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Digital and institutional mechanisms for regulating international freight and passenger transport corridors

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Abstract. Problem. *The development of international freight and passenger transport corridors is accompanied by limited digital integration and fragmented management mechanisms. Insufficient implementation of digital technologies, the absence of integrated transport flow management platforms, and inconsistency of data exchange standards reduce the operational efficiency of transport corridors.* ***Methodology.*** *A phased approach to the formalization of the transport corridor as a cyber-institutional system is proposed. Within this system, digital components, including Intelligent Transport Systems (ITS), the Internet of Things (IoT), and Big Data analytics, interact with management instruments, including customs procedures and regulatory mechanisms, within a unified adaptive management loop. The proposed model considers the interaction between digital, institutional, and external subsystems in real time.* ***Results.*** *An integrated indicator for evaluating transport corridor performance was developed, taking into account delivery time, safety level, operational costs, and service quality. In addition, a digital–institutional consistency coefficient was introduced to quantitatively assess the degree of interaction between digital platforms and institutional mechanisms. It was established that the level of synchronization between these components significantly affects overall system efficiency. The developed model includes a dynamic description of transport flows and feedback mechanisms that ensure the adaptation of digital and management components according to system performance indicators. It was determined that the efficiency of a transport corridor depends not only on technical parameters but also on the level of integration between digital and institutional environments.* ***Originality.*** *A phased approach to the formalization of an international transport corridor as a cyber-institutional system was proposed. In contrast to existing approaches, the developed framework integrates digital technologies and institutional management instruments within a unified adaptive system.* ***Practical value.*** *The obtained results make it possible to formalize transport corridor management processes, evaluate the impact of digitalization, and substantiate measures aimed at improving efficiency through the harmonization of technological and institutional solutions.*

Keywords: *international transport corridors, institutional regulation, digitalization, cyber-physical system, freight and passenger transportation, mathematical modeling.*

Introduction and Analysis of publications

The current development of international freight and passenger transport corridors is characterized by increasing complexity associated with their functioning as multi-level cyber-physical systems integrating infrastructural, logistical, informational, and institutional components. Globalization processes, market integration, and increasing transit flows determine the necessity to improve the efficiency, reliability, and safety of transport corridor operation.

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At the same time, existing approaches to the regulation of international transport corridors remain fragmented and insufficiently coordinated. On the one hand, digital technologies are actively implemented to provide operational monitoring and optimization of transport flows. On the other hand, institutional mechanisms often fail to adapt to the pace of digital transformation, resulting in regulatory gaps and reduced system efficiency.

A significant problem is the absence of an integrated model describing the interaction between digital and institutional regulation mechanisms within a unified transport corridor system. Existing studies mainly focus either on technological aspects of digitalization or on separate institutional instruments, without ensuring their integrated interaction. This complicates managerial decision-making, reduces coordination among transport process participants, and limits the possibilities for forecasting and adaptation to external environmental changes.

In addition, the absence of formalized methods for quantitative assessment of the effectiveness of digital and institutional integration does not allow adequate evaluation of the influence of regulatory decisions on transport corridor performance indicators, including throughput capacity, delivery time, service quality, and transportation safety.

Therefore, there is a scientific and practical need to develop a comprehensive approach to integrating digital and institutional mechanisms for regulating international freight and passenger transport corridors based on their representation as an integrated cyber-institutional system. This requires the development of appropriate mathematical models, assessment methods, and practical implementation tools.

Analysis of publications

Modern studies confirm the transformation of international transport corridors into integrated logistics systems operating at the intersection of infrastructure, digital technologies, and regulatory policy [3, 13, 16, 26, 28, 29]. Under such conditions, transport corridors become complex systems combining physical infrastructure, transport flows, information technologies, and institutional regulation mechanisms [1, 2, 4, 12].

One of the key directions for improving transport corridor efficiency is the implementation of digital technologies, particularly Intelligent Transport Systems (ITS), the Internet of Things (IoT), Big Data analytics, and Digital Twins, which improve the transparency and controllability of transport processes [5, 8, 9, 17, 21, 22, 25, 28, 30, 33]. Digitalization contributes to reducing transit time and operating costs and improves transport flow forecasting.

At the same time, the efficiency of international transport corridors largely depends on institutional factors, including legal regulation, customs procedures, administrative barriers, and the level of international coordination [14, 27, 32, 33]. Insufficient consistency between institutional mechanisms and digital transformation processes results in regulatory imbalances and reduces the effectiveness of transport corridor functioning.

Despite the large number of studies in this field, current approaches to transport corridor regulation generally focus either on technological aspects of digitalization or on institutional mechanisms separately [6, 10]. The absence of an integrated model describing an international transport corridor as a unified cyber-institutional system complicates effective management and limits opportunities for forecasting transport system development [7, 23].

