Вісник Національного технічного університету "ХПІ", 2026, № 2 (16)
ISSN 2079-0031 (Print) ISSN 2411-0558 (Online)

UDC 004.056:656.1 DOI: DOI: 10.20998/2411-0558.2026.02.08

O. MNUSHKA, Sen. Lect., NTU "KhPI”,
V. SAVCHENKO, Cand. Sc. (Engineering), Assoc. Prof., NTU “KhPI”,
A. POVOROZNYUK, Doctor. Sc. (Engineering), Prof., NTU “KhPI”

METAGRAPH-BASED MODELING OF DISTRIBUTED TRANSPORTATION SYSTEMS: MODELS, POLICIES, AND SECURITY

Distributed transportation systems (DTS) are evolving into large-scale cyber-physical platforms that distribute data processing, decision-making, and control across vehicles, infrastructure, and cloud services. While this evolution improves scalability and resilience, it also complicates coordination, integration, and security assurance. Several key classes of models are generalized, including IoT/edge-based monitoring, forecasting, optimization, control, and multimodal planning. Cross-sectional analysis reveals gaps in formalization. As a unifying approach, metagraphs are proposed – a mathematical apparatus for modeling structural and process dependencies, policies, and verification in distributed environments. Figs.: 1. Refs.: 32 titles.

Keywords: distributed transportation systems; intelligent transportation systems; edge computing; Internet of Things; optimization and control; graph learning; metagraph; security policies

Introduction. Modern transportation systems are evolving into distributed cyber-physical ecosystems in which computation, data, and control are shared among vehicles, infrastructure, edge nodes, and cloud services. While this improves scalability and fault tolerance, it complicates real-time coordination, the integration of heterogeneous components, and data and process security. In intelligent transportation systems (ITS), monitoring and control increasingly rely on IoT-based architectures, telemetry streams, and near–real-time analytics [1, 2], alongside forecasting and optimization methods such as reinforcement learning and online optimization for dispatching, routing, and fleet management [3, 4].

In addition, many contemporary DTS explicitly incorporate remote and supervisory control loops, where operational decisions and corrective actions are issued from distributed control centers or cloud platforms to vehicles and

---

infrastructure components over communication networks, introducing further requirements on latency, reliability, and policy consistency [5 – 7].

However, the literature often treats individual subproblems – traffic prediction, demand management, multimodal transfers, and logistics optimization – using separate formalisms, which hampers the construction of a unified system model [8, 9]. This issue is amplified in heterogeneous environments that combine diverse objects and abstraction levels. Although graph models and graph-based learning are widely used, they frequently lack explicit means to represent group dependencies, roles, policies, and component composition [10, 11]. Security further complicates the picture due to cyber threats, limited edge resources, privacy constraints, and the need for formal access control and policy consistency [12, 13].

In this context, metagraphs are considered a promising integrative formalism that extends graphs to model relationships between sets of elements, enabling explicit representation of complex dependencies and policies [14, 15]. They have been applied to macro-level transportation modeling [16], distributed computation analysis [17], and, more recently, to policy verification and secure mobile and edge architectures [18–20]. Modern transportation systems are becoming distributed cyber-physical ecosystems, improving scalability but complicating coordination and security. ITS depend on IoT, data analytics [1, 2], and advanced optimization methods [3, 4].

Research mostly solves subproblems like prediction and optimization in isolation, hindering unified models [8, 9]. Graph models are common but rarely capture group dependencies or policies [10, 11]. Security is challenged by threats and resource limits [12, 13].

Metagraphs extend graphs to represent complex relationships and policies [14, 15]. They are applied in transport modeling [16], distributed systems [17], and policy verification [18–20].

The publication aims is to systematize models of distributed transportation systems and their associated requirements – functional, computational, and security-related – and to substantiate the adoption of metagraphs as a unifying mathematical formalism for the formalization, analysis, and implementation of such systems. The objectives of the study are to:

– summarize the principal families of models and approaches in ITS – including IoT-based monitoring, forecasting, optimization and control, multimodality, and digital twins – and identify common limitations in their formalization;

– define the requirements for a unified formalism from a computer systems perspective, encompassing component composition, data interoperability, distributed execution, observability, and scalability;

– analyze the security dimension – including access policies, rule consistency, threats, and resource constraints – and demonstrate the necessity of formal verification;

– demonstrate that metagraphs can serve as a unified representation for structure, processes, and policies in distributed transportation systems, thereby establishing a foundation for further research on mathematical models and operators based on metagraphs.

