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Research Article

Transportation Digitalization in Indonesia: A Narrative Review of Intelligent Transportation Technologies for Sustainable Mobility

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Abstract

Transportation digitalization has emerged as a strategic solution for addressing contemporary mobility challenges, including traffic congestion, limited infrastructure capacity, road safety issues, high logistics costs, and the increasing demand for efficient, safe, and integrated transportation services. As digital technologies continue to evolve, transportation systems are increasingly transitioning from conventional operations toward data-driven and intelligent mobility ecosystems. This study aims to provide a narrative review of transportation digitalization in Indonesia by examining its conceptual foundations, enabling technologies, implementation across transportation modes, associated benefits, existing challenges, and future development opportunities. The review employed a narrative approach using secondary data collected from national and international journal articles, conference proceedings, academic books, government reports, and institutional publications. The findings indicate that transportation digitalization in Indonesia has progressed through the implementation of Electronic Traffic Law Enforcement (ETLE), e-toll systems, e-ticketing services, online transportation platforms, smart traffic management, digital railway services, smart airports, digital port management, and real-time monitoring systems. The transformation is supported by Intelligent Transportation Systems (ITS), the Internet of Things (IoT), Artificial Intelligence (AI), Big Data Analytics, Digital Twin, and Mobility as a Service (MaaS). These technologies contribute to improved operational efficiency, enhanced safety, reduced congestion, better service quality, and support for sustainable and low-emission transportation. Nevertheless, challenges related to infrastructure disparities, interoperability, cybersecurity, regulatory readiness, and human resource capacity remain significant. Therefore, strengthening an integrated, secure, inclusive, and data-driven transportation ecosystem is essential to accelerate sustainable mobility and smart transportation development in Indonesia.

Keywords: *Transportation Digitalization; Smart Transportation; Intelligent Transportation System; Sustainable Transportation*

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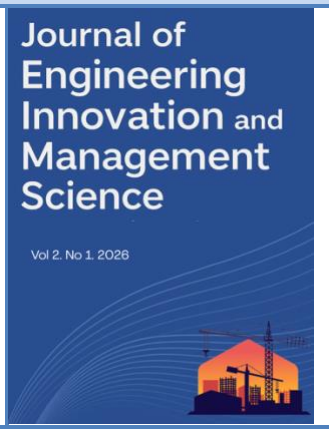

INTRODUCTION

The rapid advancement of digital technology has significantly transformed the way transportation systems are planned, managed, operated, and evaluated across the world. Transportation is no longer perceived solely as a physical network consisting of roads, vehicles, terminals, and transfer facilities (Adamos & Nathanail, 2022; Alaei et al., 2024; Karam et al., 2023; Monios & Bergqvist, 2020). Instead, it has evolved into a complex and interconnected ecosystem driven by real-time data, digital connectivity, and intelligent decision-making processes (Basole et al., 2024; Nativi et al., 2021; Saeed et al., 2024; Secundo et al., 2025). The emergence of technologies such as the Internet of Things, Artificial Intelligence, Big Data Analytics, cloud computing, smart sensors, Geographic Information Systems, and Digital Twin has accelerated this transformation (Matei & Cocoșatu, 2024; Wu et al., 2022). These technologies enable transportation stakeholders to collect, process, and analyze large volumes of information in real time. As a result, transportation systems can respond more effectively to changing traffic conditions, user demands, and operational challenges. Digital technologies also facilitate automation, predictive analysis, and data-driven planning that were previously difficult to achieve using conventional approaches. Furthermore, the integration of intelligent technologies supports the development of transportation systems that are more adaptive, efficient, and sustainable. The growing importance of digitalization reflects the increasing need for transportation systems that can accommodate dynamic mobility patterns and rapidly changing urban environments. Consequently, transportation digitalization has become a key component in the development of modern mobility systems and smart cities.

The transportation sector plays a strategic role in supporting economic development, regional integration, goods distribution, and social mobility in Indonesia. As the largest archipelagic country in the world, Indonesia depends heavily on effective transportation networks to connect its diverse regions and facilitate economic activities. However, rapid population growth, urbanization, and increasing vehicle ownership have intensified transportation-related challenges in many parts of the country. Major metropolitan areas continue to experience severe traffic congestion that negatively affects productivity, travel reliability, and fuel consumption (Chandel, 2025; Nurhidayat et al., 2023; Rahman et al., 2022). High logistics costs remain a significant concern and can reduce the competitiveness of domestic industries and supply chains. In addition, the efficiency of public transportation services varies considerably across regions, limiting accessibility for many communities (Bittencourt & Giannotti, 2023; Cui et al., 2020; Karner et al., 2020; Olsson et al., 2021). Environmental concerns have also become increasingly important due to growing greenhouse gas emissions generated by fossil fuel-based transportation systems. These challenges indicate that traditional infrastructure expansion alone is insufficient to address contemporary transportation problems. More comprehensive solutions are needed to improve transportation performance while simultaneously supporting economic growth and environmental sustainability. Therefore, the integration of digital technologies into transportation systems has become an increasingly important strategy for achieving these objectives.

In recent years, transportation digitalization in Indonesia has accelerated through the implementation of various digital initiatives across multiple transportation modes. The adoption of Electronic Traffic Law Enforcement systems has improved traffic monitoring and strengthened law enforcement processes through automated technologies. Electronic toll collection systems have enhanced transaction efficiency and reduced delays at toll gates. Digital ticketing platforms and online transportation applications have transformed the way people access and utilize transportation services. Smart traffic management systems have also been introduced to support traffic optimization and improve mobility in urban areas. In the railway sector, digital services have enhanced passenger experiences through online reservations, electronic boarding systems, and real-time travel information (Anwer et al., 2024). Similar developments have occurred in airports and seaports through the adoption of smart operational systems and digital logistics management platforms (Liao et al., 2023). Moreover, the growing implementation of Intelligent Transportation Systems has expanded opportunities for improving safety, efficiency, and service quality. Despite these achievements, transportation digitalization in Indonesia remains fragmented and unevenly distributed across regions and transportation sectors. Challenges related to interoperability, digital infrastructure disparities, cybersecurity risks, human resource readiness, and regulatory adaptation continue to influence the effectiveness and scalability of digital transportation initiatives.