Therefore, the relevance of the study is determined by the necessity to develop an integrated approach to regulating international freight and passenger transport corridors based on combining digital and institutional mechanisms within a unified cyber-institutional system.

Research Objective and Methodological Framework

The purpose of the study is to develop a theoretically and methodologically substantiated approach to the integration of digital and institutional mechanisms for regulating international freight and passenger transport corridors through their interpretation as an integrated cyber-institutional system, as well as to develop an integrated model of a transport corridor as a complex cyber-physical system.

The methodological basis of the study combines general scientific and specialized approaches aimed at the systematic analysis of international transport corridors as cyber-institutional systems under conditions of digital transformation. The application of systems, cybernetic, and cyber-institutional approaches made it possible to consider the transport corridor as a multi-level integrated system in which technological solutions are combined with organizational and management mechanisms, taking into account feedback, adaptation, and self-regulation processes.

The system structure was formalized using conceptual modeling, in which the transport corridor is represented as the interaction of the digital subsystem (D) and institutional subsystem (M), the external environment (E), and performance indicators (R). Their dynamics were described using mathematical models based on a functional-structural approach and recurrent dependencies, which made it possible to substantiate the existence of a closed-loop management mechanism.

The efficiency assessment was carried out using a multi-criteria approach integrating key indicators into a unified generalized criterion. The level of consistency between digital and institutional components was determined using mathematical statistics methods, particularly covariance analysis, which enabled the development of a digital–institutional consistency coefficient.

Additionally, methods of analysis, synthesis, and factor modeling were applied to investigate system behavior over time, evaluate the influence of external factors, and analyze possible scenarios of transport corridor functioning.

Development of an Integrated Model of the Transport Corridor as a Complex Cyber-Physical System

The development of international freight and passenger transport corridors takes place under conditions of several systemic constraints, among which insufficient digitalization and the absence of integrated transport flow management platforms are the most significant [2, 16, 34]. The lack of unified data exchange standards additionally limits the effective implementation of digital technologies and reduces the overall efficiency of corridor functioning [13, 15, 27]. Solving these problems requires the formalization of transport corridor efficiency based on an integrated performance indicator [11].

Within this study, a phased approach to integrating technical and organizational factors into a unified management model is proposed, in which digital platforms (ITS, IoT, Big Data) and management instruments (customs procedures, regulatory mechanisms) operate as components of an integrated system [9, 15, 16, 31].

Accordingly, a transport corridor can be interpreted as an integrated cyber-physical management system, in which digital platforms form the information level, management decisions form the institutional level, and their interaction ensures the formation of an adaptive management mechanism [18, 20].

At the first stage, the transport corridor system is represented as

$$S = \langle D, M, E, R \rangle, \quad (1)$$

where: D – digital subsystem (*ITS*, *IoT*, *Big Data*); M – institutional subsystem (customs authorities, regulators); E – external environment (traffic intensity, demand, risks); R – performance indicators.

The structure of the digital subsystem is represented as

$$D = f\left(IoT, ITS, BD\right), \quad (2)$$

where: IoT – sensor data (speed, location, vehicle condition); ITS – transport flow management systems; BD – analytical and forecasting tools [2, 6].

The institutional subsystem is represented as

$$M = g\left(C, Reg, Pol\right). \quad (3)$$

where: C – customs procedures; Reg – regulatory instruments; Pol – management policies (flow prioritization, restrictions) [2, 3].

The integration of digital and institutional subsystems forms the key relationship within the cyber-institutional system. At the same time, management decisions are dynamic and depend on digital information flows in real time [31]

$$M(t) = g\left(D(t), E(t)\right), \quad (4)$$

Conversely, management decisions influence the parameters of the digital subsystem

$$D(t+1) = f\left(M(t)\right)D(t+1), \quad (5)$$

The formalization of the interaction between digital and institutional components confirms the existence of a closed-loop management mechanism, within which information flows, digital platforms, and regulatory instruments interact in real time. This ensures management adaptability, optimization of system performance, and increased resistance to destabilizing external factors [18, 20].

Integrated Performance Indicator

At the second stage, an integrated indicator of transport corridor efficiency is introduced. A generalized criterion is represented as

$$R = \alpha T^{-1} + \beta S + \gamma C^{-1} + \delta Q, \qquad (6)$$

where: *T* – corridor transit time; *S* – safety level; *C* – operational costs; *Q* – service quality; *α, β, γ, δ* – weighting coefficients [11].

To determine the degree of consistency between digital information and management decisions, a digital–institutional consistency coefficient is introduced, which characterizes the level of interaction between digital and institutional components of the transport corridor [19, 24].

$$k_{int} = \frac{\mathrm{Cov}(D, M)}{\sigma_D \; \sigma_M}, \qquad (7)$$

where: *Cov(D, M)* – covariance between variables *D* and *M*; *D* – digital parameters (digitalization level, IoT, ITS); *M* – institutional parameters (regulation, customs procedures, management policies); σ_D – standard deviation of digital parameters; σ_M – standard deviation of institutional parameters.