Models of Distributed Transportation Systems. A distributed transportation system (DTS) is a multi-layer network of resources, infrastructure, digital services, and control mechanisms. Data collection, decision-making, and execution are distributed across vehicles, infrastructure, dispatch centers, logistics hubs, and edge/cloud platforms. In modern ITS, monitoring and control rely on IoT architectures and near–real-time analytics [1, 2], while planning and optimization use learning-based methods, online optimization, and reinforcement learning [3, 4].

A key property of DTS is decentralized coordination through data exchange and consistent policies, improving scalability and fault tolerance over centralized schemes. Distribution requires data interoperability, real-time consistency, and correctness despite delays or partial node availability [8, 11]. Effectiveness depends on both prediction/optimization quality and integration of heterogeneous components [21, 22].

DTS can be modeled as compositions of interacting submodels: infrastructure/environment topology [23], resources/actors [24], data flows/observability [8], control/policies [3, 25], and multimodal integration [26, 27]. DTS involve heterogeneous entities and relations of varying arity, including set–set relations for policies, group constraints, and collective actions. This demands a formalism that compactly expresses multi-party dependencies, supports hierarchical abstractions, and enables consistency and security analysis [14, 15].

Modern ITS and distributed platforms are heterogeneous systems of systems, integrating sensing, analytics, optimization, and service mechanisms (MaaS, dispatch, digital twins). Observability models define what data are collected and how they move across IoT, edge, and cloud, focusing on reliability and consistency [1, 2]. Forecasting relies on spatio-temporal, graph-based, and meta-learning models [28, 8, 10, 9], which often capture correlations, not explicit roles or policies.

Optimization and control models address routing, dispatch, fleet management, multimodal balancing, and incidents. Modern methods combine classical and learning-based optimization, supporting uncertainty and partial observability [3, 4, 25]. Multimodal planning increases heterogeneity, with routes spanning modes and constraints [26, 27]. Digital-twin and integration models require consistent component descriptions and end-to-end controllability [21, 22, 11].

Despite progress, integrating these model families into a coherent DTS exposes a persistent formalization gap. Most lack a unified apparatus for structure, heterogeneity, group constraints, distributed composition, and security analysis. Further challenges: supporting hierarchical abstraction [16, 29], distributed/subgraph execution [2, 17], real-time consistency under streams [1, 8], and formal security/access control [12, 13, 18–20]. Integrating ML/optimization into certifiable, policy-aware architectures is also difficult [10, 9, 3].

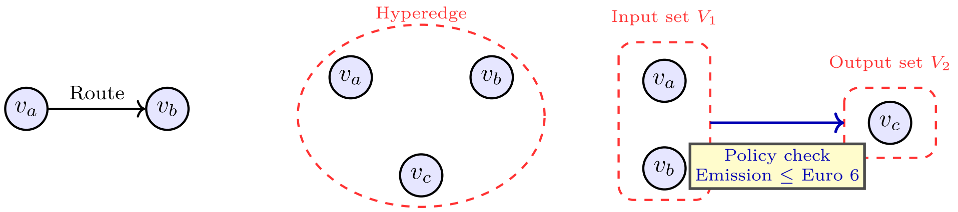
These gaps show the need for a unified formalism supporting higher-arity relations, hierarchical abstractions, distributed execution, real-time consistency, and security. Metagraphs are a promising candidate, naturally representing set relations and enabling formalization of structure, process, and policy in DTS [14, 15, 18].

Metagraphs as a Formalism for Modeling and Analysis of DTS. Metagraphs generalize classical graphs by enabling relationships between subsets of elements, thereby supporting group interactions and policy constraints in complex systems [14, 15]. Formally, a metagraph is defined as

$$S = \langle X, E \rangle,$$

where X is the set of elements (the generating set) and E is the set of metaedges. Each metaedge $e = \langle V_e, W_e \rangle$, with $V_e, W_e \subseteq X$, encodes a directed relationship between the input set V_e and the output set W_e. This framework naturally represents policies, control conditions, and resource constraints in distributed systems [18, 20].