Despite the rapidly growing literature on transportation digitalization and intelligent transportation systems, several important research gaps remain. Existing studies have extensively examined specific technological domains, including Intelligent Transportation Systems (ITS), Artificial Intelligence (AI), Internet of Things (IoT), Digital Twin, machine learning, and Mobility as a Service (MaaS), with a primary focus on technological architectures, operational optimization, and smart city applications (Elassy et al., 2024; Gong et al., 2023; Rahmani et al., 2023; Wang et al., 2023; Yuan et al., 2022). Similarly, recent reviews have highlighted the contribution of digitalization to sustainable transportation, carbon reduction, and future mobility transitions through technologies such as AI, IoT, and blockchain (Kashem et al., 2025; Kwilinski et al., 2023; Song et al., 2022). Furthermore, extensive research has explored MaaS implementation, smart mobility development, and sustainable mobility frameworks in urban contexts (Alyavina et al., 2020; Karlsson et al., 2020; Paiva et al., 2021). However, the existing literature largely investigates these technologies and mobility concepts independently, resulting in limited understanding of how they collectively contribute to an integrated transportation digitalization ecosystem. In addition, most studies have been conducted in developed countries characterized by advanced digital infrastructure and mature governance systems, while evidence from developing countries remains scarce. Consequently, challenges related to infrastructure readiness, interoperability, governance, cybersecurity, regulatory adaptation, and human resource capacity within the context of transportation digitalization in Indonesia have received insufficient attention (Cucor et al., 2022; Tsakalidis et al., 2020). Moreover, the relationship between intelligent transportation technologies, implementation readiness, and sustainable mobility outcomes has not been comprehensively synthesized within a developing-country perspective. Therefore, a comprehensive review that

integrates technological, institutional, governance, and sustainability dimensions is needed to provide a holistic understanding of transportation digitalization and its implications for sustainable mobility development in Indonesia.

This study aims to present a comprehensive narrative review of transportation digitalization in Indonesia by examining its conceptual foundations, enabling technologies, implementation practices, benefits, challenges, and future development opportunities. The review focuses on intelligent transportation technologies that support the transformation of conventional transportation systems into data-driven and interconnected mobility ecosystems. Particular attention is given to technologies such as Intelligent Transportation Systems, the Internet of Things, Artificial Intelligence, Big Data Analytics, Digital Twin, and Mobility as a Service. The study also explores how these technologies have been implemented across various transportation sectors, including land, railway, air, and maritime transportation. Furthermore, the review investigates the potential contribution of transportation digitalization to operational efficiency, transportation safety, service quality, and environmental sustainability. In addition, key challenges associated with infrastructure readiness, governance, cybersecurity, interoperability, and human resource capacity are examined. The study seeks to provide a holistic understanding of the current state of transportation digitalization in Indonesia. It also identifies opportunities for future development and areas that require further policy attention. By synthesizing existing knowledge from multiple sources, this review aims to support evidence-based decision-making and strategic transportation planning. Ultimately, the study contributes to the broader discussion on sustainable mobility and digital transformation in transportation systems within developing-country contexts.

METHODS

Research Design

This study employed a narrative review design to examine the development of transportation digitalization in Indonesia and its implications for sustainable mobility. A narrative review was selected because transportation digitalization represents a multidisciplinary field that integrates transportation engineering, information technology, sustainability science, public policy, urban planning, and digital governance. Unlike systematic reviews that focus on narrowly defined research questions and strict inclusion criteria, narrative reviews provide greater flexibility in synthesizing diverse forms of evidence and emerging knowledge. This approach allows the integration of conceptual, technological, empirical, and policy-oriented perspectives into a comprehensive analytical framework. The review aimed to identify major developments in intelligent transportation technologies, implementation practices across transportation sectors, opportunities for sustainable mobility, and challenges associated with digital transformation. Particular emphasis was placed on understanding the interactions among technological innovation, transportation management, governance systems, and sustainability objectives. Through this approach, the study sought to provide a holistic overview of transportation digitalization rather than evaluating a single technology or transportation mode. The narrative review also enabled the identification of research trends and emerging issues that may not yet be sufficiently addressed in

empirical studies. Furthermore, the approach facilitated the exploration of future development opportunities relevant to developing-country contexts. Therefore, the narrative review design was considered appropriate for generating an integrated understanding of transportation digitalization in Indonesia.

Study Area

The study focused on Indonesia as the primary context for examining transportation digitalization and sustainable mobility development. Indonesia represents one of the largest archipelagic countries in the world, consisting of thousands of islands connected through complex land, rail, air, and maritime transportation networks. The transportation sector plays a strategic role in facilitating economic growth, regional connectivity, logistics distribution, tourism development, and social mobility. However, Indonesia also faces significant transportation challenges associated with rapid urbanization, population growth, increasing vehicle ownership, infrastructure limitations, and environmental pressures. These challenges have intensified the need for innovative transportation solutions capable of improving efficiency, accessibility, and sustainability. In response, the government and transportation operators have increasingly adopted digital technologies to modernize transportation services and infrastructure. Recent initiatives include Electronic Traffic Law Enforcement systems, electronic toll collection, ride-hailing platforms, smart traffic management, digital railway services, smart airport operations, and digital port management systems. These initiatives provide valuable examples of transportation digitalization within a developing-country context characterized by diverse geographical, economic, and institutional conditions. The Indonesian case offers important insights into the opportunities and challenges of implementing intelligent transportation technologies in emerging economies. Therefore, Indonesia was selected as an appropriate context for exploring the role of digital transformation in supporting sustainable mobility.

