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Smart urban mobility: Economic and social dimensions of sustainable development in times of digitalization

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Abstract

With accelerating urbanization, climate crises, and technological advancement, cities face increasing pressure on mobility systems, positioning digital transformation as a key driver of sustainable and inclusive urban development. This study evaluates various dimensions of the urban mobility system and how they are changing in the context of digitalization. First, we analyzed key digital solutions in city mobility and concluded that they increase the efficiency of transportation systems, reduce operating costs, and support environmental protection. Second, we examined partial operational and economic indicators of urban mobility and demonstrated the need for a comprehensive approach to assessing urban mobility quality. We then reviewed complex indices of city mobility and proposed a composite Index of Urban Mobility Quality, which combines both objective and experiential data, such as average trip time and user dissatisfaction with the transportation system. The practical part consists of two parts: (i) analysis of the relationship between transport inefficiency and key parameters of urban mobility, including travel time, carbon dioxide (CO_2) emissions, and fares. The results revealed a strong empirical link between inefficient urban transport, prolonged travel times, and increased CO_2 emissions, highlighting critical barriers to sustainable and inclusive mobility; (ii) calculation of the Index of Urban Mobility Quality for 137 cities, identifying those where targeted digital interventions are most urgently needed. The analysis also highlights cities whose experience can serve as benchmarks for smart mobility performance. Overall, the results provide a practical tool for prioritizing investments in transport digitalization and addressing inefficiencies often overlooked in conventional smart city rankings. Ultimately, the study contributes to bridging the persistent gap between technology-centric models of smart cities and citizen-centric approaches to mobility.

Keywords: Urban mobility; Smart city; Digitalization of transportation; Sustainable development; Transport efficiency; Operational indicators; Composite indices; Index of urban mobility quality

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1. Introduction

With rapid urbanization, deepening geopolitical instability, and increasingly tangible climate crises, cities are becoming critical places where global challenges are most serious. As reported by the United Nations (2024), more than half of the world's population lives in cities, and this figure is expected to approach 70% by 2050 (World Population Prospects 2024). Such a demographic shift is increasing pressure on already overloaded infrastructure and urban systems, mainly in urban mobility, and threatening progress toward the United Nations (UN) Sustainable Development Goals (SDGs), particularly those related to sustainable cities and communities (Goal 11) and climate action (Goal 13). From this perspective, digital transformation is increasingly positioned as a key driver of the transition toward more sustainable and adaptive cities, leveraging synergies between information technologies and strategic planning to reorganize urban systems in pursuit of long-term sustainability. The implications of this work are relevant not only for studies that focus directly on smart cities but also for evaluating progress toward achieving the SDGs.

Digital transformation is not merely the adoption of digital tools; it represents a foundational reform of socio-technical and institutional structures. As a core part of the smart city paradigm, this transformation emerges through the integration of data, people, and infrastructure flows into intelligent, adaptive ecosystems capable of addressing challenges related to mobility, climate adaptation, energy transition, and urban governance (Bibri *et al.*, 2023). The synthesis of artificial intelligence (AI), Internet of Things (IoT), and big data is creating more inclusive and environmentally aware urban models (Guo & Guo, 2023). The measurable impact of these technologies has been documented—digital solutions can reduce travel times by up to 35% in disadvantaged areas, reduce public transport delays by 25%, increase traffic speeds by 30%, and decrease energy consumption and waste management costs by 20% and 40%, respectively (Boston Consulting Group, 2024; Deloitte, 2021; McKinsey, 2023). These technologies enable a wider vision of smart cities where mobility is synchronized with digital governance, energy efficiency, waste management, and spatial planning, supported by tools such as AI, edge computing, wireless networks, and sensor systems (Ashwini *et al.*, 2022). This approach moves beyond technocentrism, which is still evident in many studies.

Specifically, urban mobility directly shapes spatial accessibility, productivity, and social equity, while also influencing environmental performance and energy consumption patterns (Tomadon *et al.*, 2024). In this study, we consider urban mobility as a concept that structures the movement of people and goods, mediating access to economic opportunities and public services. Its impact extends beyond the transportation system, influencing spatial equity, labor integration, and urban competitiveness (Baghersad *et al.*, 2023). Direct benefits include improved access to healthcare, education, and employment, while indirect benefits include reduced traffic congestion, pollution, and transportation-related accidents (Del Rio *et al.*, 2017). Nevertheless, the growing demand for transport systems, driven by urbanization, tourism pressure, and socioeconomic asymmetry, also brings negative consequences. For example, the most vulnerable populations often experience spatial isolation and transportation-related deprivation (Brandajs & Russo, 2023). Therefore, it is essential to address the disadvantages of such transformations, which will be examined in this study.

While digital innovations in urban mobility can lead to radical improvements, much of the existing research remains focused on technological efficiency, often overlooking broader social and economic impacts. Numerous conceptual models fail to consider environmental trade-offs and institutional readiness for necessary changes. In addition, there is a lack of integrated assessment tools that simultaneously capture user satisfaction, environmental and economic impacts, and service availability. Infrastructure modernization can deepen the digital divide or exacerbate socio-spatial inequalities. This gap highlights the need for people-centered metrics that assess mobility in terms of not only digital inclusivity but also equity, sustainability, and quality of life. Addressing this gap also confronts the fundamental shortcoming of early smart city models, which focused more on technology than on people.

The purpose of the study was to measure the quality of urban mobility, environmental sustainability, and social equity in global cities with the highest levels of digitalization. The study also aimed to compare successful strategies for implementing digital solutions in cities worldwide. To achieve this, successful cases of technological innovation and smart transport system implementation were analyzed, along with their economic, social, and environmental effects. Most existing studies focus on technological efficiency while disregarding the impact of innovation on quality of life. The proposed Index of Urban Mobility Quality (based on six parameters) integrates environmental (carbon dioxide [CO_2]), economic (fare/salary), and social (satisfaction with the system) metrics. Including these metrics helps overcome the technocentric focus of previous models and fills a gap in the literature. It is worth emphasizing that the primary aim of this work is to improve people's quality of life. The developed index enables the ranking of cities based on their readiness for and need for digital transformation in urban mobility.

Given the multidimensional nature of this topic, different sections address different issues. Section 2 presents a literature review in three areas: (i) digital solutions as key determinants of urban mobility; (ii) operational and economic indicators of mobility systems; and (iii) composite indices assessing urban mobility performance. Section 3 outlines the research question, provides evidence from major cities, and explains the methodology. Section 4 introduces several indices that measure different dimensions of urban mobility quality and develops the composite index. **S**ection 5 applies this index to global cities and discusses the results, focusing on both the best- and worst-performing cities. Section 6 covers policy implications. Section 7 discusses the model's limitations and suggests directions for future research. Finally, **Section 8** concludes the study.

2. Literature review

2.1. Digitalization as a key factor of urban mobility quality

Transportation systems have played a key role in economic development throughout human history, influencing national and international trade and providing global connectivity. Later, urban transportation became a routine necessity due to increasing city populations, labor diversification, and the division of cities into districts (Cattaneo *et al*., 2022). With the advent of digital technologies, urban mobility started to transform, giving rise to the concepts of the smart city and smart mobility. The range of technologies used in transportation can be grouped into three major areas: data analytics and visualization; automation of operations and equipment management; and communication technologies enabling interaction among individuals, companies, and government bodies (Arenkov *et al*., 2019). The transformation of urban mobility is most evident in the innovations described below.

Intelligent traffic management systems use IoT sensors, surveillance cameras, geolocation systems, and AI to monitor and optimize traffic in real time (to adjust traffic lights, road signs, and warning systems) (ISO, 2024). These systems help minimize traffic congestion, increase road safety, and improve the quality of life of urban residents. The implementation of Smart Mobility 2030 in Singapore reduced travel time by 15% through automated traffic management systems (Medium, 2024). Transport for London implemented predictive algorithms for traffic management, resulting in a 10% increase in road capacity (Balawi *et al*., 2024).

Mobility as a Service (MaaS) refers to the technological integration of transportation-related products and services, whether new or previously provided by individuals or employers (Rahman *et al*., 2022). All modes of transportation are integrated into a single digital platform, allowing residents to select options based on price, time, and convenience. MaaS systems incorporate various sensors, recording devices, IoT technologies, and communication networks, all relying on data connectivity, processing, and analytics (Beijing Municipal Commission of Transport, 2024). MaaS evolves through several stages: no integration (separate services); integration of information (multimodal travel planners and pricing information); integration of booking and payment (unified trip planning, booking, and payment); integration of service offerings (bundles/subscription and contracts); and integration of societal goals (policy alignment and incentives) (Sochor *et al*., 2018). Another study identified four functional levels of MaaS platforms: service coverage, digital platforms (online and application-based), multimodal operability, and full customer journey (informing, planning, booking, and payment) (Zhao *et al*., 2021).