In distributed transportation systems, such relations arise when outcomes depend on combinations of conditions, for example in multimodal transfers or coordinated control scenarios [11, 19]. Metagraphs therefore provide a unified language for structural and policy modeling in DTS.



(a) Classical Graph
Pairwise relation
($v_a \to v_b$)

(b) Hypergraph
Group relation
(set of vehicles)

(c) Metagraph
Conditional set-to-set
interaction

Fig.1. Conceptual comparison of topological models for DTS.

Illustrative comparison. To clarify the unifying role of metagraphs, consider the following conceptual comparison. A classical graph represents a transportation network through pairwise relations, for example a connection from location A to location B. A hypergraph extends this view by modeling group interactions, such as a set of vehicles jointly occupying a road segment. A metagraph, in contrast, explicitly captures policy-governed relations between sets of entities. For instance, it can represent that a set of vehicles $V_1 = \{v_a, v_b\}$ is granted access to a city-center zone V_2 only if specific conditions (e.g., emission class or time-based restrictions) are satisfied, with such conditions encoded as attributes of the corresponding metaedge (Fig. 1).

This capability goes beyond pure topology and enables the integration of structural, operational, and regulatory aspects within a single formal model.

Conceptual comparison of topological models for DTS. (*a*) Graphs capture pairwise connectivity. (*b*) Hypergraphs capture group relations. (*c*) Metagraphs capture policy-governed directed interactions between sets.

In this formulation, access is not merely a structural relation but a conditional interaction between sets of entities governed by system-level rules. This example illustrates why metagraphs act as a unifying formalism: they subsume graph- and hypergraph-based representations while integrating structure, processes, and policies within a single mathematical model for distributed transportation systems.

System behavior is analyzed through metapaths – sequences of metaedges – which enable reachability and workflow analysis, as well as the detection of policy conflicts [14, 15, 18]. Metagraphs can further be extended with weights, temporal attributes, or resource constraints, supporting optimization and security analysis [16, 12]. Matrix-based representations enable formal algorithmic analysis and have proven useful in macro-level transportation studies, including flow assessment and bottleneck detection [14 – 16].

Overall, metagraphs provide a concise and expressive formalism for modeling complex relations and constraints in distributed transportation systems, while remaining compatible with optimization- and learning-based approaches [14, 15, 10, 9, 17].

Security and Policies in Distributed Transportation Systems.

Security in distributed transportation systems (DTS) covers both data protection and the integrity of control actions, even in the face of failures or attacks. As DTS integrate vehicles, infrastructure, edge, and cloud, the attack surface is broad [11, 2]. Studies reveal vulnerabilities like anomalous node behavior, resource exhaustion, and telemetry compromise [12].

Key threats in DTS include:

- data compromise: telemetry manipulation, sensor spoofing, and distortion of time/location, leading to incorrect predictions and actions [1, 12];
- availability attacks: overload of links, edge nodes, or services, disrupting real-time operation [11, 2];
- control-plane compromise: interception or manipulation of dispatch/routing commands, impacting safety and stability [12, 13];

– privacy violations: leakage of data, route tracing, and deanonymization in MaaS/logistics [13];

– policy conflicts: inconsistent rules or misaligned policies, enabling unintended access or denial of operations [18, 19].

DTS security requirements combine classical CIA properties with domain-specific constraints:

– integrity of data and control commands;

– availability of services under load and attack;

– confidentiality of personal/operational data;

– authentication and authorization across domains;

– auditability and accountability of decisions;

– fail-safe behavior and isolation of compromised components [11, 12].

A major challenge is policy specification and coordination: many incidents result from inconsistent or misaligned policies, not missing cryptography [18, 19]. This is especially acute in DTS, where multiple trust domains and dynamic contexts exist.

Metagraphs provide a natural formalism for modeling security policies, relating sets of subjects, resources, and conditions to permitted actions or outcomes. A metaedge $e = \langle V, W \rangle$ links contextual conditions with allowed operations [14, 15]. These models are widely used for policy consistency analysis and detection of unintended access paths, including in transportation [18].

Within DTS, metagraphs support analysis of:

– policy consistency: detection of contradictory rules under identical conditions;

– reachability and isolation: identification of authorized or unauthorized paths to critical resources;

– cross-domain conflicts: alignment of local (vehicle/edge) and global (operator/cloud) policies under changing contexts;

– containment: can compromised components affect critical control loops? [18, 11].

