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THE IMPACT OF DIGITAL TECHNOLOGIES ON THE DEVELOPMENT OF TRANSPORT INFRASTRUCTURE

Abstract

Purpose. The article investigates the impact of digital technologies on the transport infrastructure of modern cities. It substantiates strategic directions and priorities for implementing intelligent transport systems (ITS) amid intensifying urbanization and growing pressure on transport networks. **Methodology.** The study applies systems analysis, treating transport infrastructure as an integral sociotechnical system. It is complemented by a comparative analysis of documented ITS deployments in the United States (Los Angeles), Singapore, the Republic of Korea (Seoul), and the Netherlands (Amsterdam), which represent decentralized, centralized-state, and supranationally coordinated (European Union) governance contexts; by a structural-functional analysis of ITS architecture; and by induction and deduction for formulating generalizations. **Findings.** Published evaluations associate ITS deployments with reductions in travel time of about 12–13%, in intersection delay of 21–32%, in vehicle stops of about 30% and in air emissions of about 10% (Los Angeles), with higher traffic speeds under dynamic road pricing (Singapore), with fewer bus-related accidents (Seoul) and with fewer vehicle loss hours (Amsterdam). The cases point to three institutional preconditions: a coordinating strategic framework, partnership between public authorities and the private sector, and open standards for inter-system data exchange. **Originality.** The article proposes a conceptual model that integrates the architectural, institutional, and financial dimensions of transport digitalization, along with a four-stage model for implementing ITS adapted to the conditions of transitional

economies. **Practical value.** The results can support national and municipal authorities in planning smart-mobility pilot projects, the academic community in further research on transport technologies, and the private sector in designing public-private partnerships.

Keywords: digital technologies; transport infrastructure; intelligent transport systems; traffic management; urbanization; artificial intelligence; Internet of Things; big data; urban mobility; digital transformation

Problem statement

The rapid urbanization that defines the twenty-first century places an unprecedented burden on the transport systems of cities and agglomerations, turning the modernization of transport infrastructure into one of the key priorities of strategic planning. According to the United Nations, 55% of the world's population lives in urban areas, a share projected to reach 68% by 2050, which could add another 2.5 billion people to urban areas [22]. Such growth increases demand for transport services and risks overloading networks that were designed to the standards of the previous century [22; 23]. The human cost of road transport also remains high: the World Health Organization reports about 1.19 million road traffic deaths annually [25]. Static regulations and decentralized traffic management, on which traditional approaches to transport organization are based, are poorly suited to ensuring an acceptable level of mobility in modern metropolises. Under such circumstances, the digital transformation of transport infrastructure ceases to be an optional technological choice and becomes an objective necessity [17; 5]. The theoretical significance of this study lies in understanding the mechanisms by which digital technologies are embedded in the transport sector. In contrast, its applied value lies in providing scientifically grounded recommendations for public authorities involved in developing and implementing the relevant strategies.

Analysis of recent research and publications

The topic of intelligent transport systems (ITS) and the digitalization of transport infrastructure is the subject of active scientific discourse at both the international and national levels. In international research, C. Ge and S. Qin [8] describe the architecture of digital-twin-based ITS; A. A. Musa et al. [17] and M. Elasy et al. [7] address the impact of ITS on traffic management quality, in particular IoT-oriented traffic control. The integration of transport networks into smart-city infrastructure and cooperative ITS are examined by F. Alanazi and M. Alenezi [1], M. Khanmohamadi and M. Guerrieri [13], and S. Li et al. [14]. N. Cordoș et al. [5] review ITS deployment in Europe and identify technical interoperability, inadequate regulatory frameworks, and insufficient data sharing as the main obstacles to scaling. Cybersecurity risks are addressed by A. Alderete Peralta et al. [2], and digital twins by S. Werbińska-Wojciechowska et al. [24]. Among Ukrainian scholars, ITS development and the use of foreign experience are examined by S. Gritsenko and I. Vinichenko [9], S. Gritsenko et al. [10] and A. Dziuba et al. [6]; the digitalization of transport logistics under wartime conditions is addressed by V. Hrabovets [12], and the use of ITS for preventing road-traffic offenses by N. Riabykh et al. [21]. However, a systematic analysis of the interrelationships among ITS architectural solutions, technological platforms, and the institutional conditions for their implementation remains insufficiently explored in the literature. In particular, existing studies do not offer a comprehensive view of the mutual conditioning of technological, organizational, and legal factors of transport digitalization in the context of transition economies, to which Ukraine belongs. The adaptation of foreign experience in implementing ITS to the specifics of the domestic institutional environment and infrastructure also largely remains outside researchers' attention, which underscores the relevance of this study.

