI) which can be calculated based on sustainability indicators (SIs) measuring the impact of technology on transportation sustainability. The index can be used for transportation companies' benchmarking, and support making decisions in the field of technology and sustainability. Furthermore, companies can monitor their changing technology sustainability over time to understand the impact of new technologies on sustainable performance.

This study considers only AI technology, however, TTSI can encompass other modern technologies such as blockchain, Internet of Things, virtual reality, big data, robotics, etc. The index can be used by transportation companies to assess the impact of AI or other technologies on their sustainability and to identify possibilities for sustainable improvement.

The study offers an overview of dimensions and sustainability indicators (SIs) for calculating TTSI. The dimensions and SIs were validated through qualitative research based on interviews with experts from Dutch road freight transportation companies using or going to use AI.

The main research question is: How can the Transportation Technology Sustainability Index be calculated and applied to assess the impact of AI on transportation sustainability?

Research sub-questions are: 1) How can AI enhance transportation sustainability? 2) What dimensions and sustainability indicators (SIs) can be used for the TTSI-based assessment? 3) How can SIs be used for calculating the Transportation Technology Sustainability Index?

The outcomes of this study are about defining dimensions and sustainability indicators for calculating TTSI and giving recommendations on how to apply this index in transportation companies. These outcomes can be used by the transportation industry stakeholders such as policymakers, managers, and employees. The authors also discussed the future research directions in the 'Discussion' section.

2. METHODOLOGY

The authors carried out literature research and qualitative research based on interviews with experts from Dutch road freight transportation companies to answer the main research question and research sub-questions.

The literature research explored current trends and advancements in AI applications for road freight transport in the Netherlands, focusing on sustainability performance improvement. This involves gathering and analyzing existing literature sources to understand the landscape of AI applications in freight transport and the impact of AI on sustainability. The literature research aimed to formulate dimensions and define SIs relevant to the TTSI-based assessment of the impact of AI on transportation sustainability.

To validate dimensions and SIs the qualitative research was done through operationalization and thematic analysis of data collected from interviews with experts from Dutch transportation companies (see the section 'Qualitative research').

The interviews were recorded, transcribed, and analyzed to understand experts' perceptions of AI and the relevance of dimensions and SIs for the TTSI-based assessment. The deductive approach of thematic analysis was applied to analyze qualitative data (interview transcripts) using the set of themes formulated by authors (see the section 'Qualitative research'). The overview of dimensions and corresponding SIs in combination with outcomes of thematic analysis is included in the subsection 'Expert inputs and analysis of qualitative data'.

The authors formulate the limitations and the gaps addressing the choice of dimensions and SIs and give recommendations to stakeholders on how to use the TTSI-based assessment in the section 'Discussion'.

3. LITERATURE RESEARCH

By applying modern technologies in transportation, stakeholders can improve decision-making processes, and foster innovations and sustainability. AI applications for self-driving cars and trucks, real-time road condition monitoring, driver behavior and fatigue monitoring, route planning, and optimization can significantly transform transportation.

Abduljabbar et al. [1] outlined the historical development of AI, focusing on how AI has advanced over time and its increasing applicability to real-world problems including those in transportation. AI advancements include addressing specific transportation challenges (CO_2 emissions, optimal routes for vehicles, energy consumption, etc.), developing self-driving cars and trucks, and improving their safety and efficiency. According to Srivastava [18], AI in combination with other emerging technologies like Internet of Things, machine learning, cloud computing, and big data analytics empowers interconnectivity between vehicles enhancing efficiency through collecting and processing data about traffic, driving patterns, and road conditions. Despite advancements, there remain concerns about the reliability and effectiveness of AI algorithms. Hong et al. [10] researched whether an AI system can consistently perform its intended functionality over a specified period. For example, an autonomous vehicle equipped with AI should reliably navigate and make decisions throughout its operational lifetime.

Examining various frameworks and models helped identify the trends in the application of AI in transportation and its impact on sustainability. In this context, the most notable AI-related frameworks and methods are the Smart Mobility Framework and Artificial Neural Networks (ANNs). They provide insights into sustainability in transportation and the role of AI. According to Bıyık et al. [4], the Smart Mobility framework is based on several components including intelligent transport systems, open data, big data analytics, and citizen engagement. Intelligent transport systems leverage AI to optimize traffic flow, reduce congestion, and minimize emissions. This framework fits perfectly freight transportation, fostering fleet management, routing processes, and sustainable performance. Abduljabbar et al. [1] highlighted that AI-based models such as Artificial Neural Networks (ANNs) can be widely used in transportation. ANNs can be applied for traffic planning, forecasting traffic patterns, scheduling infrastructure maintenance, and predicting traffic conditions such as weather conditions or road congestion. To sum up, ANNs can help bridge the gaps in sustainable performance and move towards more sustainable transportation.