Metagraph-based policy models are compatible with established access-control paradigms, including ACL, RBAC, and ABAC, and enable system-level reasoning about conditions, permissions, and consequences of actions. In edge/IoT and microservice-based architectures, such representations support automated configuration validation and reduce policy-related errors [19, 20, 30, 5, 31].

In this context, attributive metagraphs have also been applied to the security assessment of IoT-based information systems, where standardized vulnerability metrics are used to evaluate the impact of cyber threats on components of distributed control and monitoring systems [30, 5, 31]. For distributed transportation systems, this implies that access-control and security policies can be treated as first-class elements of the overall system model rather than as isolated configuration artifacts.

Security in DTS requires coordinated protection of data, control, availability, and policies. Correctness and consistency of interaction rules are as critical as channel security. Metagraphs offer a unified formalism for policy modeling and structural verification in DTS [18, 14, 15].

Discussion, Generalization, and Open Research Directions. The paper shows that modern distributed transportation systems (DTS) integrate several tightly coupled loops: IoT/edge/cloud-based observation and monitoring; state and flow forecasting; optimization and control (including online optimization and reinforcement learning); multimodal service integration, and security mechanisms and policies. Applied studies report substantial progress in real-time monitoring and control [1, 2], learning-based fleet and flow management [3, 4], and graph-based machine learning for transportation tasks [10, 9]. However, integrating these loops into a coherent DTS remains challenging due to formalization limits caused by heterogeneous entities, higher-arity dependencies, and the need for consistent system-wide policies.

Open Problems and Research Gaps. The following issues remain open and are critical for advancing DTS as transportation computer systems.

Current practice separates network structure, telemetry and data models, control logic, and security policies. This separation complicates consistency verification and reachability analysis. A unified formal framework capable of integrating these aspects is still insufficiently developed [14, 15, 18].

Graph-based ML and hypergraph models are widely used as effective approximations of transportation dynamics [10, 9, 32]. Yet, their integration into systems with strict constraints, security policies, and auditability requirements remains unresolved. Methods are needed to align ML-driven decisions with formal constraints and access policies [11, 13].

Since DTS are inherently distributed, any formalism must support decomposition and efficient execution. Control and analysis tasks must explicitly account for bandwidth, latency, and energy constraints at the edge [2]. Subgraph-oriented computation paradigms offer promising scalability, but require precise models of communication and interaction costs [17].

Table 1

Model families in DTS

Model family	Typical tasks	Typical limitations (integration perspective)	Metagraph contribution + sources
IoT/edge/cloud monitoring	Sensing, aggregation, awareness	Heterogeneous data, latency/resource limits, weak policy links	Set-based components, flows; policy reachability [1, 2, 14]
Spatio-temporal forecasting (graph/ML)	Traffic prediction, anomaly detection, demand forecasting	Correlations, not policies; limited traceability	Formal constraints; ML as approximation [28, 10, 15]
Optimization and control (incl. RL/online)	Dispatching, routing, fleet control, optimization	Hard to encode multi-actor constraints; implementation issues	Metagraph encodes constraints/actions; supports decomposition [3, 4, 17]
Multimodal planning and transfers	Multimode routing, transfer validation, integration	Complex constraints often ad hoc	Set–set encoding for transfers/compositions [26, 27, 14]
Security and policies	Access, integrity, secure coordination	Policy conflicts, config errors, no global verification	Metagraph for policy/conflict analysis [30, 5, 31, 12, 18, 19]

Table 1 (Continued)

IoT-based information system security model	Formalization of security requirements and mechanisms for IoT-oriented systems	Transferability to DTS requires alignment of roles, trust domains, and policies across components	Policy-oriented security modeling in IoT/edge environments [31, 30]
Set-based relations / higher-arity links	Representation of relations between sets $V \subseteq X$ and $W \subseteq X$; constraints and policies	Simple graphs encode only pairwise links; loss of group semantics; complex policy composition	Core of metagraphs: $S = \langle X, E \rangle$, $e = \langle V, W \rangle$; matrix-based analysis [14–16]

DTS security depends not only on protecting data and control loops, but also on maintaining policy consistency across multiple trust domains [12, 11]. Open challenges include formal analysis of policies under dynamic conditions (incidents, network degradation, changing resource availability) and scalable automated configuration verification [18, 19].