Purpose of the article

The purpose of this article is to provide a comprehensive examination of the transformative impact of digital technologies on the development of urban transport

infrastructure and to substantiate, on a scientific basis, the strategic directions and priorities for implementing intelligent transport systems. The findings are intended to serve as a scientific and methodological foundation for managerial decision-making at the national and municipal levels.

To achieve this purpose, a set of interrelated objectives must be addressed: to examine the architectural and technological foundations of ITS construction based on Internet of Things, big data, and artificial intelligence technologies [1; 7; 8]; to systematize international experience in the digital transformation of the transport sector; to develop a phased model for implementing ITS adapted to the conditions of Ukraine; and to assess the socio-economic consequences of digitalizing transport infrastructure. The achievement of these objectives will enable the formulation of a coherent scientific and practical concept of digital development in the transport sector, which may serve as a methodological reference point for managerial decisions at the national and municipal levels.

Presentation of the main material of the study

Methodology

The guiding scientific approach of this study is systems analysis, a choice driven primarily by the complexity and multidimensional nature of the object under investigation. The digitalization of transport infrastructure is not reducible to a purely technological phenomenon; it equally encompasses organizational, legal and socio-economic dimensions, whose mutual interdependence makes it impossible to reduce the study to the analysis of isolated components [1; 7; 8]. A systemic perspective allows intelligent transport systems to be interpreted as integrated entities in constant interaction with their institutional and infrastructural environment, while also capturing emergent properties, that is, characteristics that arise only at the level of the system as a whole and are inaccessible when its elements are considered in isolation. It is precisely this capacity that defines the methodological suitability of the systems approach for

understanding digital transformation in transport, since effectiveness here is determined not by individual solutions but by the quality of their integrated interaction [1; 8].

The study's logic was built on sequential scientific inquiry and implemented through four interrelated stages. The initial stage involved a systematic review of scientific publications, both Ukrainian and international, to form a theoretical foundation, clarify key concepts, and assess the problem's level of development. The second stage was devoted to collecting and systematizing empirical material: reports of international institutions, official evaluations and analytical reviews of ITS implementation in various countries [15; 19; 22; 23]. The third stage comprised a comparative study of documented experience to identify regularities, management practices, and typical difficulties in implementing similar initiatives. At the conclusion, the findings were synthesized into a coherent picture and served as the basis for strategic recommendations tailored to the conditions in Ukraine.

The research objective was addressed through a combination of analytical methods, each performing a clearly defined cognitive function. Comparative analysis made it possible to juxtapose documented ITS deployments in the United States (Los Angeles), Singapore, the Republic of Korea (Seoul) and the Netherlands (Amsterdam), which represent decentralized, centralized-state and supranationally coordinated (European Union) governance contexts and reveal both common features of effective approaches and their institutional preconditions [3; 15; 16; 19]. Inductive and deductive methods were applied in combination: the former generalized concrete practices into theoretical propositions, while the latter tested conceptual constructs against real cases. Structural-functional analysis focused on the architectural organization of ITS. It enabled the establishment of the functional purpose of each system component (the sensor network, the analytical platform, and the executive subsystem) within the context of overall traffic flow management [1; 7].

For the assessment of ITS effectiveness, the study relied on the published results of official evaluations, using indicators such as travel time and delay, number of stops,

traffic speed, accident frequency and emissions [15; 19; 20]. A model of phased ITS implementation was also developed, reproducing the logic of transition from traditional transport infrastructure to a fully integrated digital environment and outlining the conditions for overcoming each stage. It should be noted that the figures reported below come from evaluations that differ in period, scope, baseline and measurement method; they are therefore treated as illustrative evidence of the direction and order of magnitude of effects, not as directly comparable values.