The literature research reveals the fast growth of AI applications in transportation and their impact on sustainability. It emphasizes the relevance and importance of developing the TTSI-based assessment for evaluating the impact of AI on transportation sustainability. The authors of this study examined articles and reports about transportation sustainability and AI to formulate dimensions and define corresponding SIs.

Sustainable development fosters the awareness of the need to optimize business processes. The study by Lyamina et al. [11] discussed the definition of company sustainability and developed a model for assessing the company sustainability, including the transport aspect of company sustainability. It suggests such sustainability metrics as route optimization, vehicle utilization, number of trips, CO_2 and other pollutant emissions, and fuel consumption. The new technologies, including AI, hugely influence company processes and sustainable development. Degot et al. [6] discuss AI's impact on emissions through optimizing processes and enhancing energy efficiency. AI-driven process optimization can improve efficiency in transportation, thereby reducing carbon emissions and cutting costs. Sanghavi [16] highlights that AI has the potential to reduce traffic congestion and improve transportation system efficiency. These improvements significantly influence economic and environmental benefits. Ranyal et al. [14] provide insights into road condition monitoring systems using AI methodologies. The timely detection of faults is crucial for riding comfort and safety. According to Abduljabbar et al. [1], AI can help solve the challenge of increasing travel demand, CO_2 emissions, and safety concerns. Smith [17] emphasizes the ethical challenges of using AI in transportation, particularly in autonomous vehicles. The main ethical concerns are risks related to software malfunctions and the need for safety-enhancing measures. All in all, different areas of sustainability can be improved by AI. Based on this information, the authors formulated dimensions and defined SIs for each dimension to calculate TTSI. The dimensions are CO_2 emissions, energy efficiency, cost optimization, profit generation (new revenue streams), social benefits, and ethical principles. Table 1 illustrates the dimensions and corresponding SIs used for the TTSI-based assessment.

4. QUALITATIVE RESEARCH

Qualitative research involves collecting and analyzing qualitative data (e.g., text) to gain insights into complex, abstract topics. It requires operationalization, considered as the process of turning abstract concepts into measurable evidence. The process involves defining a concept and its dimensions and indicators to understand the full scope of the concept and facilitate data collection and analysis.

In this study, the concept is formulated as follows: assessing the impact of AI on transportation sustainability. The qualitative research consists of four steps: 1) identifying dimensions and SIs (operationalization); 2) preparing interview questions based on operationalization; 3) collecting the qualitative data through interviews with experts; and 4) the thematic analysis of data. This approach validated dimensions and SIs in the context of assessing the impact of AI on transportation sustainability.

4.1. Dimensions and SIs

The authors identified six dimensions and ten corresponding SIs based on the literature research. Table 1 comprises operationalization and explanations of the relevance of indicators.

Tab. 1

Operationalization (Source: own elaboration)

Dimensions	Sustainability indicators	Relevance
CO_2 emissions	AI-driven strategies to reduce CO_2 emissions	Relevant for emission reduction through better transportation planning and vehicle utilization. Better vehicle utilization practices reduce the number of partially loaded trucks on the road and thus prevent road congestion.
Energy efficiency	Predictive vehicle maintenance	Relevant for improved energy efficiency and cost savings.
	Optimizing transportation routes	Relevant for route optimization, fuel consumption reduction, and cost savings.
Cost optimization	AI analytics to minimize operational costs	Relevant for cost savings and cost-effectiveness analysis.
Profit generation	Exploring new revenue streams through AI-enabled services	Relevant for revenue diversification and business growth.
Social benefits	Training & Development of employee AI skills	Relevant for employee competencies.
	Health and well-being of employees	Better route optimization and workload management enhance safety conditions, contributing to the health and well-being of employees.
	Work-life balance	Relevant for reducing manual tasks, and allowing more flexible working schedules.

Ethical principles	Transparent AI algorithms	Relevant for unbiased decision-making and ethical and responsible AI implementation.
	Data-secure AI algorithms	Relevant for protecting sensitive data and for ethical and responsible AI implementation.

The dimensions and indicators were used to prepare questions for interviews with experts and collect data focusing on adopting AI applications in road freight transportation companies, and AI's potential impact on sustainability.