Instrument and Data Collection

The study utilized secondary data obtained from a wide range of academic and institutional sources. Literature was collected from peer-reviewed journal articles, conference proceedings, academic books, government reports, policy documents, technical reports, and publications issued by national and international organizations. To ensure comprehensive coverage, literature searches were conducted using academic databases and search engines, including Scopus-indexed sources, Google Scholar, ScienceDirect, SpringerLink, IEEE Xplore, and institutional repositories. The literature search employed several keywords and keyword combinations, including “transportation digitalization,” “digital transformation in transportation,” “intelligent transportation systems,” “smart transportation,” “smart mobility,” “sustainable mobility,” “Internet of Things,” “Artificial Intelligence,” “Big Data Analytics,” “Digital Twin,” and “Mobility as a Service.” The search process focused primarily on publications produced between 2020 and 2025 to capture recent developments in transportation digitalization, although foundational studies published before this period were also considered when relevant. Publications were selected based on their relevance to transportation technologies, digital transformation, transportation management, sustainability, and

transportation policy. Sources that did not address transportation digitalization or lacked sufficient academic credibility were excluded from the review. Additional references were identified through backward and forward citation tracking to ensure broader literature coverage. Through this process, the study assembled a diverse body of literature representing technological, managerial, policy, and sustainability perspectives. This comprehensive data collection strategy strengthened the breadth and depth of the review findings.

Data Analysis

The collected literature was analyzed using qualitative thematic analysis and narrative synthesis techniques. The analysis began with an intensive review of all selected documents to identify recurring themes, concepts, technologies, and implementation patterns related to transportation digitalization. Relevant information was extracted and organized into thematic categories to facilitate systematic comparison across studies. The primary themes included transportation digitalization concepts, intelligent transportation technologies, transportation sector applications, operational benefits, sustainability implications, implementation barriers, governance issues, and future development opportunities. After categorization, the findings from different studies were compared to identify similarities, differences, and emerging trends. Particular attention was given to the relationships between technological innovation and transportation performance outcomes. The analysis also explored how digital technologies contribute to transportation efficiency, safety improvement, environmental sustainability, and service quality enhancement. In addition, studies were critically examined to identify methodological limitations, knowledge gaps, and unresolved issues within the existing literature. Thematic synthesis was subsequently employed to integrate findings from multiple sources into broader conceptual insights. This analytical process enabled the development of a comprehensive understanding of transportation digitalization in Indonesia and its role in supporting sustainable mobility. The results of the analysis formed the basis for identifying future research directions and policy implications.

Research Procedure

The review process was conducted through five sequential stages. The first stage involved defining the scope of the study and establishing the conceptual boundaries related to transportation digitalization, intelligent transportation technologies, and sustainable mobility. The second stage consisted of systematically searching and collecting relevant literature from academic databases, institutional repositories, and government publications. During the third stage, the collected documents were screened based on relevance, credibility, publication quality, and alignment with the study objectives. The fourth stage involved detailed reading and thematic classification of the selected literature. At this stage, information related to technologies, implementation practices, benefits, challenges, governance issues, and sustainability outcomes was extracted and organized. The fifth stage focused on thematic analysis and narrative synthesis to identify major trends, patterns, and relationships among the reviewed studies. Subsequently, research gaps and future opportunities were identified based on areas that remained insufficiently explored in the existing literature. The synthesized findings were then interpreted within the context of Indonesia's

transportation system and sustainable mobility agenda. Finally, conclusions and recommendations were formulated to provide guidance for future research, policy development, and transportation management practices. This procedure ensured that the review was conducted systematically while maintaining the flexibility necessary for a comprehensive narrative review.