Results

The comparative analysis of four documented ITS deployments shows a consistent link between the digitalization of traffic management and measurable improvements in urban mobility. However, the evidence differs in age, scope and method. In Los Angeles, the ATSAC system, a computerized signal control and surveillance system, is reported to deliver a 12.1% reduction in travel time, 32.3% in intersection delay, 30.4% in stops, 9.4% in fuel use, and 10.0% in air emissions relative to traditional signal timing [15]. In Singapore, Electronic Road Pricing adjusts charges to observed speeds, aiming at 45–65 km/h on expressways and 20–30 km/h on arterial roads [16]; after rate increases in August 2022, traffic speeds in the affected time slots on the Central Expressway improved by 13% on average [18]. In Seoul, the 2004 public transport reform combined a redesigned bus network, median bus lanes and an integrated fare system [20]; in the first months, travel time in median-lane corridors was reported to fall by half, the number of trip segments rose by 11% and bus-related accidents fell by 21% [19]. In Amsterdam, joint automated management by municipal and national traffic centers was associated with a 10% decline in vehicle loss hours [3]; however, a field test of the roadside system also recorded additional delays on the urban network and ramps, even as throughput on the freeway arterial improved [11]. The cases represent three institutional contexts: decentralized (United States), centralized-state (Singapore, Republic of Korea), and supranationally coordinated (the

European Union, represented by the Netherlands). The sample is illustrative rather than statistically representative.

The structural-functional analysis of ITS architecture, as described in the literature, indicates a hierarchical dependence among the system's levels and their contributions to the efficiency of traffic management [1; 7; 8]. The sensing level, which encompasses detectors, video cameras, and IoT devices, provides primary data collection, and its quality conditions the quality of subsequent analytics. The analytical platform, equipped with machine learning and big data tools, transforms raw data into management decisions; digital-twin approaches extend this level towards predictive operation and maintenance [8; 24]. The executive subsystem, which includes adaptive traffic signal control, dynamic road signs, and priority passage, implements these decisions and directly affects traffic flow parameters. The Los Angeles case illustrates this chain, from detectors through central control to signal timing [15]. Effectiveness therefore depends on the integration of all three levels rather than on any one of them [1; 8]. Specific thresholds of measurement error and latency depend on the application and were not assessed in this study.

The generalization of the cases and documented institutional practices made it possible to formulate three institutional preconditions of successful digital transformation of transport. These are presented as analytical propositions that require further empirical testing. First, coordination: the improvement in Amsterdam followed regional cooperation between road managers whose measures had previously conflicted [3]; the Dutch Talking Traffic program brought together a ministry, around 60 regional and local authorities and about 20 companies [4]; and Seoul's reform was a coordinated city-wide program [20]. Second, partnership between public authorities and the private sector, as in the Talking Traffic program [4]; the cases reviewed do not provide comparable financing data, so the share of private capital remains a subject for further research. Third, open standards for data exchange: a review of ITS in Europe identifies technical interoperability, inadequate regulatory frameworks and insufficient

data sharing between stakeholders as the main obstacles to scaling and stresses the need for common standards [5]. The identified regularities have independent theoretical significance, as they form the basis for a generalized model of the institutional, technological, and financial prerequisites for sectoral digitalization.

Among the study's original results is a four-stage model of ITS deployment adapted to the institutional and infrastructural conditions in Ukraine. The first diagnostic stage involves a comprehensive assessment of the current state of transport infrastructure, the identification of critical nodes, and the recording of baseline values for key performance indicators. The second, pilot stage provides for limited-scale pilot projects in representative transport corridors to test technological solutions and develop organizational competencies. In the third, scaling, stage, the tested solutions are extended to the entire urban or regional transport network, provided that the effectiveness shown at the pilot stage is confirmed. The fourth, integration, stage aims to consolidate individual ITS subsystems into a unified digital ecosystem and to establish their interaction with adjacent sectors such as energy, emergency services, and logistics platforms. The model is oriented toward transition economies with uneven regional infrastructure development, which aligns with the Ukrainian context [9; 10]; it is a conceptual proposal and has not yet been tested empirically.