Autonomous vehicles (such as robotic cabs and driverless delivery systems) use AI technologies, sensors, cameras, and radars to navigate roads without human intervention. These technologies allow companies to accelerate logistics processes by selecting the fastest route and reducing vehicle downtime. The introduction of autonomous vehicles brings wide-ranging changes to cities, including variations in vehicle miles traveled (−35% to +341%), cost per mile (−89% to +4%), traffic collisions (−90% to +16%), and emissions (−96% to +173%) (Richter *et al*., 2022).

Digital twins are virtual models of physical objects or systems that use real-world data to simulate, monitor, and predict performance. In transportation, digital twins help model traffic flows, assess infrastructure conditions, and support effective decisions in urban planning. City authorities can use them to better predict road repair timelines, identify accident-prone areas, and extend infrastructure lifespan by redistributing traffic. Digital twins also provide real-time information on parking availability, conduct environmental behavior analysis of traffic incidents, and support efficient emergency response (Faliagka *et al*., 2024).

Looking ahead, smart urban mobility solutions are expected to expand into intelligent public transportation, MaaS, traffic prediction and routing, infrastructure maintenance, pedestrian and cyclist safety, air mobility integration, and sustainable transportation (Wolniak & Stecuła, 2024). In recent years, significant progress in transport transformation has been driven by AI (Ashwini *et al*., 2022). The global AI in mobility market was valued at

USD 8.83 billion in 2024 and is projected to reach around USD 337.27 billion by 2033, growing at a compound annual growth rate of 49.89% from 2024 to 2033 (Acumen Research and Consulting, 2024; Cervicorn Consulting, 2024). In general, improvements in urban mobility create synergies across different sectors of the urban economy, strengthen connections between urban and rural areas, reduce regional disparities in living standards, and increase the attractiveness of non-metropolitan cities.

2.2. Operational and economic characteristics of urban mobility

Most papers consider the operational indicators of urban mobility, namely, technical performance, traffic safety, service quality, and environmental impact. Road and bridge monitoring systems, including the use of drones, have improved defect detection efficiency by 65%, while 5G monitoring systems have increased risk detection on roads by 20% (Gui *et al*., 2023). In Copenhagen, travel time was reduced by almost 20% (from 51 to 42 h) over the past 2 years, and CO_2 emissions decreased by 42% compared to 2005 (Carbon Neutral Cities Alliance, 2024), improving air quality through two main factors—the expansion of renewable energy sources and investment in cycling infrastructure, including the installation of hundreds of millions of smart traffic lights aimed at optimizing the movement of cyclists and buses. For bus passengers, time reductions have ranged between 5% and 20%, while for cyclists, between 5% and 10% (Gössling, 2013). The Shenzhen Intelligent Twin system, introduced by the city authorities in collaboration with Huawei, decreased waiting time at intersections by 17.7%, increased traffic capacity by 10%, and improved the efficiency of violation camera recognition by a factor of 10 (Huawei, 2021).

The INRIX Annual Global Traffic Scorecard report, which covers more than 900 cities in 37 countries, demonstrates that in 2023, only one city recorded 100 h of time lost per driver due to traffic jams, while in 2024, this number increased to four. The average time lost in the 20 most congested cities rose from 78.7 h to 84.25 h (INRIX, 2025). A recent study also analyzed the implementation of an intelligent traffic light system, which reduced travel time by 16%, decreased waiting time at intersections by 12%, and lowered noise and pollution associated with slow-moving vehicles at toll points, thus reducing energy waste as well (Elassy *et al*., 2024). The indicators are presented in Table 1.

Table 1. Operational indicators of urban mobility

Indicator group	Examples
Technical	(i) Level of digitalization of infrastructure (e.g., number of automated devices, sensors, and cameras) (ii) Share of vehicles connected to the IoT (iii) Number of smart traffic lights and automatic adjustment solutions used
Traffic safety	(i) Number of accidents (ii) Users' awareness through digital services and mobile applications (iii) Response time of emergency services equipped with modern navigation systems
Ecology	(i) CO_2 emissions reduced through the optimization of public transport routes and traffic congestion (ii) Share of environmentally friendly transport, including electric and hybrid vehicles (iii) Use of alternative energy sources in urban transport infrastructure
Quality of passenger service	(i) Convenience of using transport services (e.g., ticket processing time and online schedule availability) (ii) Frequency of information updates on transport traffic (iii) User satisfaction with the quality of services provided (based on surveys and feedback)

Note: Compiled by the authors
Abbreviation: CO_2: Carbon dioxide, IoT: Internet of things

Another group of publications focuses on economic indicators such as operational costs, revenues, and labor productivity, all of which can be improved through digital solutions (Chi & Mazzer, 2022; Odeck & Welde, 2010; Yusuf, 2024). These are summarized in Table 2.

Table 2. Economic characteristics of smart mobility systems

Indicator	Operations	Metrics examples
Labor productivity	Effective scheduling and coordination; Efficient use of resources; Fast decision-making; Effective supply chain management	Average passenger/cargo delivery time; Number of passengers or cargo volume moved per month/week
Economic efficiency of transportation	Optimal logistics schemes and routing; High-quality service provision; Transport system competitiveness	Cost per passenger or freight unit
Revenue from digital services	Development of mobile applications; Implementation of electronic payments and integration of supplementary commercial services	Revenue from ticket and related goods/service sales through electronic channels

Note: Compiled by the authors

The cities with the highest congestion levels in 2023 and 2024, in terms of time lost per driver (in hours), are shown in Figure 1, which directly relates to the economic implications of smart mobility systems.

The largest increase in absolute terms is observed in

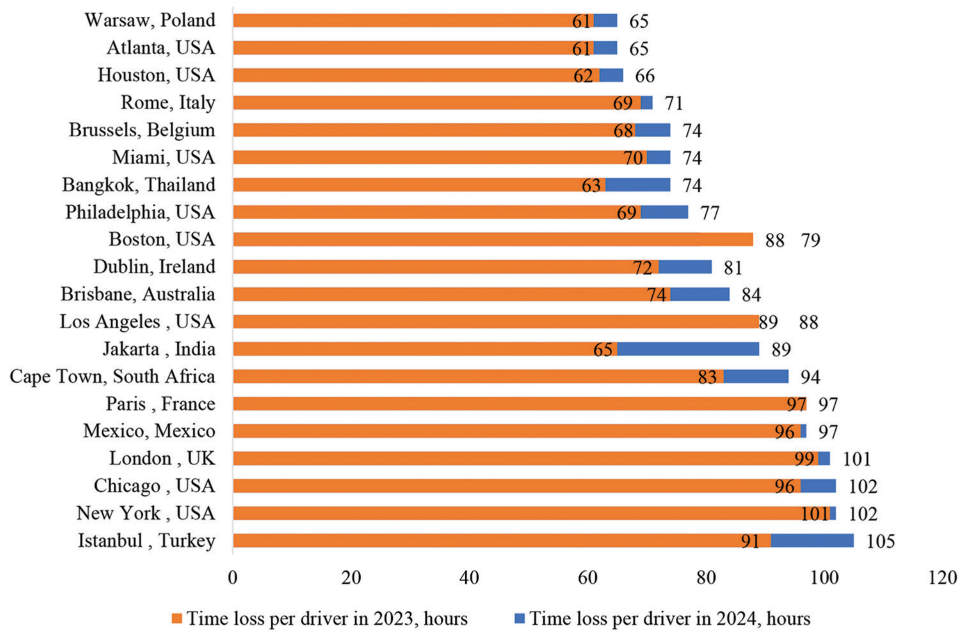

Figure 1. The busiest cities in 2023 and 2024
Source: Graph by INRIX, 2025

Jakarta, where time losses increased by 24 h per driver on average over the year. Given that India is the most populous country in the world, with an average monthly salary of more than USD 568 (Country Cassette, 2024), the economic loss from this increase amounts to hundreds of billions of dollars. The actual loss is much higher, as the Global Traffic Scorecard report does not consider environmental impact, freight delays, fuel overruns, production process disruption, opportunity costs (i.e., time spent in traffic that could have been spent on work tasks), and more.

From an economic point of view, the most noteworthy are the time losses for the three major countries covered in this report. For example, in the United States, time lost multiplied by the price of fuel amounts to USD 771 per driver; in the United Kingdom, USD 726, and in Germany, USD 498. On a national economic scale, the losses amount to several billion dollars, and within individual cities, millions of dollars annually (INRIX, 2025).

Partial indicators of the urban mobility system are used to evaluate the effectiveness of actions taken and to support future decision-making. To evaluate the evolution of urban mobility and compare different systems, composite indices must be applied.