The authors applied the deductive thematic analysis of interviews. According to Hecker and Kalpokas [9], deductive thematic analysis in qualitative research applies predefined themes or concepts to qualitative data. The following themes were identified based on the dimensions and indicators of the study concept (Table 1) and focus points of the field research: 1) stakeholders' perceptions towards AI technology; 2) change in management and training; 3) routing planning and vehicle utilization processes; 4) vehicle maintenance practices; 5) balancing cost-effectiveness and sustainability within companies operations; 6) health and well-being of employees; 7) the environmental impact of transportation activities (CO_2 emissions); etc.

4.2. Expert inputs and analysis of qualitative data

The qualitative research was carried out in April and May 2024 and was quite challenging and time-consuming because it was difficult to find interviewees. Moreover, many companies approached did not know what AI is or do not utilize it in their operations yet. The authors contacted Dutch transportation companies that met such criteria as the size of companies (more than 50 employees), utilization of AI applications, or consideration of implementing AI in their business processes in the future. Experts from six companies agreed to give interviews. Two companies operate internationally, and the rest operate locally in the Netherlands. The names of companies are not mentioned on their request. The operations manager, head of IT, software engineer, logistics manager, and transport and logistics specialists participated in interviews. All interviews were recorded via Microsoft Teams and transcribed.

The qualitative research indicated that across the companies, there is a shared recognition of the potential benefits in the field of sustainability that AI can bring to operations and fleet management practices [5]. The expert inputs support the idea that the assessment of the impact of AI on transportation sustainability is important for understanding how to reach sustainable goals.

On the one hand, the experts highlighted the growing trust in AI capabilities, although it requires time and effort to overcome technical challenges and ensure effective integration into existing systems. On the other hand, they described existing barriers such as a lack of employee awareness and specific examples of AI tools implemented for sustainability. Moreover, they expressed concerns about technological limitations such as the range of electric trucks and the reliability of AI algorithms. They also see challenges associated with adopting and implementing AI-driven solutions for sustainable fleet management.

An expert at Company 1 emphasized the need for thorough research and exploration before full-scale implementation. There are also concerns about security, privacy, and data management which need to be addressed to ensure smooth integration and effective utilization of AI technology. He added that employee training and awareness-raising efforts are ongoing to prepare all employees for the integration of AI into their workflows.

An expert at Company 2 mentioned the need for guidelines for employees to adapt to AI integration effectively. Furthermore, ensuring that drivers and other staff understand the technology and its implications for their roles is crucial for successful implementation. The lack of specific rules and regulations for the application of AI creates difficulties, requiring proactive guidance and collaboration with regulatory organizations to guarantee the ethical and responsible use of AI.

Despite these barriers, there are notable contributions of AI to collaboration and continuous improvement. Company 1 and Company 3 collaborate with external experts or partners in the context of the potential for knowledge sharing and partnerships to drive innovation. Various departments at Company 1 and Company 3 are involved in the initial stages of AI implementation, emphasizing collaboration across business units. Training programs are being developed to equip employees with the necessary skills to work effectively with AI tools and systems.

According to an expert from Company 4, there are AI-related benefits for sustainable fleet management. These include improvements in operational efficiency, cost-effectiveness, emission reduction, and increased driver safety. AI technologies offer the potential for optimizing routes, reducing fuel consumption, and minimizing emissions, contributing to environmental sustainability and cost savings. Moreover, AI-driven solutions improve data accuracy and precision, thus enhancing operational efficiency and decision-making, leading to smoother operations and greater customer satisfaction.

Company 5 views AI as a key solution for improving matches between shipments and carriers, leading to more efficient and environmentally friendly transportation. They integrate AI systems into their operations using logistics platforms. This indicates a management shift towards utilizing AI for greater efficiency and sustainability by focusing on full truck utilization.

Company 6, focusing on safety and health in the workplace, emphasizes the contribution of AI to enhancing employee well-being by reducing stress and improving working conditions. Furthermore, the technical sophistication of AI-based automatic planning systems such as Ortec presents opportunities for continued innovation and advancement in sustainable fleet management practices within this company.

The experts' answers to interview questions confirmed the relevance of dimensions and SIs for assessing the impact of AI on transportation sustainability. Experts’ perceptions and remarks about possible barriers are presented in Table 2.

Tab. 2

Expert inputs (Source: [5])

Dimensions	Sustainability indicators	Expert inputs
CO_2 emissions	AI-driven strategies to reduce CO_2 emissions	Stakeholders positively perceive the impact of AI on emission reduction, but lack specific examples; barriers include awareness gaps (knowledge of AI among employees) and security concerns (data security).
Energy efficiency	Predictive vehicle maintenance	Recognition of AI's potential to improve efficiency in maintenance planning (predictive maintenance); barriers include technological limitations and reliability concerns.