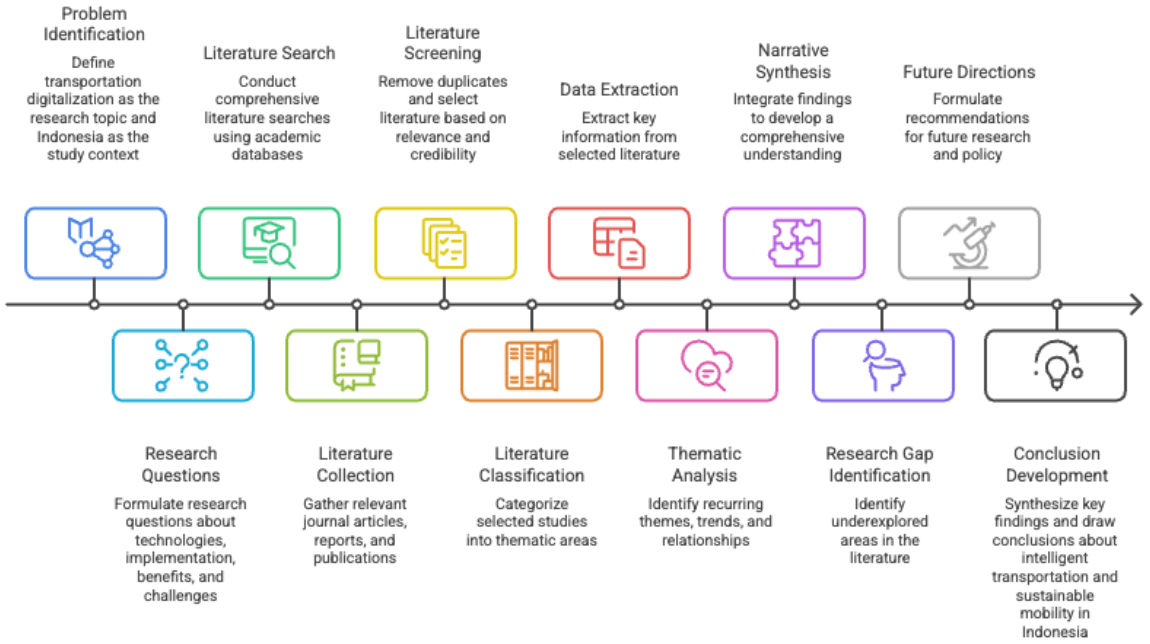

Figure 1. Research Method flow

Figure 1. The research procedure consisted of twelve sequential stages designed to systematically examine the current state of transportation digitalization in Indonesia and its implications for sustainable mobility development. The first stage involved identifying the research problem and defining the scope of the study by establishing transportation digitalization as the central topic of investigation and determining Indonesia as the primary context of analysis. The second stage focused on formulating research questions to guide the review process, particularly regarding intelligent transportation technologies, implementation practices, benefits, challenges, and future development opportunities. The third stage involved conducting a comprehensive literature search using academic databases and scientific search engines to identify relevant publications related to transportation digitalization, intelligent transportation systems, smart transportation, and sustainable mobility. The fourth stage consisted of collecting relevant literature from peer-reviewed journal articles, conference proceedings, academic books, government reports, and institutional publications. Subsequently, the fifth stage involved screening the collected literature by removing duplicate records and excluding sources that were not directly relevant to the objectives of the study. The sixth stage focused on classifying the selected literature into thematic categories, including transportation digitalization concepts, intelligent transportation technologies, implementation practices, sustainability implications, governance issues, and implementation challenges. The seventh stage involved extracting relevant information from the selected publications, including research objectives, technologies examined, implementation contexts,

major findings, and recommendations. Following data extraction, the eighth stage employed thematic analysis to identify recurring themes, emerging trends, relationships among variables, and common patterns across the reviewed studies. The ninth stage consisted of conducting a narrative synthesis to integrate findings from multiple sources and develop a comprehensive understanding of transportation digitalization in Indonesia. The tenth stage focused on identifying research gaps by examining areas that remain insufficiently explored in the existing literature, particularly those related to technology integration, implementation readiness, governance frameworks, and sustainable mobility outcomes. The eleventh stage involved formulating future research and policy directions based on the identified challenges, opportunities, and knowledge gaps. Finally, the twelfth stage synthesized all findings to develop comprehensive conclusions regarding the role of intelligent transportation technologies in supporting transportation transformation and sustainable mobility development in Indonesia.

RESULT AND DISCUSSIONS

Concepts and Key Technologies of Transportation Digitalization

Globally, the transportation sector is one of the sectors experiencing the fastest digital transformation. According to the International Energy Agency (IEA), the transportation sector accounted for approximately 37% of global CO_2 emissions from energy use in 2023, highlighting the need for technological innovation to create more efficient and environmentally friendly transportation systems [16]. In addition, a McKinsey report states that the application of digital technologies in transportation can improve operational efficiency by 20–30% through traffic optimization, fleet management, and predictive maintenance. Transportation digitalization can be understood as the process of integrating digital devices, communication networks, sensors, information systems, and data analytics into transportation systems. Its main objective is to improve operational efficiency, safety, connectivity, service quality, and sustainability. In practice, digitalization enables transportation systems to collect data, interpret real-time field conditions, predict potential disruptions, and respond more quickly and accurately.

One of the technologies most commonly associated with transportation digitalization is the Intelligent Transportation System (ITS). ITS uses sensors, cameras, computers, and communication systems to manage traffic in real time. Its applications include adaptive traffic lights, AI-based surveillance cameras, real-time traffic information, electronic toll collection, and traffic monitoring systems. These systems can help reduce travel time, improve traffic discipline, and strengthen urban transportation safety. The Internet of Things (IoT) serves as the backbone of connectivity by enabling vehicles, infrastructure, user devices, and control centers to communicate with one another. IoT sensors can be used to monitor vehicle volume, road conditions, air quality, fleet position, and the technical condition of transportation infrastructure. The collected data can then be analyzed using Artificial Intelligence and Big Data Analytics to predict congestion, optimize routes, manage fleet schedules, and support predictive maintenance. Digital Twin has also emerged as an important technology in transportation infrastructure management. Through

virtual representations of roads, bridges, railways, ports, or transportation nodes, operators can simulate conditions, monitor performance, and estimate potential damage risks before actual disruptions occur. Meanwhile, the concept of Mobility as a Service (MaaS) promotes the integration of various transportation modes into a single platform that provides trip planning, booking, payment, and real-time route information. As a result, users can move between transportation modes more easily and efficiently.

Tabel 1. Key Technologies and Functions of Transportation Digitalization

Technology	Main Function	Implementation Example	Potential Impact
ITS	Intelligent traffic management	Smart traffic lights, AI-based CCTV, traffic monitoring	Reduces congestion and accident risks
IoT	Real-time monitoring	Vehicle sensors, road sensors, fleet tracking	Improves operational responsiveness
AI and Big Data	Analysis, prediction, and optimization	Congestion prediction, route optimization, predictive maintenance	Supports data-driven decision-making and cost efficiency
Digital Twin	Virtual infrastructure simulation	Digital models of roads, bridges, railways, and ports	Supports predictive maintenance
MaaS	Integration of multimodal services	Travel applications, integrated payment systems	Reduces dependence on private vehicles

Implementation of Transportation Digitalization in Indonesia

The development of transportation digitalization in Indonesia can be observed across various modes of transport. In land transportation, digital transformation has taken place through ride-hailing services, Electronic Traffic Law Enforcement (ETLE), e-toll systems, Intelligent Transportation Systems (ITS), smart traffic management, and Automatic Traffic Counters. Application-based transportation services have changed people's mobility patterns by providing vehicle booking, digital payment, real-time tracking, and fare transparency. Meanwhile, ETLE strengthens traffic law enforcement through automatic camera-based monitoring, while e-toll systems accelerate payment transactions and reduce queues at toll gates. In the railway sector, digitalization has been implemented through e-ticketing, digital boarding passes, online ticket booking applications, face recognition boarding, and real-time travel monitoring. These innovations help reduce passenger queues, accelerate service delivery, improve the accuracy of passenger data, and enhance the overall user experience. The development of MRT, LRT, and high-speed rail also reflects a shift toward a more modern, information-based mass transportation system that is connected to digital payment services.

Digitalization in air transportation has developed through the implementation of smart airports. Technologies such as self check-in kiosks, e-boarding passes, baggage tracking systems, passenger biometrics, and integrated airport systems are used to accelerate travel processes. These systems improve check-in efficiency, strengthen security, and enable more accurate baggage monitoring.