2.3. Composite indices of urban mobility condition

Several types of composite indices can be distinguished to measure the condition of city mobility. These indices generally apply accumulated data normalization, followed by weighting (typically arithmetic, and less often geometric), and finally summation. Usually, weights are equal, with some exceptions made to account for city-specific conditions. These indices differ in their core purpose and can be classified into three groups.

The first group includes indices that measure the functionality of city transportation systems. Among these are the Global Urban Mobility Indicators (UITP, 2022), which track public transport metrics from 46 cities worldwide, including public transport network length, metro network length, light rail transit network length, public transport fare, ridership levels, fleet sizes, and more. The Urban Mobility Readiness Index (OliverWymanForum, 2024) ranks cities using 71 key performance indicators across five key dimensions: infrastructure, social impact, market attractiveness, systems efficiency, and innovation.

The second group includes indices that analyze the sustainability component of urban mobility. For instance, the Sustainable Urban Transport Index is based on 10 indicators representing transport system, social, economic, and environmental dimensions. It is used to compare city performance in the Asia-Pacific region and inform policymaking in sustainable urban transport systems and services (UN.ESCAP, 2017). The European Sustainable Urban Mobility Indicators Project provides a standardized evaluation of the sustainability of city transport systems, with 20 indicators including affordability, transport fatalities, greenhouse gas emissions, and accessibility for mobility-impaired groups (Eurocities, 2023). The Sustainable Public Transport Index for Latin America evaluates environmental, social, and economic dimensions, along with system effectiveness, governance, and integrated transport planning (Velasco & Gerike, 2024).

The third group emphasizes innovations in the organization of city mobility, especially digital ones. These indices assess the adoption of digital technologies to improve transportation systems and measure their impact on efficiency, accessibility, sustainability, and overall quality of life. The Urban Mobility Innovation Index 2021 (UITP, 2021) evaluates nine levels of innovation development grouped into three dimensions: readiness, deployment, and liveability. It includes both qualitative and quantitative indicators to evaluate city performance in specific areas. The goal of the index framework is not to rank cities but to share best practices and innovative solutions. The Composite Index for Intelligence in the context of Portuguese cities aims to analyze smart city transportation systems across dimensions such as efficiency, mobility, traffic safety, pollution, and public transportation capacity, thereby assessing urban mobility as a component of city intelligence (Rodrigues & Franco, 2019).

As we have shown, most publications evaluate a wide range of principal characteristics of smart mobility systems. However, there is a lack of research on citizen attitudes and satisfaction with improved mobility services. Only one study (Netov & Lomev, 2022) examined how digital services for urban and intercity mobility influence passengers' decisions to switch to low-emission travel modes, thereby reducing congestion and time spent in traffic. The authors employed dynamic methods, specifically the Markov regime-switching model.

Thus, we can conclude that there is a need for a new index that combines intrinsic characteristics of mobility systems with citizens' attitudes toward smart mobility. This index is presented in the following section.

3. Hypotheses, methods, and data

The main research question was formulated as follows: how do urban transport inefficiencies, CO_2 emissions, public and private transport costs, and travel time losses affect the efficiency of the digital transformation of urban mobility? This formulation allows for an empirical assessment of the dynamics of urban transportation and enables indirect conclusions about the role of digital transformation, even in the absence of complete technological metadata.

Three hypotheses (H) were investigated in this study:

H_1: Cities with a high transportation inefficiency index have longer travel times. This hypothesis is empirically consistent with existing research, which shows that more integrated and digitized transportation systems are associated with reduced travel times.

H_2: Cities with a high transportation inefficiency index have higher CO_2 emissions. In modern cities with efficient transport systems, public transport is used more actively, and emission reduction measures (e.g., electric buses and smart traffic management systems) are implemented.

H_3: Cities with a high transportation inefficiency index have a higher cost of a monthly travel pass. This hypothesis is based on real-world examples where high transportation inefficiency is accompanied by high fares. For example, cities with congested roads and underdeveloped transportation infrastructure (e.g., Los Angeles) tend to have higher monthly travel pass costs compared to cities with highly integrated systems (e.g., Singapore).

To empirically test these hypotheses, the study utilized data from the Numbeo platform, which provides multi-year, cross-sectional data on key indicators of urban quality of life and mobility for over 200 cities worldwide. The dataset includes:

(i) Average one-way daily travel time (in minutes)
(ii) An index of dissatisfaction with the transportation system due to long travel times, based on the assumption that dissatisfaction increases exponentially with each minute beyond 25 min of one-way travel
(iii) A transportation inefficiency index that reflects the inefficiency of a city's transportation system. A high index typically indicates a preference for personal car use over public transport, as well as general deficiencies in the road infrastructure
(iv) CO_2 emissions per trip (in grams).

It is worth referring to the hypotheses proposed in the introduction, whose aim is to investigate the relationships between transport inefficiency, travel time, CO_2 emissions, and fare. Instead of hypothesizing based on transportation efficiency, we considered inefficiency, as the transportation inefficiency index directly indicates systemic problems (e.g., congestion and low public transport speed). This approach also allows us to immediately analyze the impact of inefficiency on key aspects of urban mobility, such as travel time and CO_2 emissions.

All data were taken separately for more than 200 cities for the period from 2021 to 2025. Separate data for 2025 were used for average wages, average fuel costs, average monthly fare, and the cost of a cab ride per km. The analysis of these data will allow conclusions to be drawn on how the digital transformation of transportation affects relevant parameters in cities. The data were processed at the level of individual cities and then aggregated at the level of countries and five global regions (Table 3).

The table shows that over the 5-year period, the overall global situation has remained virtually unchanged—emissions have decreased slightly, the indices of dissatisfaction with the transport system and the inefficiency index have fluctuated marginally in both positive and negative directions, and travel time has remained largely the same. This dynamic is generally consistent throughout the period, with the exception of 2024, when the most significant deterioration in the indices occurred.

It is important to stress that the impact of digital transformation varies across regions. In Oceania, all indicators worsened, contributing significantly to the negative global trend. In contrast, the most effective transportation innovations were observed in Europe and Asia. Europe saw the most substantial reduction in CO_2 emissions, while Asia experienced a decrease in the transportation dissatisfaction index. Thus, it can be tentatively concluded that the digital transformation of urban mobility has a positive impact on the indicators presented in the table, with the greatest effectiveness currently observed in Europe and Asia, including Russia and China.

Correlation analysis was used to test the hypotheses and identify the relationships between indicators.

The H_1 hypothesis was confirmed for each year within the 2021–2025 period. The correlation coefficients between the transportation inefficiency index and trip length were 78.25% in 2021, 78.56% in 2022, 77.75% in 2023, 70.13% in 2024, and 75.73% in 2025. The consistent confirmation of the hypothesis with minimal variation indicates that transportation inefficiency remains a key determinant of travel time. It can be concluded that shorter travel times are strongly associated with transportation efficiency.

Table 3. Evaluation of the effectiveness of digital transformation of cities in different parts of the world from 2021 to 2025 (Numbeo, 2025)

Region	Number of cities	Name of parameter	2021	2022	2023	2024	2025	Difference (2025–2021)
Africa	15	Time per trip (min)	38.5	38.3	38.4	39.6	38.3	−0.2
		Index of dissatisfaction with the transportation system	3,560.5	3,478.6	3,452.1	3,471.2	3,526.7	−33.8
		Inefficiency index	233.4	230.7	233.7	261.2	237.9	4.5
		Carbon dioxide emissions per trip (g)	8,073.2	8,020.4	8,067.2	8,319.8	8,118.6	45.4
Asia	32	Time per trip (min)	44.6	44.5	44.4	44.4	44.3	−0.3
		Index of dissatisfaction with the transportation system	5,006.3	4,823.5	4,827.3	4,830.8	4,724.9	−281.4
		Inefficiency index	217.6	216.7	216.2	219.6	216.8	−0.8
		Carbon dioxide emissions per trip (g)	5,632.5	5,620.5	5,618.0	5,611.4	5,580.2	−52.3
America	67	Time per trip (min)	36.7	36.7	37.1	39.1	37.1	0.4
		Index of dissatisfaction with the transportation system	1,782.7	1,789.7	1,837.2	2,199.0	1,772.3	−10.4
		Inefficiency index	199.8	199.6	202.6	258.9	207.2	7.4
		Carbon dioxide emissions per trip (g)	6,919.3	6,926.8	6,976.1	7,400.2	6,998.7	79.4
Europe	80	Time per trip (min)	33.1	33.1	32.8	32.3	32.2	−0.9
		Index of dissatisfaction with the transportation system	1,782.7	1,789.7	1,837.2	2,199.0	1,772.3	−10.4
		Inefficiency index	128.8	129.3	127.5	131.8	126.4	−2.4
		Carbon dioxide emissions per trip (g)	3,419.4	3,447.2	3,399.4	3,403.7	3,290.1	−129.3
Oceania	8	Time per trip (min)	34.1	34.1	36.5	46.9	39.1	5.0
		Index of dissatisfaction with the transportation system	983.9	973.4	1,192.6	4,519.5	1,498.1	514.2
		Inefficiency index	170.4	170.5	192.3	369.4	236.5	66.1
		Carbon dioxide emissions per trip (g)	5,425.8	5,445.4	5,864.7	7,891.5	6,464.3	1,038.5
World	202	Time per trip (min)	36.5	36.5	36.6	37.6	36.5	0.0
		Index of dissatisfaction with the transportation system	1,993.2	1,960.1	1,973.4	2,227.0	1,943.2	−50.0
		Inefficiency index	175.8	175.6	176.9	206.9	180.1	4.3
		Carbon dioxide emissions per trip (g)	5,355.9	5,364.3	5,381.5	5,621.8	5,367.2	11.3

The same applies to the index of dissatisfaction with the transportation system. However, as mentioned earlier, dissatisfaction increases with each additional minute of waiting time; therefore, a separate hypothesis was not formulated for this indicator.