	Optimizing transportation routes	Acknowledgment of AI's role in route optimization; barriers include the need for thorough research and exploration.
Cost optimization	AI analytics to minimize operational costs	Growing trust in AI capabilities for cost optimization; barriers include security and privacy concerns.
Profit generation	Exploring new revenue streams through AI-enabled services	Recognition of AI's potential for revenue generation; barriers include lack of specific regulations.
Social benefits	Training & Development of employees AI skills	Recognition of a need for comprehensive training and development programs to ensure employees can effectively integrate AI into their workflows. This includes raising awareness and providing guidance on AI technologies to prepare employees for its adoption and use.
	Health and well-being of employees	Recognition of AI’s potential to improve the health and well-being of employees. This includes reducing stress through better route optimization, workload management, and enhancing safety conditions, contributing to a safer and healthier work environment.
	Work-life balance	AI can contribute positively to work-life balance by optimizing work schedules, reducing manual tasks, and allowing for more flexible working conditions.
Ethical principles	Transparent AI algorithms	Emphasis on transparent, unbiased AI algorithms; barriers include reliability concerns.
	Data-secure AI algorithms	Concern for ethical AI use; barriers include security and privacy concerns.

Experts made valuable remarks and expressed reasonable concerns, for example, about the reliability of AI applications. These concerns are critical for ensuring the safe and effective deployment of AI.

Interviews with experts provided useful information regarding the impact of AI on transportation sustainability. This information proved the relevance of dimensions and SIs formulated based on the literature research.

5. FINDINGS

The literature research findings address the sustainable effects of several frameworks and models used in road freight transportation and the definition of dimensions and SIs for the TTSI-based assessment. The existing literature focuses on public transit and has only a few frameworks on the relationship between new technologies and transportation sustainability. The Smart Mobility framework and ANNs can significantly assist in implementing AI (or other advanced technologies) and improving transportation sustainability. By applying these models, stakeholders can develop targeted strategies to optimize operations, reduce costs, and minimize environmental impact in transportation. Considering the growing potential of AI for improving sustainable performance, the authors developed TTSI to assess the impact of AI on transportation sustainability and identified dimensions and SIs (Table 1).

The qualitative research findings include dimensions and SIs validated by expert inputs (Table 2). They are used for assessing the impact of AI on transportation, as described below.

5.1. The TTSI-based assessment

The assessment is based on performance scores assigned by managers or stakeholders. The calculation includes three steps: 1) defining the performance scores; 2) determining SIs weights in case of the need for prioritizing; and 3) calculating TTSI.

Performance scores can be assigned using a scale from 1 to 4 (1 - insufficient, 2 - sufficient, 3 - good, 4 - excellent) to measure the success of AI integration regarding transportation sustainability (Table 3). Scores might be assigned with one or two decimals (e.g., 1.25 or 3.4).

Tab. 3

The TTSI-based assessment (Source: own elaboration)

Dimensions	Sustainability indicators	Performance scores (1 to 4)	Targets (3 to 4)
CO_2 emissions	AI-driven strategies to reduce CO_2 emissions		
Energy efficiency	Predictive vehicle maintenance		
	Optimizing transportation routes		
Cost optimization	AI analytics to minimize operational costs		
Profit generation	Exploring new revenue streams through AI-enabled services		
Social benefits	Training & Development of employees AI skills		
	Health and well-being of employees		
	Work-life balance		
Ethical principles	Transparent AI algorithms		
	Data-secure AI algorithms		
		TTSI	

5.2. Calculation of TTSI

The study employs equal waiting for indicators. It is possible to assign weights to indicators if policymakers or managers want to emphasize the priorities of indicators.

The performance scores for each SI are used for the calculation of TTSI as follows:

$$TTSI = \frac{\sum SI_i}{n} \quad (1)$$

where:
SIi – a score of a sustainability indicator,
n – the number of indicators.

For weighted scores w_i, the formula must be adjusted:

$$TTSI = \frac{\sum w_i * SI_i}{\sum w_i} \quad (2)$$

where w_i is the weight of SIi.

The greater the TTSI achieved, the greater the impact of AI on sustainability enhancement is in a transportation company.