In the maritime sector, digital transformation is carried out through the Automatic Identification System (AIS), digital port management, e-logistics systems, container tracking, and vessel monitoring systems. Port digitalization is essential for improving loading and unloading efficiency, accelerating logistics flows, and supporting inter-island connectivity.

Tabel 2. Summary of Transportation Digitalization Implementation in Indonesia

Sector	Digital Implementation	Main Function	Benefits
Land Transportation	ETLE, e-toll, ITS, ride-hailing	Traffic monitoring and management	Travel efficiency and improved traffic discipline
Railway Transportation	E-ticketing, online applications, face recognition	Digitalization of passenger services	Faster and more convenient services
Air Transportation	Self check-in, e-boarding pass, biometrics	Smart airport system	Improved airport security and efficiency
Maritime Transportation	AIS, digital port management, container tracking	Vessel and logistics monitoring	National distribution efficiency

Benefit of Transportation Digitalization

The benefits of transportation digitalization can be seen in the improvement of operational efficiency. Real-time data-based systems enable operators to monitor fleet positions, manage schedules, optimize routes, and estimate maintenance needs. Decision-making processes that were previously carried out manually can be transformed into data-driven processes, thereby reducing waiting times, energy consumption, and operational costs. In addition, transportation digitalization plays an important role in reducing traffic congestion. Smart traffic management, adaptive traffic lights, vehicle sensors, and real-time travel information allow traffic control to respond more effectively to actual conditions. Users can also access alternative route information, while governments can analyze congestion patterns and develop more appropriate traffic engineering strategies. As a result, transportation digitalization can contribute to travel time savings, reduced fuel consumption, and lower air pollution.

Another expected benefit of implementing transportation digitalization is improved safety. AI-based cameras, digital sensors, early warning systems, intelligent navigation, and Electronic Traffic Law Enforcement (ETLE) can help detect traffic violations, monitor potential hazards, and reduce human error. In the long term, accident data and traffic behavior data can also be used to design more precise safety interventions. Furthermore, transportation digitalization can support the development of sustainable transportation. Digitalization contributes to the development of electric vehicles, smart EV charging systems, emission monitoring, and energy-efficient route optimization. Application-based public transportation services can also improve accessibility and encourage people to reduce their dependence on private vehicles. Another important benefit is the improvement of public service quality through e-ticketing, cashless payments, real-time schedule information, fare transparency, and digital complaint services.

Implementation Challenges in Indonesia

Despite offering various benefits, transportation digitalization in Indonesia still faces several challenges. One of the main challenges is the uneven distribution of digital infrastructure. The quality of internet networks, availability of sensors, data centers, and communication devices are still largely concentrated in urban areas. This disparity causes technologies such as Intelligent Transportation Systems (ITS), real-time monitoring, and digital payment systems to be implemented less optimally in several regions. Cybersecurity is also a strategic issue in the implementation of transportation digitalization. Digital transportation systems manage user data, travel data, transaction records, vehicle location data, and operational information. Without adequate protection, these systems are vulnerable to hacking, data theft, service disruption, and declining public trust. Therefore, digital transportation systems need to be supported by strong data security governance, encryption, system audits, and incident response mechanisms.

Another challenge is the weak integration of systems. Many operators and institutions use different platforms, data formats, and technology standards. This condition hinders the development of Mobility as a Service (MaaS), fare integration, route integration, and real-time information exchange across transportation modes. Furthermore, transportation digitalization also faces challenges related to uneven human resource readiness. Digital transformation requires skilled personnel in data analytics, Artificial Intelligence, cybersecurity, system management, and digital-based transportation operations. These challenges are also closely related to regulatory issues, as regulations often develop more slowly than technological innovation. Autonomous vehicles, data protection, system interoperability, and platform collaboration require a clear legal framework to ensure safe implementation and legal certainty. Therefore, the success of transportation digitalization in Indonesia depends not only on technological readiness, but also on infrastructure equity, cybersecurity governance, system integration, human resource capacity, and adaptive regulation.

Tabel 3. Main Challenges and Policy Response Directions

Challenges	Impacts	Response Directions
Uneven digital infrastructure	Digital implementation is concentrated in major cities	Expansion of networks, sensors, and transportation data centers
Cybersecurity and privacy	Risk of data breaches and service disruptions	Security standards, audits, encryption, and incident response mechanisms
Low interoperability	Cross-modal data is difficult to integrate	National data standards and integration architecture
Human resource readiness	Technology utilization remains suboptimal	Training, certification, and university-industry collaboration
Adaptive regulation	Uncertainty in the implementation of innovation	Regulatory sandbox and evidence-based policy

Development Opportunities and Future Directions

Indonesia has significant opportunities to accelerate transportation digitalization. The high number of internet and smartphone users provides a strong user base that is ready to adopt application-based transportation services, digital payment systems, and real-time travel information. In addition, rapid urbanization has increased the need for urban transportation systems that are more efficient, integrated, and low in emissions. Issues such as traffic congestion, air pollution, and limited urban space make smart transportation an increasingly urgent necessity. The smart city agenda in various regions also creates opportunities to integrate transportation systems with urban governance, environmental management, energy systems, and public services. In this context, digital transportation should not operate independently, but should be connected to smart governance, smart environment, and smart economy. Furthermore, national digital transformation programs, the development of telecommunications infrastructure, and the growth of the digital economy can strengthen the smart transportation ecosystem. The expansion of digital payment systems also supports the development of more efficient and transparent cashless transportation services.

Future development should prioritize intermodal integration, data interoperability, cybersecurity strengthening, analytics-based planning, and the expansion of digital transportation technologies to medium-sized cities and non-metropolitan areas. The development of digital transportation should also consider inclusiveness to prevent new forms of inequality among communities with limited digital access. Therefore, the success of transportation digitalization should not only be measured by technological sophistication, but also by its ability to improve access, safety, efficiency, and equity in mobility services.

Research Gap and Research Implaications

To ensure that the literature search was relevant and comprehensive, this study used a combination of keywords in both English and Indonesian. The main keywords used in the literature search are presented in Table 4.