The H_2 hypothesis was also confirmed over the entire study period. The correlation coefficients between the inefficiency index and CO_2 emissions were 72.07% in 2021, 72.93% in 2022, 74.35% in 2023, 79.56% in 2024, and 73.42% in 2025. In each year, a strong correlation between the indicators was observed, indicating that transportation efficiency is closely linked to emissions per passenger.

The H_3 hypothesis was tested using data from 199 cities in 2025. The correlation was only 10.41%, indicating that these two parameters are not significantly related. The same applies to the index of dissatisfaction with the transportation system, as no correlation was found between it and the cost of a monthly travel ticket.

4. Index of urban mobility quality: Calculation and analysis

In the final part of the study, we introduced the Index of Urban Mobility Quality. In addition to the four parameters mentioned earlier, two additional parameters were incorporated—the index of the ratio of the monthly cost of public transport fare to average monthly salary, and the cab affordability index (calculated as: average kilometers per trip × cost per km of cab travel/average monthly salary). These two additional parameters were added to provide a deeper and more multifaceted analysis of the factors affecting a city's transport system and its digitalization. They also help identify correlations between accessibility, affordability, and user preferences, which can significantly influence transport choices and urban mobility patterns. After normalizing the parameters using the min-max scale, we obtained the following six parameters:

X1 - Index of time spent per trip (lower is better)
X2 - Index of dissatisfaction with the transportation system (lower is better)
X3 - Transportation inefficiency index (lower is better)
X4 - CO_2 emissions index (lower is better)
X5 - Index of the ratio of monthly public transportation fare to average monthly salary (lower is better)
X6 - Taxi affordability index (lower is better).

X1 and X2 were designed to combine objective data with subjective experiences. Travel time is an objective metric, but it does not capture how residents perceive the transport system. Dissatisfaction, on the other hand, is subjective but reflects accumulated institutional failures. Together, they offer an integrated assessment of transport efficiency.

X3 and X4 reflect system efficiency and environmental performance. The inefficiency index allows us to measure losses arising from duplication, downtime, and suboptimal behavior of system agents. CO_2 emissions represent the environmental costs imposed by the transportation system.

X5 and X6 evaluate both public and private transportation systems. The former indicates how much a citizen's income is burdened by public transport participation, while the latter assesses whether alternatives to public transport (e.g., taxis) are available to the population. These parameters also allow conclusions to be drawn about the relative attractiveness of private versus public transport.

Normalization of parameters with different units through min-max scaling enables cross-regional comparisons, allowing for meaningful comparisons between cities with contrasting characteristics (e.g., megacities vs. small cities) and the identification of anomalies, even when absolute differences are large.

Using individual indicators alone would not allow the research objective to be fully achieved. A comprehensive set of indicators is needed to reflect transportation system effectiveness (both objective and subjective), environmental sustainability, and economic development. For this reason, six parameters were selected. These form logical pairs and complement each other while also being sufficiently informative individually.

Table 4 presents the input parameters, their units of measurement, calculation methods, normalization formulas, and the resulting output parameters, using the city of Vienna as an example.

The Index of Urban Mobility Quality (IUMQ) can be calculated according to the following formula:

$$IUMQ = 1 - (X1 \times w1 + X2 \times w2 + X3 \times w3 + X4 \times w4 + X5 \times w5 + X6 \times w6) \tag{I}$$

The weights are assigned equally due to the lack of historical data for the last two model parameters and the limited sample size.

5. Results and discussion

For the 137 cities with available data, we ranked them according to the calculated coefficient. The ranking results for the top-performing cities are presented in Figures 2 and 3. A complete list of cities and source data is provided in Table S1.

It is notable that the final list includes cities such as Copenhagen and Shenzhen, which are cities frequently cited as leading examples of developed urban mobility systems. Moreover, almost all cities on the list exhibited

Table 4. Input parameters, normalization methodology, and output parameters of the Index of Urban Mobility Quality (Vienna case study)

Input parameter	Units of measurement	Calculation method	Normalization formula	Output parameter	Vienna, Austria, input parameters example	Vienna, Austria, output parameters example
Time per trip	Minutes	Average one-way commute time, measured from user surveys. Takes into account delays, traffic congestion, and typical trip duration	$X1 = (x_{1i}-x_{1\ min})/(x_{1\ max}-x_{1\ min})$	Index of time spent per trip	22.3	X1 = (22.3–17.4)/(61.4–17.4) = 0.11
Index of dissatisfaction with the transportation system	-	A component index modeling subjective dissatisfaction from long trips, increasing exponentially after 25 min on the road. The base time per trip increases according to the amount of travel time exceeding 25 min, scaled exponentially	$X2 = (x_{2i}-x_{2\ min})/(x_{2\ max}-x_{2\ min})$	Index of dissatisfaction with the transportation system	22.3	X2 = (22.3–17.4)/(17,566.0–17.4) = 0.00
Transportation inefficiency index	-	An aggregated and non-normalized indicator of a city's overall transport inefficiency. It considers parameters such as average travel time, traffic density, car-dependence, and subjective perceptions	$X3 = (x_{3i}-x_{3\ min})/(x_{3\ max}-x_{3\ min})$	Transportation inefficiency index	63.5	X3 = (63.5–38.8)/(685.90–38.8) = 0.04
Carbon dioxide emissions per trip	Grams	Average CO_2 emissions per person per one-way trip, calculated using the standard formula: 10 km×specific emissions from cars, based on typical fuel consumption	$X4 = (x_{4i}-x_{4\ min})/(x_{4\ max}-x_{4\ min})$	CO_2 emissions index	1,523.6	X4 = (1,523.6–1,255.7)/(1,4242.8–1,255.7) = 0.02
Ratio of monthly public transportation fare to average monthly salary	-	Monthly pass cost divided by the average monthly salary	$X5 = (x_{5i}-x_{5\ min})/(x_{5\ max}-x_{5\ min})$	Index of ratio of monthly public transport fare to average monthly income	0.015	X5 = (0.015–0.000)/(0.110–0.000) = 0.14
Taxi affordability	-	(Average kilometer per trip×cost per km of cab ride)/average monthly salary	$X6 = (x_{6i}-x_{6\ min})/(x_{6\ max}-x_{6\ min})$	Taxi affordability index	0.007	X6 = (0.007–0.001)/(0.045–0.001) = 0.13

Note: Compiled by the authors
Abbreviation: CO_2: Carbon dioxide

an index of dissatisfaction with the transportation system that is either zero or very close to zero. This suggests that maximizing the coefficient of efficiency of technological innovation is largely achieved by minimizing this index. Other indicators included in the calculation of the coefficient did not vary significantly between cities.

It is also worth noting that cities with populations over 1 million tend to show higher composite index values. Specifically, 18 out of the top 20 cities in this category exceeded the 0.85 threshold, while only 4 out of 20 cities with populations under 1 million achieved this level. The graphs for both categories appear similar, indicating that the index provides a balanced assessment regardless of population size.

Figures 4 and 5 present the rankings of the lowest-performing cities by the Index of Urban Mobility Quality. It is important to highlight that the cities at the bottom of the rankings tend to have the highest amount of CO_2 emissions and the longest average travel times. Interestingly, this does not prevent them from ranking highly in broader smart city indices. However, the application of the Index of Urban Mobility Quality allows us to identify cities that require significant improvements in transportation systems. With effective digital transformation of urban mobility, these cities have the potential to rise in smart city rankings.

These figures show that larger cities tend to have lower composite index values. This may be because transportation problems are more severe in cities with over 1 million inhabitants than in smaller cities. For example, smaller cities do not require expensive infrastructure to encourage walking or cycling. It is worth noting again that the graphs for different groups of cities look similar, suggesting that population size does not significantly affect the representativeness of the index.