The reviewed evaluations indicate benefits in time, safety, and the environment. Reductions in travel time and delays in Los Angeles [15] and speed gains in Singapore [16; 18] translate into time savings for road users. The 21% reduction in bus-related accidents in Seoul [19] gains significance against a global toll of about 1.19 million road traffic deaths per year [25]. The reported 10% emissions reduction for Los Angeles [15] adds an environmental dimension. At the same time, the sources reviewed do not provide comparable cost-benefit data, so the claim that the aggregate economic effect of ITS exceeds its investment costs remains a hypothesis warranting further research. Thus, the digital transformation of transport infrastructure is not merely a

technological but a complex socio-economic phenomenon; its effective management requires an interdisciplinary approach and coordinated public policy [5; 22].

Scientific novelty and practical significance

A set of interrelated theoretical contributions defines the scientific novelty of the results. A holistic conceptual model is proposed that considers the architectural, institutional and financial dimensions of transport infrastructure digitalization as structurally interdependent determinants of efficiency rather than as independent analytical categories [1; 5; 9]. The comparison of documented cases from decentralized, centralized-state, and supranationally coordinated contexts made it possible to formulate cross-cutting propositions that are not tied to a specific national context: the role of coordination among road managers and levels of government, the importance of partnership between public authorities and the private sector, and the early introduction of open standards for inter-system compatibility [3; 4; 5]. An independent contribution is the four-stage model of ITS deployment, deliberately oriented toward the institutional and infrastructural conditions of transition economies with uneven spatial development [9; 10].

The practical significance of the study is realized through a range of applied opportunities for various stakeholder groups. Central executive authorities receive an analytical basis for formulating a national transport digitalization strategy, developing the regulatory framework, including the use of ITS for road-safety enforcement [21], and determining priorities for public funding and international technological cooperation [23]. Municipal administrations of large Ukrainian agglomerations can use the proposed phased model as a methodological reference for planning pilot initiatives and drafting technical specifications to attract private partners. The academic community gains a foundation for further research in adjacent areas, ranging from the cybersecurity of critical transport infrastructure to traffic flow modeling and digital-twin applications [2; 17; 24]. The private sector, primarily technology companies and institutional investors, receives an analytical framework to assess market potential and

design proposals in the public-private partnership format. The study materials may also be used in educational programs for specialists in digital transport management.

Conclusions

The study demonstrates the complex nature of the digital transformation of transport infrastructure: its effective implementation requires coordinated consideration of technological, institutional and financial components. Published evaluations of the cases reviewed report the following effects: in Los Angeles, reductions in travel time of 12–13%, in intersection delay of 21–32%, in stops of about 30% and in emissions of about 10% [15]; in Singapore, a 13% average speed improvement in the time slots affected by higher road-pricing rates [18]; in Seoul, a 21% reduction in bus-related accidents [19]; in Amsterdam, a 10% decline in vehicle loss hours [3]. These figures come from evaluations that differ in period, scope, and method and are not directly comparable; moreover, ITS effects depend on context and may include local trade-offs, as the Amsterdam field test showed [11].

The analysis of the institutional dimension made it possible to formulate three preconditions of effective ITS implementation: coordination among road managers and levels of government under a shared strategic framework; partnership between public authorities and the private sector; and early formation of open standards for inter-system data exchange [3; 4; 5]. These preconditions are derived from a limited number of cases and should be treated as propositions for further empirical testing.

Regarding the prospects of the Ukrainian transport sector, the study substantiates a phased model of ITS integration that comprises diagnostic, pilot, scaling, and integration stages. At the diagnostic stage, the priority is a comprehensive audit of transport infrastructure and the determination of baseline values of key performance indicators. Kyiv, Kharkiv and Odesa can be considered as candidate sites for pilot projects, given the concentration of transport load and the potential for scaling, subject to the results of the diagnostic stage. Alongside the deployment of technology, it is necessary to develop a regulatory framework harmonized with European ITS

approaches and to invest in training specialists in digital transport management [5; 23]. Implementation of this strategy can contribute not only to the efficiency of the national transport system but also to its integration into the European transport area [5]. Further research should test the proposed model empirically and collect comparable cost-benefit data.

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