Tabel 4. Literature Search Keywords for Transportation Digitalization

No.	Indonesian Keywords	English Keywords
1	Digitalisasi transportasi	Transportation digitalization
2	Transformasi digital transportasi	Digital transformation in transportation
3	Transportasi cerdas	Smart transportation
4	Infrastruktur transportasi digital	Digital transportation infrastructure

Based on the collected literature, several main variables and indicators were identified and formulated, as shown in Table 2

Tabel 5. Research Variables and Indicators of Transportation Digitalization

Main Variables	Indicators
Transportation Digitalization	Use of digital applications, IoT, AI, Big Data, blockchain, Digital Twin, e-ticketing, and GPS tracking
Transportation Efficiency	Travel time, operational costs, service speed, route optimization, and fleet productivity
Transportation Safety	Accident reduction, early detection, traffic monitoring, ETLE, and safety sensors
Environmental Sustainability	Emission reduction, energy efficiency, use of electric vehicles, and low-carbon transportation
Service Quality	Ease of access, real-time information, digital payment, user convenience, and fare transparency
Implementation Readiness	Digital infrastructure, human resources, regulation, cybersecurity, and inter-system integration

Based on the literature review, several research gaps remain open and have the potential to be developed in future studies, particularly in the fields of transportation digitalization, smart transportation,digital transformation in transportatiom, digital transportation infrastructure

Tabel 6. Findings of the Literature Review

No.	Study Aspect	Summary of Literature Findings	Potential Research Data
1	Concept of transportation digitalization	Transportation digitalization transforms conventional transportation systems into data-driven systems based on automation and digital connectivity.	Definition of transportation digitalization, forms of technology implementation, and changes in transportation service models
2	Key technologies	The most frequently discussed technologies include AI, IoT, Big Data, blockchain, Digital Twin, cloud computing, autonomous vehicles, and V2V/V2I communication.	Types of digital technologies used in transportation
3	Intelligent Transportation System	ITS is used for traffic management, congestion reduction, road safety improvement, and transportation monitoring through sensor- and camera-based systems.	Data on ITS implementation, smart traffic lights, AI-based CCTV, and traffic monitoring
4	Internet of Things	IoT enables real-time monitoring of vehicles, roads, parking areas, traffic conditions, and safety.	Road sensors, GPS tracking, smart parking, and real-time monitoring
5	Artificial Intelligence	AI is used for congestion prediction, route optimization, predictive maintenance, accident analysis, and transportation decision-making.	Route optimization, machine learning, traffic prediction, and accident detection
6	Blockchain and smart contracts	Blockchain is used for electronic transportation documents, digital contracts, logistics transactions, and data security.	E-documents, smart contracts, electronic consignment notes, and digital transactions

7	Digital Twin	Digital Twin is used to create virtual models of road infrastructure, traffic systems, ports, and transportation networks.	Transportation simulation, digital road models, and infrastructure damage prediction
8	Sustainable transportation	Digitalization supports emission reduction through route optimization, electric vehicles, energy efficiency, and smart transportation management.	Emission data, energy efficiency, smart EV charging, and green transportation
9	Mobility as a Service	MaaS integrates various modes of transportation into a single digital platform to facilitate user mobility.	Mode integration, transportation applications, digital payments, and trip planning
10	Logistics digitalization	Logistics digitalization improves transparency, supply chain efficiency, paperless documentation, and goods tracking.	E-logistics, container tracking, digital freight, and electronic documents
11	Transportation safety	Digital technology improves safety through early accident detection, road monitoring, vehicle sensors, and warning systems.	Road safety, accident detection, V2I communication, and automatic traffic offence recording
12	Operational efficiency	Digitalization can accelerate services, reduce costs, increase productivity, and improve fleet management.	Operational costs, travel time, fleet efficiency, and service productivity
13	Implementation challenges	The main challenges include high costs, uneven infrastructure, limited digital human resources, weak regulation, data privacy issues, and cybersecurity risks.	Cost barriers, infrastructure gaps, skill gaps, regulation, and cybersecurity
14	Governance and regulation	The success of smart transportation requires policy support, interoperability standards, public-private collaboration, and data protection.	Digital transportation policy, governance, PPP, and data regulation
15	Research gap	Many studies remain conceptual and have not empirically evaluated the effectiveness of technology, particularly in developing countries such as Indonesia.	ITS evaluation, digital readiness, integration models, and Indonesian case studies

The literature review indicates that several important research gaps remain. First, many existing studies discuss technologies such as IoT, AI, Big Data, blockchain, and Digital Twin separately. Future research should develop a multi-technology integration model within a unified smart transportation ecosystem. Second, studies in the context of developing countries, including Indonesia, remain relatively limited compared to those conducted in countries with more mature digital infrastructure. In fact, limitations in infrastructure, financing, and human resources create different implementation characteristics and challenges. The review also shows that studies on infrastructure readiness and human resource capacity still need to be strengthened. Research should not only discuss the benefits of technology, but also assess the readiness of organizations, operators, local governments, and users. In addition, the governance and regulatory aspects of digital transportation remain largely conceptual. Therefore, empirical studies are needed to

examine the relationship between policy frameworks, financing models, public-private partnerships, and the successful implementation of digital transportation infrastructure. Furthermore, the social impacts and user behavior aspects of transportation digitalization require greater attention. Public acceptance, digital inclusiveness, privacy, technological literacy, and changes in mobility behavior are important factors that determine the success of digitalization. Cybersecurity and data privacy issues also require a more practical and implementable framework. Finally, the relationship between digital transportation and net-zero emission targets needs to be examined at the city or project level, rather than only at the conceptual level. By addressing these gaps, digital transportation research in Indonesia can move beyond descriptive discussions toward a more operational, measurable, and locally contextualized implementation model.