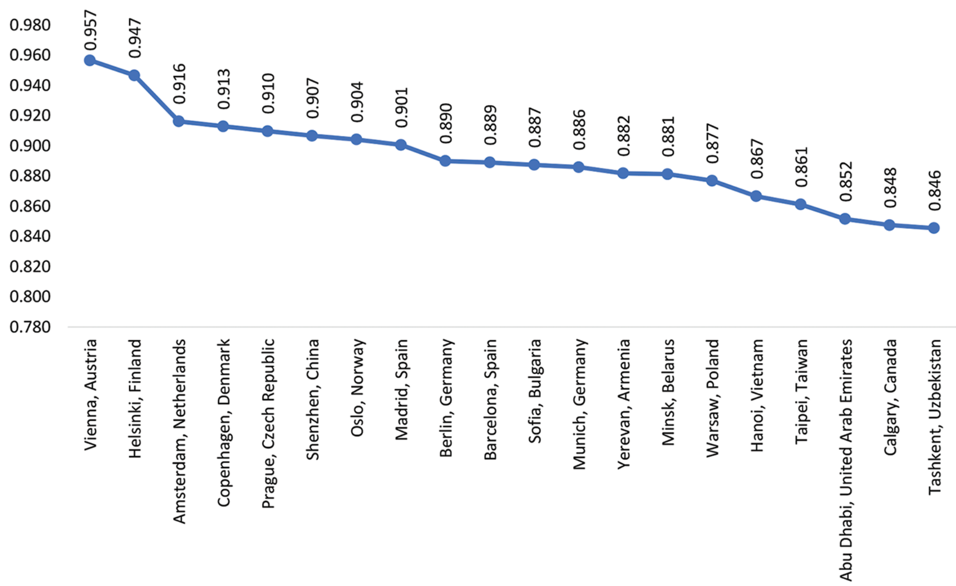

Figure 2. Ranking of the best cities with a population of over 1 million by the Index of Urban Mobility Quality (calculated by the authors)

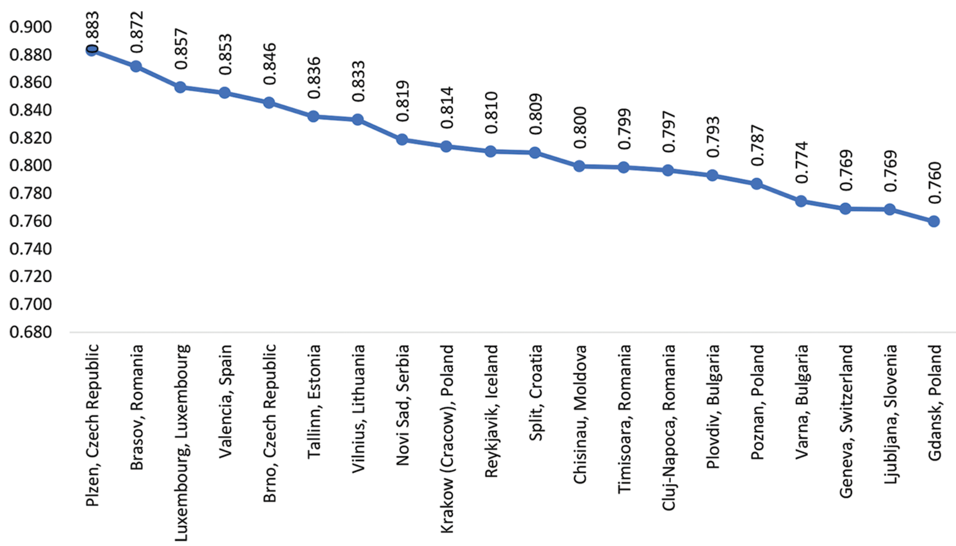

Figure 3. Ranking of the best cities with a population of less than 1 million by the Index of Urban Mobility Quality (calculated by the authors)

In addition, the correlation between population size and the six factors in the 137 cities under consideration should be examined. The sample is limited to cities with populations up to 5 million to ensure the density of the source data in the graphs. The results of this analysis are displayed in Figures 6-8.

It can be observed that the time spent on a single trip increased significantly with city population size. In most cases, transport infrastructure cannot accommodate the corresponding passenger volume. The index of dissatisfaction with the transportation system, subjectively reflecting time spent, also increased, though to a lesser extent, as the indicator itself remained relatively low.

The transport inefficiency index and the CO_2 emissions index exhibited a slight upward trend. In the first case, the data are clustered, allowing us to confidently assert the presence of a correlation. In the second case, however, a significant number of anomalous values appear on the graph, which may require further investigation in future studies.

The index of the ratio of monthly public transportation fare to average monthly salary, as well as the taxi

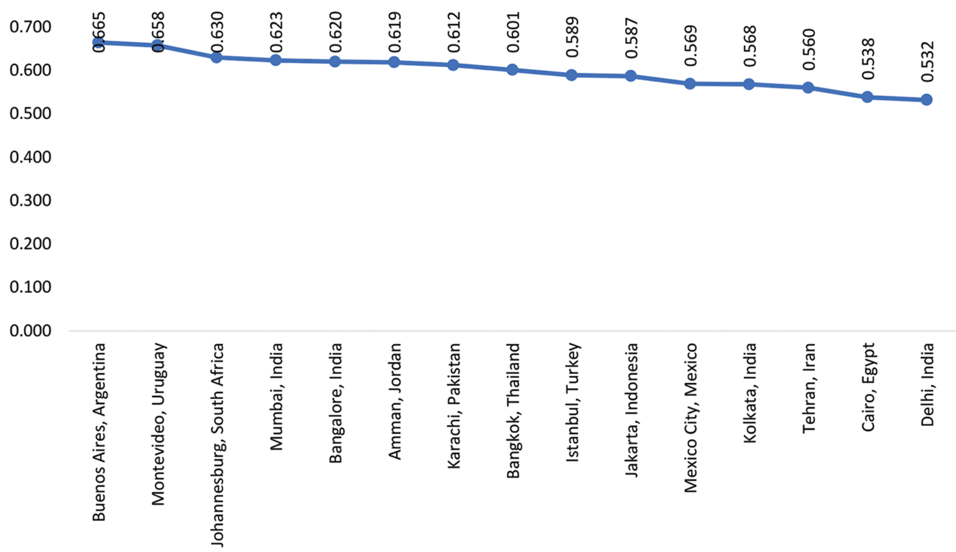

Figure 4. Ranking of the lowest-performing cities with a population of over 1 million by the Index of Urban Mobility Quality (calculated by the authors)

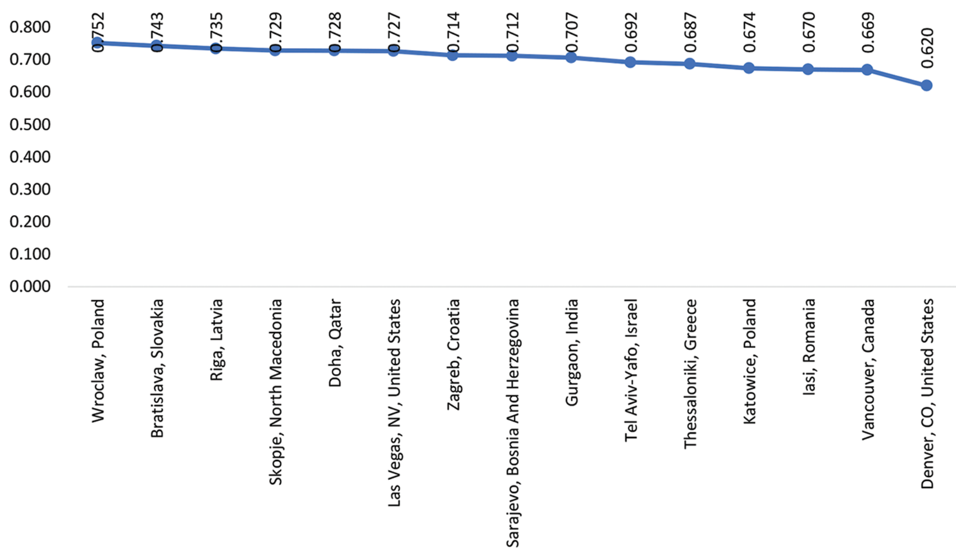

Figure 5. Ranking of the lowest-performing cities with a population of less than 1 million by the Index of Urban Mobility Quality (calculated by the authors)

affordability index, remained in a similar range regardless of population size. This suggests that the accessibility of public and private transport is approximately the same in all cities. Moreover, the higher the level of prosperity, the higher the associated transport cost.

The practical relevance of the index lies in its capacity to operationalize the SDGs. Cities with the highest index scores are already well-positioned for digital transformation, which can be implemented with minimal time and financial resources. Meanwhile, best practices should be directed toward cities with low index scores. In such cases, digital transformation is not merely beneficial but necessary, as it addresses social, environmental, and economic challenges. However, unprepared infrastructure in these cities will require the highest levels of financial investment compared to others.