As shown in Table~1, existing model families in distributed transportation systems address specific tasks but exhibit integration and formalization gaps that can be systematically mitigated using metagraph-based representations.

Multimodal transportation introduces layered dependencies between transport modes, tariffs, time windows, and infrastructure availability [27, 26]. Building models that simultaneously support full multimodality, integration of incomplete planners, and formal consistency analysis remains an open problem.

Design Recommendations for DTS as Computer Systems. Based on the review, the following design rules are recommended:

– separate structural, process, and policy layers, while linking them through a shared formal representation [14, 15];

– explicitly model context (conditions, constraints, roles, trust domains) as part of the system model rather than as external configuration [18, 11].

– design for distributed execution (edge/cloud) with controlled boundaries between submodels and communication costs [2, 17].

– integrate ML and optimization as decision modules operating within formal constraints and policies, ensuring traceability and auditability [10, 3].

– Embed security by design into interaction models, including consistency checks and analysis of undesirable reachable states [12, 19].

Conclusions and Future Work. Distributed transportation systems, viewed as transportation computer systems, require joint consideration of structural heterogeneity, environmental dynamics, control optimization loops, and security policies. Existing approaches (IoT/edge architectures, forecasting, GNNs, RL, robust optimization) are effective in isolated settings, but leave open the challenges of unified representation and formal verification. Metagraphs constitute a promising formalism for capturing multi-party dependencies and policies, making them a relevant foundation for further advances in the analysis and design of DTS [14, 15, 18].

A key direction for future research is the development of comprehensive metagraph-based models of distributed transportation systems, enabling the integrated representation of structure, processes, and policies. Such models would support formal analysis of consistency, security, and reachability, facilitate decomposition for distributed and edge-based execution, and provide a principled framework for embedding optimization and learning components within policy-aware and verifiable system architectures.

References:

1. Dui, H., Zhang, S., Liu, M., Dong, X. and Bai, G. (2024), "IoT-enabled real-time traffic monitoring and control management for intelligent transportation systems", IEEE Internet of Things Journal, Vol. 11, No. 9, pp. 15842–15854, doi: 10.1109/jiot.2024.3351908.

2. Peyman, M., Copado, P.J., Tordecilla, R.D., Martins, L. do C., Xhafa, F. and Juan, A.A. (2021), "Edge computing and IoT analytics for agile optimization in intelligent transportation systems", Energies, Vol. 14, No. 19, pp. 6309, doi: 10.3390/en14196309.

3. Jungel, K., Parmentier, A., Schiffer, M. and Vidal, T. (2023), "Learning-based online optimization for autonomous mobility-on-demand fleet control", INFORMS Journal on Computing [Preprint], doi: https://doi.org/10.1287/ijoc.2024.0637.

4. Sumathi, N. and Navamani, G. (2025), "Real-time traffic optimization: A graph-based reinforcement learning framework", in 2025 International Conference on Inventive Computation Technologies (ICICT), IEEE, pp. 767–771, doi: 10.1109/icict64420.2025.11004682.

5. Mnushka, O., Savchenko, V., Leonov, S. and Shaposhnikova, O. (2021), "Information technology of remote monitoring and control", in 2021 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME), IEEE, pp. 1–5, doi: 10.1109/iceccme52200.2021.9590889.

6. Mnushka, O., Leonov, S., Shaposhnikova, O. and Savchenko, V. (2021), "Model of information technology of remote monitoring with a possibility of control of technological processes and objects", Bulletin of the National Technical University “KhPI” A Series of “Information and Modeling”, No. 1 (5), pp. 99–114, doi: 10.20998/2411-0558.2021.01.08.

7. Mnushka, O., Pivnieva, O. and Savchenko, V. (2019), "Application protocol of data transfer in the internet of things", Bulletin of Kharkov National Automobile and Highway University, Vol. 0, No. 87, pp. 54, doi: 10.30977/bul.2219-5548.2019.87.0.54.

8. Jalil, K., Xia, Y., Chen, Q., Zahid, M.N., Manzoor, T. and Zhao, J. (2024), "Integrative review of data sciences for driving smart mobility in intelligent transportation systems", Computers and Electrical Engineering, Vol. 119, pp. 109624, doi: 10.1016/j.compeleceng.2024.109624.