Discussion

The findings of this review demonstrate that transportation digitalization has evolved into a fundamental component of modern transportation systems, particularly in supporting efficiency, connectivity, safety, and sustainability objectives. The integration of Intelligent Transportation Systems (ITS), Internet of Things (IoT), Artificial Intelligence (AI), Big Data Analytics, Digital Twin, and Mobility as a Service (MaaS) reflects the transition from infrastructure-centered transportation management toward data-driven mobility ecosystems. This finding is consistent with previous studies that describe transportation digitalization as a transformative process that enables transportation systems to become more adaptive, intelligent, and responsive to dynamic mobility demands (Kashem et al., 2025; Nikitas et al., 2020; Shamsuddoha et al., 2025; Wu et al., 2022). Earlier studies have emphasized the role of ITS in improving traffic operations through real-time monitoring, automated traffic control, and predictive traffic management. Similarly, research on IoT and AI applications has demonstrated their effectiveness in facilitating vehicle-to-infrastructure communication, congestion forecasting, and route optimization (Gheorghe & Soica, 2025; Mohsen, 2024). The current review further supports these findings by showing that digital technologies increasingly operate as interconnected systems rather than standalone innovations. This technological convergence allows transportation operators to integrate data collection, analysis, and decision-making within a unified platform. Compared with earlier transportation management approaches that relied heavily on manual operations, digitalized transportation systems offer significantly greater operational flexibility and responsiveness. Therefore, transportation digitalization can be viewed as a critical enabler of next-generation mobility systems that support both transportation performance and sustainability goals.

The review findings also indicate that transportation digitalization has been progressively implemented across multiple transportation modes in Indonesia, including land, railway, air, and maritime transportation. The emergence of Electronic Traffic Law Enforcement, electronic toll collection systems, digital ticketing services, ride-hailing platforms, smart airports, and digital port management demonstrates the growing institutional commitment to transportation modernization. These developments are consistent with previous studies conducted in Europe, North America, and East Asia, which reported that digital platforms significantly improve operational efficiency

and service accessibility. However, the Indonesian context presents unique characteristics that distinguish it from many developed countries. While transportation digitalization in developed economies often occurs within highly integrated infrastructure environments, implementation in Indonesia must address geographical fragmentation, infrastructure disparities, and varying levels of technological readiness. Consequently, the pace and effectiveness of digital transformation may differ considerably across regions. Similar observations have been reported in studies conducted in other developing countries, where infrastructure limitations and institutional capacity constraints influence the adoption of intelligent transportation technologies (Ajayi et al., 2021; Himawan et al., 2025; Tran et al., 2023). The findings suggest that transportation digitalization in Indonesia should not simply replicate models developed elsewhere but must be adapted to local socioeconomic and infrastructural conditions. Such contextual adaptation is essential to ensure that digital technologies generate meaningful and equitable transportation outcomes. Therefore, the Indonesian experience highlights the importance of aligning technological innovation with local implementation realities.

Another important finding concerns the contribution of transportation digitalization to operational efficiency and transportation safety. The review indicates that real-time monitoring systems, AI-supported analytics, smart traffic management, and predictive maintenance technologies can substantially improve transportation performance. These findings align with previous research showing that intelligent transportation technologies reduce travel delays, optimize fleet utilization, improve route planning, and lower operational costs (Dikshit et al., 2023; Fatorachian & Kazemi, 2025; Hu et al., 2020). The implementation of AI-based surveillance systems and Electronic Traffic Law Enforcement also demonstrates the potential of digital technologies to strengthen compliance with traffic regulations and reduce accident risks. Previous studies have similarly reported that automated monitoring systems contribute to safer transportation environments by minimizing human error and enhancing enforcement effectiveness (Alobaidallah et al., 2025). Furthermore, the integration of predictive analytics allows transportation operators to identify potential disruptions before they occur, thereby increasing system reliability and resilience. The review additionally highlights the growing role of digital technologies in supporting evidence-based transportation planning through the generation of large-scale operational data. Compared with conventional transportation management approaches, data-driven systems provide more accurate and timely information for decision-making. These advantages create opportunities for improving service quality while simultaneously enhancing transportation safety and operational sustainability. As a result, transportation digitalization represents not only a technological innovation but also a strategic management approach capable of transforming transportation governance.

The findings further demonstrate that transportation digitalization contributes significantly to sustainable mobility objectives through improved resource efficiency, reduced congestion, and support for low-emission transportation systems. Previous studies have consistently shown that smart transportation technologies contribute to carbon emission reduction by optimizing traffic

flows, reducing idle time, and improving transportation network efficiency (Dikshit et al., 2023; Fatorachian & Kazemi, 2025; Mohsen, 2024). The present review confirms these findings by identifying several digital applications that facilitate more sustainable transportation operations, including smart traffic management systems, digital logistics platforms, electric vehicle support systems, and integrated mobility services. The concept of Mobility as a Service is particularly important because it encourages multimodal transportation use and reduces dependence on private vehicles. Similar conclusions have been reported in studies examining sustainable mobility transitions in urban environments, where integrated transportation platforms improve accessibility while reducing environmental impacts (Alipour & Dia, 2023; Anthony Jnr, 2023; Garus et al., 2024; Rui & Othengrafen, 2023). Furthermore, the use of digital technologies enables transportation agencies to monitor environmental performance more effectively and support data-driven sustainability policies. However, the review also suggests that the relationship between transportation digitalization and sustainability outcomes remains insufficiently evaluated in many developing-country contexts. Most existing studies focus on conceptual benefits rather than measuring actual environmental impacts. Therefore, future research should investigate how intelligent transportation technologies contribute to measurable sustainability indicators, including emission reductions, energy efficiency, and modal shifts. Such evidence is necessary to strengthen the role of transportation digitalization within broader sustainable development strategies.