The proposed Index of Urban Mobility Quality makes both theoretical and practical contributions to the study of urban transportation systems during technological transition. Theoretically, the index advances existing scholarship by introducing a multidimensional framework that incorporates not only

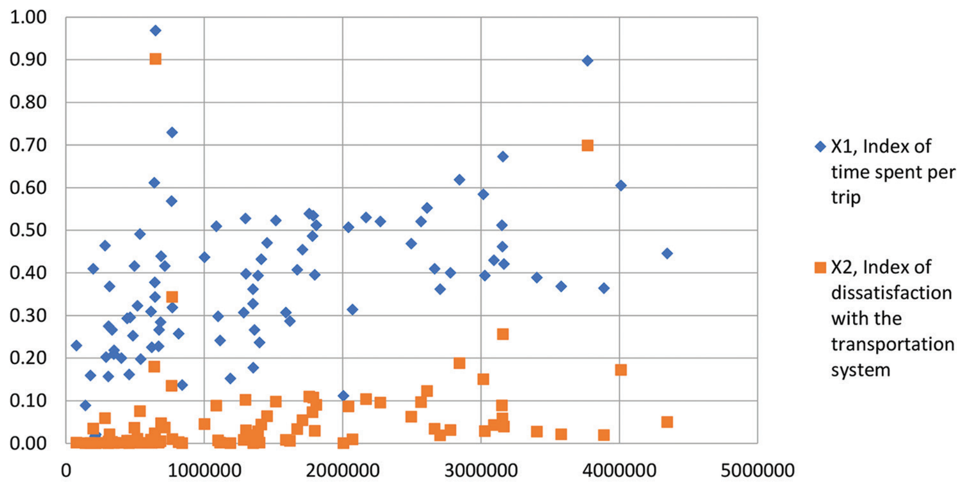

Figure 6. Distribution of indices X1 and X2 by population size
Source: Graph by the authors

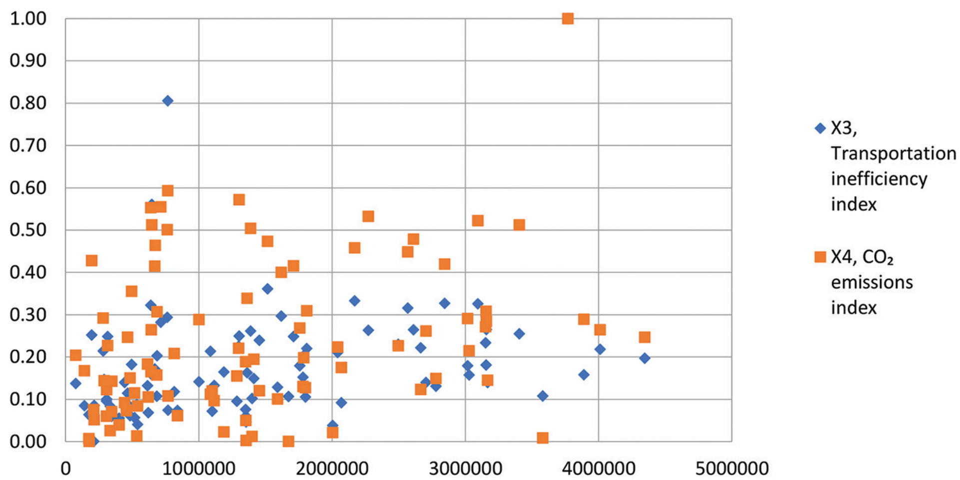

Figure 7. Distribution of indices X3 and X4 by population size
Source: Graph by the authors

infrastructural efficiency or environmental—commonly emphasized in the smart mobility literature—but also user dissatisfaction, accessibility, and affordability. This broader conceptualization allows digital transformation to be viewed from a socio-technical perspective, in which technological modernization interacts with economic constraints and users' lived experiences.

The analysis presented in this paper presents a multidimensional Index of Urban Mobility Quality, constructed using publicly available data across several indicators, including smart infrastructure, transport efficiency, digital inclusion, and regulatory capacity. The index enables the comparison of several parameters that are typically evaluated in isolation. For example, cities that demonstrate high levels of investment in digital infrastructure may still lag in terms of transportation accessibility or service affordability. The composite scores revealed significant differences not only between large metropolitan areas and small urban areas but also among cities of similar scale.

This study makes a clear contribution to the literature on smart urban mobility and digitalization. It proposes measuring digitalization in transport not as an abstract ideal but as a multi-scalar, contested, and uneven process. By integrating performance, access, and affordability indicators into a single framework, it moves beyond supply-side narratives to offer a more holistic assessment of outcomes. Providing a comparative framework, the index serves as a replicable and adaptable tool for urban analysts and decision-makers to monitor trends in the

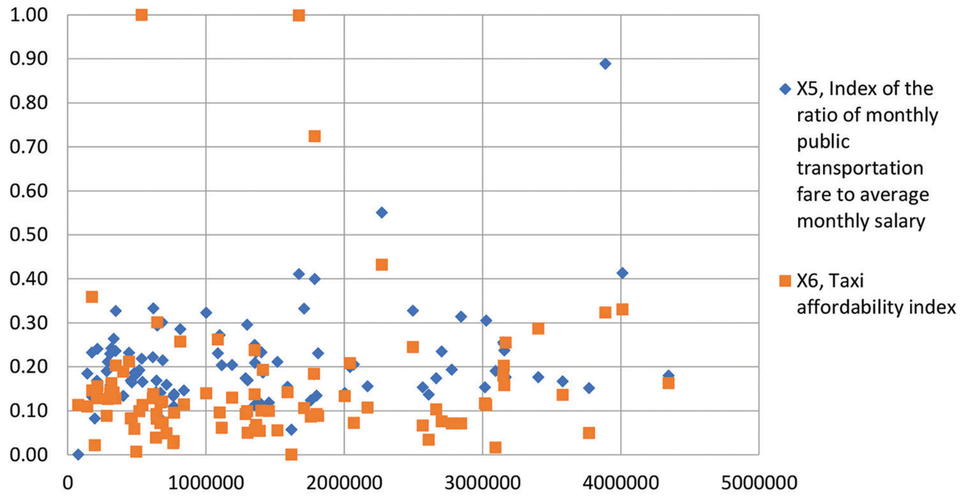

Figure 8. Distribution of indices X5 and X6 by population size
Source: Graph by the authors

digitalization of mobility and to identify areas of tension between innovation and public value.

Digital transformation is often complicated by the mismatch between modern equipment and legacy infrastructure. For example, autonomous vehicles require carefully marked roads and standardized signage, which is not feasible in the short term for many cities. This is essential to ensure a high level of reliability for autonomous vehicles. Worn road signs and faded markings can lead to recognition failures (Mihalj *et al.*, 2022). This performance degradation not only increases the risk of accidents but also hinders the scalability of autonomous vehicle systems in real-world conditions.

The risks and challenges associated with the digital transformation of transportation systems are multidimensional. Overcoming them requires strategic planning aimed at addressing structural, social, and regulatory barriers. Without this, innovations in digital mobility may exacerbate urban vulnerabilities, potentially destabilizing infrastructure, infringing civil liberties, and deepening existing inequalities in urban transport systems.

Among the most serious issues in building a smart city are data availability, specialized tools for data access, data quality, and the security of data infrastructures (Bunders *et al.*, 2019). For instance, Helsinki is taking a data-centric approach to cybersecurity as part of its smart city initiatives, prioritizing the protection of citizens' data and privacy rights. The city's MyData initiative empowers citizens to control and manage their personal data, ensuring transparency and accountability in how it is handled (Hämäläinen, 2020).

Finally, the standardization of technologies within the same city is of critical importance. Autonomous vehicles produced by different manufacturers often fail to communicate effectively due to incompatible communication protocols. In countries with a strict government, especially regarding personal data protection, imports of non-compliant technologies may be restricted. Digital transformation cannot be fully realized in environments where fragmented systems lack interoperability. In these cases, the city is effectively deprived of a unified, functional digital application (Albouq *et al.*, 2022). From a practical perspective, this fragmentation compels cities and manufacturers to invest heavily in custom middleware and regulatory adaptations for each deployment. This not only increases costs but also slows innovation and undermines equitable, citywide digital transformation.

6. Policy implications

Despite the significant potential of digital in transport systems, its implementation is accompanied by substantial risks and challenges. Within the framework of smart city development, the integration of digital technologies into transportation infrastructure demands more than mere technological innovation. Special attention should be paid to robust socioeconomic planning and regulatory adaptation. One of the key barriers to digital transformation is the high cost of developing and implementing new technologies. Innovative solutions such as intelligent transportation systems, digital twins, and autonomous vehicles require significant investment in research and development, infrastructure upgrades, and personnel training. For example, installing IoT sensors, cameras, and other real-time monitoring devices can cost billions of dollars in megacities. For small and medium-sized cities, such projects may be unfeasible without governmental support. At the same time, businesses may lack incentives to scale up such technologies, as the social and environmental benefits often outweigh direct economic returns. However, not all companies prioritize sustainable urban development in their decision-making. Moreover, infrastructure modernization alone does not guarantee successful outcomes without adequate institutional capacity and financial frameworks (Moghayedi & Awuzie, 2023).