Interpretation of the consistency coefficient:

$k_{int} \to 1$ – complete synchronization of digital and institutional components;

$k_{int} \to 0$ – inconsistency between digital information and management mechanisms.

The obtained model demonstrates that digital technologies (ITS, IoT, Big Data) not only collect information but also influence management decisions, whereas customs and regulatory mechanisms transform from static instruments into adaptive management tools [6, 15].

The coefficient k_{int} allows the interaction between digital platforms and institutional mechanisms to be formalized, quantitatively assesses the level of transport corridor integration, and may be used as a criterion of cyber-institutional system efficiency.

Integrated Transport Corridor Model

At the third stage, the coefficient k_{int} is integrated into a comprehensive transport corridor model. The transport corridor is considered as a system.

$$S = \{D(t),\ M(t),\ F(t),\ E(t)\}, \qquad (8)$$

where: D(t) – digital subsystem (ITS, IoT, Big Data); M(t) – institutional subsystem (regulation, customs procedures, management policies); F(t) – transport flows; E(t) – system performance efficiency.

Accordingly, the integrated efficiency function of the transport corridor can be represented as

$$E(t) = \alpha \cdot Q(t) + \beta \cdot V(t) + \gamma \cdot R(t) + \delta \cdot k_{int}(t), \qquad (9)$$

where: *Q* – throughput capacity; *V* – delivery speed; *R* – reliability (resistance to disruptions); k_{int} – level of consistency between digital and institutional components; α, β, γ, δ – weighting coefficients.

The model analysis indicates that transport corridor efficiency depends not only on technical parameters but also on the level of integration between digital and institutional environments [16, 31].

The dynamics of transport flows are described as.

$$\frac{dF}{dt} = f\,(D,\ M,\ k_{\text{int}}), \qquad (10)$$

In expanded form.

$$\frac{dF}{dt} = aD(t) + bM(t) + c\,k_{\text{int}} - \mu F(t), \qquad (11)$$

where: a, b, c – influence coefficients; μ – loss coefficient (delays, downtime, disruptions).

The feedback mechanisms of the transport corridor management system are represented as.

$$D(t+1) = D(t) + \varphi_1 E(t), \qquad (12)$$

$$M(t+1) = M(t) + \varphi_2 E(t), \qquad (13)$$

where: φ_1, φ_2 – system adaptation coefficients.

Therefore, feedback mechanisms form an adaptive closed-loop management system capable of adjusting transport corridor operation according to changes in environmental conditions and performance indicators.

Thus, the developed mathematical model of the transport corridor as a cyber-institutional system makes it possible to:

– represent the transport corridor as an integrated system;

– account for the interaction between technological and institutional components;

– formalize the influence of digitalization on transport and logistics processes;

– evaluate the effect of harmonizing policies and standards.

Discussion of Results

The obtained results confirm the feasibility of moving from fragmented approaches to the management of international transport corridors toward their consideration as integrated cyber-institutional systems. In contrast to conventional approaches, in which digital tools and regulatory mechanisms function separately, the proposed approach demonstrates that system efficiency significantly depends on the consistency of their interaction.

The study confirms the existence of a closed-loop management mechanism in which digital technologies (IoT, ITS, Big Data) perform not only monitoring functions but also directly influence management decisions in real time. At the same time, institutional and organizational mechanisms affect the parameters of the digital environment, forming a bidirectional interaction between technological and management components. Such an interpretation corresponds to the principles of cyber-physical systems and supplements them with an institutional component.

The proposed integrated efficiency indicator demonstrates the limitations of traditional performance assessment criteria, including delivery speed, throughput capacity, operational costs, and reliability, which do not fully characterize transport corridor functioning. The introduction of the coefficient k_{int} shows that even with a high level of technical support, corridor efficiency may remain low due to insufficient consistency between digital information and management decisions.

The analysis also indicates that the coefficient k_{int} acts as a system-forming parameter. Its increase is accompanied by higher efficiency due to improved interaction among system components. Conversely, low values of this coefficient lead to imbalances, increased delays and operational costs, and deterioration in transport service quality, even under conditions of developed digital infrastructure.

The developed dynamic model of transport corridors, including feedback mechanisms, makes it possible to consider the transport corridor as an adaptive system capable of self-adjustment. This creates conditions for improving transport corridor management through forecasting methods and real-time data analysis.

Therefore, the efficiency of international freight and passenger transport corridors is determined not only by individual indicators but also by the degree of consistency and integration of digital and institutional components, which ensures system adaptability and operational stability under conditions of digital transformation.