Despite the considerable opportunities offered by transportation digitalization, the review reveals several persistent implementation challenges that may limit its effectiveness. Infrastructure disparities remain one of the most significant barriers, particularly in regions where digital connectivity and technological resources are limited. Similar challenges have been documented in previous studies, which emphasize that transportation digitalization requires reliable communication networks, data centers, sensors, and supporting digital infrastructure (Gu et al., 2026; Kashem et al., 2025; Pundir et al., 2022). Cybersecurity and data privacy concerns also emerge as critical issues due to the increasing volume of transportation data generated by digital systems. Existing literature consistently highlights cybersecurity as a major challenge in intelligent transportation environments because data breaches and system disruptions can undermine public trust and operational reliability. Additionally, weak interoperability among transportation platforms continues to hinder the development of integrated mobility ecosystems. The review further identifies human resource readiness as an important factor influencing successful technology adoption. Transportation organizations require personnel with expertise in data analytics, Artificial Intelligence, cybersecurity, and digital system management to maximize the benefits of technological innovation. Regulatory frameworks also need to evolve alongside technological development to address emerging issues related to data governance, autonomous systems, and platform integration. Therefore, the successful implementation of transportation digitalization requires a multidimensional approach that combines technological advancement with infrastructure development, institutional capacity building, governance reform, and adaptive policy frameworks. Addressing these challenges will be essential for achieving an integrated, resilient, and sustainable transportation ecosystem in Indonesia.

Implication

The findings of this review have several important implications for the advancement of transportation systems, digital transformation strategies, and sustainable mobility development in Indonesia. From a theoretical perspective, the study contributes to the growing body of knowledge on transportation digitalization by integrating technological, institutional, governance, and sustainability dimensions within a single analytical framework. The review demonstrates that transportation digitalization should not be viewed solely as a technological innovation process but as a systemic transformation involving infrastructure, policy, organizational readiness, and stakeholder collaboration. From a practical perspective, the findings provide evidence that intelligent transportation technologies can significantly improve operational efficiency, transportation safety, service quality, and environmental performance when implemented within an integrated ecosystem. The study also highlights the importance of interoperability, data governance, and cybersecurity as foundational elements for achieving successful digital transformation in transportation systems. For policymakers, the findings emphasize the need to develop adaptive regulatory frameworks, national interoperability standards, and long-term digital transportation roadmaps that support innovation while ensuring public trust and data security. For transportation operators, the review underscores the importance of investing in digital infrastructure, predictive analytics, and workforce development to maximize the benefits of intelligent transportation technologies. Furthermore, the findings suggest that transportation digitalization can serve as a strategic instrument for supporting smart city initiatives, low-carbon transportation policies, and broader sustainable development agendas. The review also indicates that expanding digital transportation solutions beyond major metropolitan areas is essential for reducing regional disparities and promoting inclusive mobility services. For researchers, the identified knowledge gaps provide opportunities for future empirical studies focusing on technology effectiveness, digital readiness assessment, governance models, and sustainability outcomes within developing-country contexts. Ultimately, the successful integration of intelligent transportation technologies has the potential to accelerate the transition toward a more efficient, resilient, equitable, and environmentally sustainable transportation ecosystem in Indonesia.

Limitation and Suggestion for Further Research

This study has several limitations that should be considered when interpreting its findings. First, the review employed a narrative review approach, which emphasizes comprehensive synthesis and conceptual interpretation rather than the systematic evaluation and quantitative assessment of evidence. As a result, the findings are dependent on the scope, quality, and availability of the literature included in the review. Second, the study relied exclusively on secondary data obtained from published academic and institutional sources, which may not fully capture recent technological developments, operational practices, or policy changes occurring in real-world transportation systems. Third, the review primarily focused on identifying concepts, technologies, benefits, challenges, and opportunities associated with transportation digitalization without conducting empirical validation of their effectiveness in specific transportation settings. Fourth, although the review concentrated on Indonesia, many of the available studies remain conceptual

in nature and provide limited evidence regarding implementation outcomes at the local or regional level. Furthermore, the study did not evaluate the economic feasibility, cost-effectiveness, or long-term sustainability performance of individual digital transportation technologies. Future research should therefore employ empirical approaches, including case studies, surveys, longitudinal analyses, and quantitative modeling, to assess the actual impacts of intelligent transportation technologies on transportation efficiency, safety, environmental sustainability, and user satisfaction. Additional studies are also needed to examine digital readiness among transportation agencies, infrastructure operators, policymakers, and end users. Moreover, future investigations should explore governance mechanisms, interoperability frameworks, cybersecurity strategies, and data-sharing models that support integrated transportation ecosystems. Comparative studies involving different cities, regions, or developing countries would further enhance understanding of contextual factors influencing transportation digitalization. Researchers should also examine the relationship between transportation digitalization and measurable sustainability indicators, including carbon emissions, energy consumption, modal shifts, and mobility accessibility. By addressing these limitations and research needs, future studies can provide stronger evidence to support the design and implementation of sustainable, resilient, and inclusive digital transportation systems.

CONCLUSION

It can be concluded that transportation digitalization makes a significant contribution to the modernization of transportation systems. Digital technologies are capable of improving efficiency, reducing congestion, accelerating logistics services, enhancing safety, and supporting sustainable development goals. However, these benefits cannot be achieved optimally as long as several barriers remain, including limited digital infrastructure, weak data integration, a lack of skilled human resources, immature regulations, and cybersecurity risks. In the Indonesian context, these findings can be used as a basis for examining how transportation digitalization is implemented across land, maritime, air, and railway transportation sectors. Future research can also focus on Indonesia's readiness to develop a smart transportation system that is integrated with the concepts of smart cities and sustainable transportation.

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Fera Lestari contributed to the conceptualization of the study, research design, literature search, data collection, thematic analysis, interpretation of findings, manuscript drafting, visualization development, and project administration. H. C. O. Unegbu contributed to the development of the theoretical framework, methodology refinement, literature validation, critical analysis of the reviewed studies, manuscript review and editing, and supervision of the research process. Both authors participated in the synthesis and interpretation of the literature, contributed substantially to the discussion of the findings, critically revised the manuscript for important intellectual content, approved the final version of the manuscript for publication, and agreed to be accountable for all aspects of the work, ensuring the accuracy and integrity of the study.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. All contributions were conducted independently and without any financial, commercial, or institutional influence that could be perceived as a potential conflict. The research was carried out solely for academic and professional purposes.

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