In countries where sustainability principles are not prioritized by local businesses, there is a significant risk of limiting access to digital services for vulnerable populations, particularly if these services cannot generate sufficient returns. In addition, not all countries have high levels of digital literacy and internet penetration, meaning parts of the population may be excluded from modern technological advances. In this context, issues of digital inclusion arise. The success of smart mobility services depends heavily on citizens' ability to access and use digital platforms. Kolotouchkina *et al.* (2024) argue that digital exclusion should be regarded as a structural barrier to smart city development, rather than a secondary outcome. The consequences of digital inequality may become further exacerbated during the digital transformation of urban mobility. Vulnerable populations excluded from digital platforms face reduced access to basic transportation services, thereby reinforcing spatial and social exclusion. According to Delaere *et al.* (2024), this digital mobility gap contributes to mobility poverty, in which limited transportation options hinder access to employment, healthcare, education, and social participation. The failure of digital systems to incorporate inclusive design principles such as multilingual interfaces, offline accessibility, and user-centered adaptability further compounds these barriers.

7. Limitations and future research perspectives

Several limitations should be acknowledged. First, index construction relies on publicly available and aggregated data, which may mask intra-urban differences and dynamic shifts over time. Second, the equal weighting of indicators, while methodologically justified for research typologies, may not fully reflect the relative importance of different dimensions in specific local contexts. Third, behavioral aspects of mobility, such as user satisfaction, technological literacy, or adaptability, are not included in the analysis. These factors are critical in determining the utilization and societal value of digital transportation solutions, but fall outside the scope of this quantitative framework.

Future research should focus on improving the index methodology through sensitivity analysis and by expanding the indicators set to include user-centered and environmental variables. Qualitative case studies and fieldwork in high-risk cities can provide deeper insights into institutional dynamics and social perceptions of smart mobility. In addition, comparative studies involving cities across regions and countries, especially in rapidly urbanizing regions, will enhance the understanding of how political, cultural, and infrastructural conditions shape digital mobility transformations globally.

8. Conclusion

Urban mobility plays an important role in the economic and social development of cities. In recent years, the introduction of innovative technologies in transportation systems has contributed to significant improvements in efficiency, while also addressing environmental and social challenges. In particular, the development of electromobility, intelligent transportation systems, and the integration of various modes of transportation, such as MaaS, has created opportunities to increase the sustainability of urban mobility and improve the quality of life for residents.

Despite these clear advantages, the introduction of new technologies into the transportation systems comes with several challenges. Chief among them are the high costs of infrastructure modernization and the need for effective legislation, regulation, and coordination between public and private stakeholders. In addition, the adoption of autonomous vehicles, electric scooters, and other innovative solutions requires addressing issues related to safety, data protection, and equitable access to technology for all social groups.

This study, based on economic and mathematical inference, concluded that the most effective digital transformation of urban mobility is observed in Europe and Asia. This conclusion is supported by the final ranking of the top 20 cities according to the calculated efficiency ratio of technological innovation, none of which are located in Africa, the Americas, or Oceania. The study also found that a low transportation inefficiency index is closely associated with reduced travel time and lower CO_2 emissions.

The hypotheses H_1 and H_2, concerning the relationship between the transportation inefficiency index and travel duration, and between the inefficiency index and CO_2 emissions, respectively, were confirmed. However, hypothesis H_3, which proposed a correlation between the inefficiency index and the high cost of public transportation passes, was not supported. This suggests that non-economic factors are more closely linked to dissatisfaction with transportation. It can thus be inferred that the public may be willing to pay higher prices in exchange for improved quality and speed of service.

This study empirically confirms that transportation inefficiency remains a critical determinant of urban mobility outcomes. The consistent and strong correlations between the inefficiency index and both travel time and CO_2 emissions indicate that inefficiency systematically undermines the functional and environmental dimensions of urban transport systems. Conversely, the lack of significant correlation between inefficiency and fare affordability suggests that structural shortcomings in transport provision are not necessarily reflected in price-based accessibility. These findings emphasize the importance of treating inefficiency as a distinct analytical category in urban mobility research. Importantly, the proposed index serves not only a diagnostic but also a prescriptive utility. By identifying cities with high inefficiency and poor sustainability outcomes, it highlights priority areas for the application of digital mobility solutions. These may include intelligent traffic management systems, digital integration of multimodal networks, and the use of real-time data analytics to optimize flows and reduce emissions.

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Conflict of interest

The authors declare that they have no competing interests.

Author contributions

Conceptualization: All authors
Investigation: All authors
Methodology: All authors
Writing–original draft: All authors
Writing–review & editing: All authors

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

The datasets used and/or analyzed during the present study are available in the **Supplementary File**.

References

Acumen Research and Consulting. (2024). *AI in Mobility Market Size to Reach USD 53.75 Billion by 2033*. Available from: https://www.acumenresearchandconsulting.com/press/releases/ai-in-mobility-market [Last accessed on 2025 Jul 01].

Albouq, S. S., Abi Sen, A. A., Almashfi, N., & Yamin, M. (2022). A survey of interoperability challenges and solutions for dealing with them in IoT environment. *IEEE Access*, *10*:36416-36428.

https://doi.org/10.1109/ACCESS.2022.3162219

Arenkov, I., Tsenzharik, M., & Vetrova, M. (2019). Digital technologies in supply chain management. In: *Proceedings of the International Conference on Digital Technologies in Logistics and Infrastructure (ICDTLI 2019)*. France: Atlantis Press; p. 448-453.

https://doi.org/10.2991/icdtli-19.2019.78

Ashwini, B., Savithramma, R., & Sumathi, R. (2022). Artificial intelligence in smart city applications: An overview. In: *Proceedings of the Sixth International Conference on Intelligent Computing and Control Systems (ICICCS 2022)*. United States: IEEE; p. 986-993.

https://doi.org/10.1109/ICICCS53718.2022.9788152

Baghersad, M., Gumus, G., Huang, C.D., & Behara, R. S. (2024). Regional policy coordination of pandemic responses using an iterative mobility-driven algorithm. *Regional Studies*, *58*(2):393-408.

https://doi.org/10.1080/00343404.2023.2220749

Balawi, M., & Tenekeci, G. (2024). Time series traffic collision analysis of London hotspots: Patterns, predictions and prevention strategies. *Heliyon*, *10*:e25710.

https://doi.org/10.1016/j.heliyon.2024.e25710

Boston Consulting Group (BCG). (2024). *Moving Millions: Transforming Urban Mobility*. Available from: https://www.bcg.com/publications/2024/transforming-urban-mobility [Last accessed on 2025 Jun 01].

Beijing Municipal Commission of Transport. (2024). *Beijing Releases MaaS2.0 Work Plan: Beijing MaaS Moves to the 2.0 Stage*. Available from: https://jtw.beijing.gov.cn/xxgk/dtxx/202306/t20230629_3150511.html [Last accessed on 2025 Jan 02].

Bibri, S. E., Alexandre, A., Sharifi, A., & Krogstie, J. (2023).

Environmentally sustainable smart cities and their converging AI, IoT, and big data technologies and solutions: An integrated approach to an extensive literature review. *Energy Informatics*, *6*(9):9.

https://doi.org/10.1186/s42162-023-00259-2

Brandajs, F., & Russo, A. P. (2023). Smarter city, less just destination? Mobilities and social gaps in Barcelona. *Journal of Place Management and Development*, *16*(2):293-308.

https://doi.org/10.1108/JPMD-03-2022-0020

Bunders, D. J., & Varró, K. (2019). Problematizing data-driven urban practices: Insights from five Dutch 'smart cities. *Cities*, *93*:145-152.

https://doi.org/10.1016/j.cities.2019.05.004

Carbon Neutral Cities Alliance. (2024). *Copenhagen, Denmark*. Available from: https://carbonneutralcities.org/cities/copenhagen [Last accessed on 2024 Dec 20].

Cattaneo, A., Adukia, A., Brown, D. L., Christiaensen, L., Evans, D. K., Haakenstad, A., *et al*. (2022). Economic and social development along the urban-rural continuum: New opportunities to inform policy. *World Development*, *157*:105941.

https://doi.org/10.1016/j.worlddev.2022.105941

Cervicorn Consulting. (2024). *AI in Mobility Market Size, Share, Growth, Trends 2024-2033*. Available from: https://www.cervicornconsulting.com/artificial-intelligence-in-mobility-market [Last accessed on 2025 Jan 08].