The scores can be compared with targets assigned by a manager of a transportation company to analyze the gaps and make decisions on possible improvements. Setting a target for CO_2 emissions (measured in kg) depends on the way of emissions calculation. According to Gazzard et al. [8], different formulas are used considering the data available (e.g., the total fuel used by all the vehicles, or total distance travelled). The next step is to assign the target score, for example, a score of 3 to the target of 3-5% emissions reduction after implementing AI tools for transportation planning.

TTSI can be calculated for other new technologies used in a company (for each technology the set of dimensions and corresponding SIs should be identified as it is done for AI), and then the overall TTSI can be calculated as an average of all TTSIs.

6. DISCUSSION

In this section, the authors discuss the answers to the main research question and research sub-questions, the relevance and implications of the findings for transportation, and address the study's limitations and future research directions.

The literature research was done to answer the research sub-question 'How can AI enhance transportation sustainability?'. This research examined various frameworks and models and identified the trends in applying AI in transportation and its impact on sustainability. Various AI algorithms used in transportation can significantly enhance sustainability. The Smart Mobility Framework and Artificial Neural Networks (ANNs) provide insights into the role of AI and sustainability in transportation.

The literature and qualitative research helped answer the second research sub-question 'What dimensions and sustainability indicators (SIs) can be used for the TTSI-based assessment?'. The authors formulated dimensions and defined SIs for TTSI assessing the impact of AI on transportation sustainability. The qualitative research based on interviews with experts validated these dimensions and SIs. There were similarities in answers to interview questions but also discrepancies. The discrepancies can be explained by differences in companies' business activities, levels of AI adoption, and various backgrounds of respondents.

El Makhloufi [7] states that the Netherlands and Western Europe are lagging in using AI compared to global leaders like China and the USA. The results of the interviews partially confirmed this statement but also showed significant stakeholders' interest in AI. Experts also expressed concerns about the difficulties of implementing AI tools due to the need for computational resources and employees' competencies.

The literature and qualitative research were used when answering the research sub-question ‘How can SIs be used for calculating the Transportation Technology Sustainability Index?’ and the main research question ‘How can the Transportation Technology Sustainability Index be calculated and applied to assess the impact of AI on transportation sustainability?’. The study suggests dimensions and SIs for the TTSI-based assessment for measuring and monitoring the impact of AI on sustainability. The authors showed how SIs are used for calculating TTSI and decision-making in using AI in transportation and enhancing sustainability.

TTSI can also be used for understanding the impact of other new technologies on a company's sustainable performance, so further research might be needed to identify dimensions and SIs relevant to the blockchain, Internet of Things, virtual reality, big data, or robotics.

The TTSI can be applied for internal and external benchmarking. Large companies could compare departments or subsidiaries to identify performance and improvement areas. External benchmarking implies a comparison with other companies to gain insights beyond the company's boundaries. Regulatory organizations can use the assessment to understand the current state of the technology performance in transportation and the impact of technologies on sustainability.

The findings are related to the current state of the use of AI in transportation and assessing the impact of AI on transportation sustainability. Since the number of AI applications rapidly grows, there is a need for further research, like looking at new applications of AI in transportation and adjusting the dimensions and indicators used in the TTSI-based assessment.

The study focuses on several dimensions and corresponding SIs for the TTSI-based assessment however there can also be some other relevant dimensions (e.g., employee experience in the context of using AI, or data privacy) and corresponding SIs so it might require additional literature and field research.

The experts interviewed were from Dutch companies, and the number of interviews was limited to six. Future research can encompass interviewing experts from multiple countries to explore other experiences and opinions concerning the use of AI and its impact on sustainability.

7. CONCLUSION

The authors suggested TTSI to measure the success of AI integration regarding transportation sustainability. The TTSI-based assessment offers valuable insights for sustainable enhancement in transportation and making informed decisions on AI deployment. Companies can significantly benefit from AI applications enhancing sustainability. To maximize AI's benefits, companies should focus on overcoming barriers, collaborating with regulatory organizations, and investing in training programs to ensure ethical and effective AI integration.

The literature and qualitative research showed a lack of AI technology in the Dutch road freight transportation sector. The study indicates that the implementation of AI notably impacts transportation sustainability, and the companies should incorporate this technology to improve sustainable performance and gain competitive advantages. The stakeholders can use the TTSI-based assessment to monitor technological development and the impact of AI (or other technologies) on sustainability. This assessment also implies a comparison of performance scores with targets and supports decision-making processes in a company. Benchmarking transportation companies based on TTSI can help understand the current state of technological development and its influence on sustainable performance. Future research could provide more information about the use of technologies in transportation and their impact on sustainability.

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