Conclusions

The conducted study confirms that the main constraints affecting the development of international freight and passenger transport corridors are fragmented digitalization, the absence of integrated transport flow management platforms, and inconsistency of data exchange standards. This determines the necessity of transitioning from the consideration of transport corridors as separate elements to their interpretation as integrated systems combining digital and institutional components.

The main result of the study is the development of an integrated cyber-institutional model of an international transport corridor. Within the proposed approach, the following results were obtained:

– an international freight and passenger transport corridor was conceptualized as a cyber-physical management system with digital (*D*) and institutional (*M*) subsystems interacting through the external environment and performance indicators;

– a formalized representation of the dynamic interaction between digital platforms and management decisions was developed through the relationships: $M(t)=g(D(t), E(t))$ and $D(t+1)=f(M(t))$ which reflect adaptive real-time management;

– the existence of a closed-loop management mechanism was substantiated, within which system performance affects management parameters, while management decisions influence digital and institutional system characteristics.

In addition, a digital–institutional consistency coefficient k_{int} was introduced, making it possible to:

– formalize the degree of synchronization between digital information and management mechanisms;

– quantitatively assess the level of transport corridor integration;

– determine a system-forming parameter affecting the interaction efficiency of technological and institutional components.

An integrated transport corridor performance function was developed. Unlike existing approaches, it includes not only traditional logistics indicators (delivery speed, throughput capacity, reliability), but also the consistency coefficient k_{int}, which makes it possible to evaluate the interaction of system components in an integrated manner.

The developed mathematical model enables:

– the formalization of the impact of digitalization on transport process efficiency through feedback mechanisms;

– the integration of technical (ITS, IoT, Big Data) and organizational (customs procedures, regulation, management policies) factors within a unified analytical framework;

– the simulation of adaptive transport corridor functioning under changing environmental conditions and risks.

It was established that the efficiency of international freight and passenger transport corridors depends not only on technical parameters but also on the degree of consistency between digital and institutional components. This creates a methodological basis for improving transport corridor management under conditions of digital transformation.

Conflict of interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Цифрові та інституційні механізми регулювання міжнародних транспортних коридорів вантажних і пасажирських перевезень

Анотація. Проблема. *У статті розглянуто проблематику розвитку міжнародних транспортних коридорів вантажних і пасажирських перевезень в умовах обмеженої цифрової інтеграції та фрагментарності управлінських механізмів. Обґрунтовано, що ключовими стримувальними чинниками є недостатній рівень впровадження цифрових технологій, відсутність єдиних платформ управління транспортними потоками та неузгодженість стандартів обміну даними, що знижує ефективність функціонування коридорів.* ***Мета.*** *Метою дослідження було формування теоретично та методологічно обґрунтованого підходу до інтеграції цифрових та інституційних механізмів регулювання міжнародних транспортних коридорів вантажних і пасажирських перевезень шляхом їх інтерпретації як цілісної кібер-інституційної системи, а також розроблення інтегрованої моделі транспортного коридору як складної кіберфізичної системи.* ***Методологія.*** *Запропоновано поетапний підхід до формалізації транспортного коридору як кібер-інституційної системи, у межах якої цифрові компоненти (ITS, IoT, Big Data) та управлінські інструменти (митні процедури, регуляторна політика) взаємодіють у єдиному адаптивному контурі. Модель передбачає опис системи через взаємопов'язані цифровий, інституційний та зовнішній контури з урахуванням їх динамічної взаємодії в режимі реального часу.* ***Результати.*** *Сформовано інтегральний показник ефективності функціонування транспортного коридору, який враховує час доставлення, рівень безпеки, витрати та якість сервісу. Додатково введено коефіцієнт узгодженості, що дозволяє кількісно оцінити рівень інтеграції між цифровими платформами та інституційними механізмами. Показано, що саме ступінь їх синхронізації істотно впливає на загальну ефективність системи. Розроблена модель доповнена динамічним описом транспортних потоків і механізмами зворотного зв'язку, які забезпечують адаптацію цифрових і управлінських компонентів залежно від результатів функціонування системи. Доведено, що ефективність транспортного коридору визначається не лише технічними параметрами, а й рівнем інтеграції цифрового та регуляторного середовищ.* ***Оригінальність.*** *Запропоновано поетапний підхід до формалізації транспортного коридору як кібер-інституційної системи, у межах якої цифрові компоненти (ITS, IoT, Big Data) та управлінські інструменти (митні процедури, регуляторна політика) взаємодіють у єдиному адаптивному контурі.* ***Практичне значення.*** *Отримані результати дозволяють формалізувати процеси управління транспортними коридорами, оцінювати вплив цифровізації та обґрунтовувати напрями підвищення ефективності шляхом гармонізації технологічних і інституційних рішень.*

Ключові слова: *міжнародні транспортні коридори, інституційне регулювання, цифровізація, кіберфізична система, вантажні та пасажирські перевезення, математична модель.*

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