Chi, S., & Mazzer, S. (2022). Identifying MaaS schemes that maximise economic benefits through an economic appraisal. *European Journal of Transport and Infrastructure Research*, *22*:1-24.

https://doi.org/10.18757/ejtir.2022.22.4.6379

Country Cassette. (2024). *Average Monthly Salary by Country 2024 (After Tax)*. Available from: https://countrycassette.com/average-monthly-salary-by-country-2023 [Last accessed on 2025 Jan 04].

Del Rio, M., Hargrove, W.L., Tomaka, J., & Korc, M. (2017). Transportation matters: A health impact assessment in rural New Mexico. *International Journal of Environmental Research and Public Health*, *14*(6):629.

https://doi.org/10.3390/ijerph14060629

Delaere, H., Basu, S., Macharis, C., & Keseru, I. (2024). Barriers and opportunities for developing, implementing and operating inclusive digital mobility services. *European Transport Research Review*, *16*:67.

https://doi.org/10.1186/s12544-024-00684-8

Deloitte. (2021). *City Operations Through AI*. Available from: https://www.deloitte.com/gh/en/Industries/government/public/perspectives/urban/future/with/a/purpose/city-operations-throuh-ai.html [Last accessed on 2025 Jun 03].

Elassy, M., Al-Hattab, M., Takruri, M., & Badawi, S. (2024). Intelligent transportation systems for sustainable smart cities. *Transportation Engineering*, *16*:100252.

https://doi.org/10.1016/j.treng.2024.100252

Eurocities. (2023). *Sustainable Urban Mobility Indicator*. Available from: https://eurocities.eu/projects/sustainable-urban-mobility-indicators [Last accessed on 2025 Jul 10].

Faliagka, E., Christopoulou, E., Ringas, D., Politi, T., Kostis, N., Leonardos, D., *et al*. (2024). Trends in digital twin framework architectures for smart cities: A case study in smart mobility. *Sensors (Basel)*, *24*(5):1665.

https://doi.org/10.3390/s24051665

Gössling, S. (2013). Urban transport transitions: Copenhagen, city of cyclists. *Journal of Transport Geography*, *33*:196-206.

https://doi.org/10.1016/j.jtrangeo.2013.10.013

Guo, X., & Guo, X. (2023). A research on blockchain technology: Urban intelligent transportation systems in developing countries. *IEEE Access*, *11*:40724-40740.

https://doi.org/10.1109/ACCESS.2023.3270100

Hämäläinen, M. (2020). A framework for a smart city design: Digital transformation in the Helsinki smart city. In: *Entrepreneurship and the Community*. Berlin: Springer; p. 63-86.

https://doi.org/10.1007/978-3-030-23604-5_5

Huawei. (2021). *Intelligent Twins: A Bridge to All-Scenario Intelligence*. Available from: https://www-file.huawei.com/-/media/corp2020/pdf/publications/communicate/comm91-en2.pdf [Last accessed on 2024 Dec 25].

INRIX. (2025). *Global Traffic Scorecard 2024*. Available from: https://inrix.com/scorecard [Last accessed on 2025 Jan 05].

ISO. (2024). *Intelligent Transportation Systems: Transforming Modern Mobility*. Available from: https://www.iso.org/transport/its-intelligent-transportation-systems [Last accessed on 2025 Jun 06].

Kolotouchkina, O., Ripoll, L., & Belabas, W. (2024). Smart cities, digital inequalities, and the challenge of inclusion. *Smart Cities*, *7*(6):3355-3370.

https://doi.org/10.3390/smartcities7060130

McKinsey. (2023). *Solutions for Smart Mobility in Urban Areas*. Available from: https://www.mckinsey.com/industries/infrastructure/our/insights/infrastructure/technologies/challenges-and-solutions-for-smart-mobility-in-urban-areas [Last accessed on 2025 Jun 03].

Medium. (2024). *Driving the Future: How AI is Powering Singapore's Smart City Vision for 2030*. Available from: https://medium.com/@dirsyamuddin29/driving/the/future/how/ai/is/powering-singapores-smart-city-vision-for-2030-7d371db705fd [Last accessed on 2025 Jan 15].

Mihalj, T., Li, H., Babic, D., Lex, C., Jeudy, M., Zovak, G., *et al*.

(2022). Road infrastructure challenges faced by automated driving: A review. *Applied Sciences*, *12*:3477

https://doi.org/10.3390/app12073477

Moghayedi, A., & Awuzie, B. O. (2023). Towards a net-zero carbon economy: A sustainability performance assessment of innovative prefabricated construction methods for affordable housing in Southern Africa. *Sustainable Cities and Society*, *99*:104907.

https://doi.org/10.1016/j.scs.2023.104907

Netov, N., & Lomev B. (2022). Impact of digitalization of public transport and city mobility on traffic structure and on-road emissions. In: 2022 6th *European Conference on Electrical Engineering & Computer Science (ELECS)*. United States: IEEE; p. IO71-IO74.

https://doi.org/10.1109/ELECS55825.2022.00019

Numbeo. (2025). *Traffic Index by City 2025*. Available from: https://www.numbeo.com/traffic/rankings.jsp [Last accessed on 2025 Jan 20].

Odeck, J., & Welde, M. (2010). Economic evaluation of intelligent transportation systems strategies: The case of the Oslo toll cordon. *IET Intelligent Transport Systems*, *4*:221-228.

https://doi.org/10.1049/iet-its.2010.0027

OliverWymanForum. (2024). *Urban Mobility Readiness Index*. Available from: https://www.oliverwymanforum.com/mobility/urban-mobility-readiness-index/about.html [Last accessed on 2025 Jul 10].

Rahman, M., Polunsky, S., & Jones, S. (2022). Transportation policies for connected and automated mobility in smart cities. In: *Smart Cities Policies and Financing: Approaches and Solutions*. Netherlands: Elsevier Science; p. 97-116.

https://doi.org/10.1016/B978-0-12-819130-9.00008-5

Richter, M. A., Hagenmaier, M., Bandte, O., Parida, V., & Wincent, J. (2022). Smart cities, urban mobility and autonomous vehicles: How different cities need different sustainable investment strategies. *Technological Forecasting and Social Change*, *184*:121857.

https://doi.org/10.1016/j.techfore.2022.121857

Rodrigues, M., & Franco, M. (2019). Measuring cities' performance: Proposal of a Composite Index for the intelligence dimension. *Measurement*, *139*:112-121.

https://doi.org/10.1016/j.measurement.2019.03.008

Sochor, J., Arby, H., Karlsson, I. C. M., & Sarasini, S. (2018). A topological approach to mobility as a service: A proposed tool for understanding requirements and effects, and for aiding the integration of societal goals. *Research in Transportation Business and Management*, *27*:3-14.

https://doi.org/10.1016/j.rtbm.2018.12.003

Tomadon, L., Do Couto, E., De Vries, W., & Moretto, Y. (2024). Smart city and sustainability indicators: A bibliometric literature review. *Discover Sustainability*, *5*(1):1-21.

https://doi.org/10.1007/s43621-024-00328-w

UITP. (2021). *Urban Mobility Innovation Index 2021*. Available from: https://www.uitp.org/publications/urban-mobility-innovation-index-2021 [Last accessed on 2025 Jul 10].

UITP. (2022). *Global Urban Mobility Indicators 2022*. Available from: https://www.uitp.org/publications/global-urban-mobility-indicators-2022 [Last accessed on 2025 Jul 10].

United Nations. (2024). *World Population Prospects 2024*. Available from: https://population.un.org/wpp [Last accessed on 2024 Dec 25].

UN.ESCAP. (2017). *Assessment of Urban Transport Systems*. Available from: https://repository.unescap.org/items/ee3020d0-3f5e-4a93-b979-f52c57c47f36 [Last accessed on 2025 Jul 10].

Velasco, A., & Gerike, R. (2024). A composite index for the evaluation of sustainability in Latin American public transport systems. *Transportation Research Part A: Policy and Practice*, *179*:103939.

https://doi.org/10.1016/j.tra.2023.103939

Wolniak, R., & Stecuła, K. (2024). Artificial intelligence in smart cities - applications, barriers, and future directions: A review. *Smart Cities*, *7*:1346-1389.

https://doi.org/10.3390/smartcities7030057

Yusuf, J. A. (2024). Economic evaluation of smart traffic management systems in reducing carbon emissions. *Journal of Economics, Business, and Commerce*, *1*(1):30-35.

https://doi.org/10.69739/jebc.v1i1.82

Zhao, X., Andruetto, C., Vaddadi, B., & Pernestål, A. (2021). Potential values of MaaS impacts in future scenarios. *Journal of Urban Mobility*, *1*:100005.

https://doi.org/10.1016/j.urbmob.2021.100005