9. Wu, H., Yan, S. and Liu, M. (2023), "Recent advances in graph-based machine learning for applications in smart urban transportation systems", arXiv, doi: 10.48550/ARXIV.2306.01282.

10. Li, H., Zhao, Y., Mao, Z., Qin, Y., Xiao, Z., Feng, J., Gu, Y., Ju, W., Luo, X. and Zhang, M. (2024), "Graph neural networks in intelligent transportation systems: Advances, applications and trends", arXiv, doi: 10.48550/ARXIV.2401.00713.

11. Graf, D., Retschitzegger, W., Schwinger, W., Kapsammer, E., Pröll, B. and Baumgartner, N. (2019), "Towards operational technology monitoring in intelligent transportation systems: Key challenges and research roadmap", in Proceedings of the 11th International Conference on Management of Digital EcoSystems, ACM (MEDES ’19), pp. 237–241, doi: 10.1145/3297662.3365788.

12. Alabi, C. and Ugboya, I. (2024), "Autonomous vehicle sensor network security framework using anomaly detection and resource limitation", SSRN Electronic Journal [Preprint], doi: 10.2139/ssrn.4839942.

13. Ali, W.A., Fanti, M.P., Roccotelli, M. and Ranieri, L. (2023), "A review of digital twin technology for electric and autonomous vehicles", Applied Sciences, Vol. 13, No. 10, pp. 5871, doi: 10.3390/app13105871.

14. Basu, A. and Blanning, R.W. (2007), Metagraphs and Their Applications, Integrated Series in Information Systems, Springer US, doi: 10.1007/978-0-387-37234-1.

15. Li, Z., Zhai, W. and Tan, Q. (2022), "Improved metagraph method of information system process modeling", in 2022 8th International Conference on Big Data and Information Analytics (BigDIA), IEEE, pp. 95–98, doi: 10.1109/bigdia56350.2022.9874046.

16. Lipiński, C. (1983), "Modelling the structure of urban public transport systems by metagraphs", IFAC Proceedings Volumes, Vol. 16, No. 12, pp. 701–705, doi: 10.1016/s1474-6670(17)62179-7.

17. Dindokar, R., Choudhury, N. and Simmhan, Y. (2016), "A meta-graph approach to analyze subgraph-centric distributed programming models", in 2016 IEEE International Conference on Big Data (Big Data), IEEE, pp. 37–47, doi: 10.1109/bigdata.2016.7840587.

18. Ranathunga, D., Roughan, M. and Nguyen, H. (2022), "Verifiable policy-defined networking using metagraphs", IEEE Transactions on Dependable and Secure Computing, Vol. 19, No. 1, pp. 482–494, doi: 10.1109/tdsc.2020.2974727.

19. Hou, Y., Garg, S., Hui, L., Jayakody, D.N.K., Jin, R. and Hossain, M.S. (2020), "A data security enhanced access control mechanism in mobile edge computing", IEEE Access, Vol. 8, pp. 136119–136130, doi: 10.1109/access.2020.3011477.

20. Miller, L., Mérindol, P., Gallais, A. and Pelsser, C. (2021), "Securing workflows using microservices and metagraphs", Electronics, Vol. 10, No. 24, pp. 3087, doi: 10.3390/electronics10243087.

21. Cao, Y., Derrible, S., Le Pira, M. and Du, H. (2024), "Advanced transport systems: The future is sustainable and technology-enabled", Scientific Reports, Vol. 14, No. 1, doi: 10.1038/s41598-024-59438-0.

22. Cui, S., Anric, J., Xue, Y. and Jia, R. (2024), "Enhancing urban logistics through integrated public transit vehicles and unmanned aerial vehicles", in Smart Transportation Systems 2024, Springer Nature Singapore, pp. 1–11, doi: 10.1007/978-981-97-6748-9_1.

23. Yang, L., Dam, K.H. van, Majumdar, A., Anvari, B., Ochieng, W.Y. and Zhang, L. (2019), "Integrated design of transport infrastructure and public spaces considering human behavior: A review of state-of-the-art methods and tools", Frontiers of Architectural Research, Vol. 8, No. 4, pp. 429–453, doi: 10.1016/j.foar.2019.08.003.

24. Katerna, O. (2019), "Intelligent transport system: The problem of definition and formation of classification system", Economic Analysis, No. 29(2), pp. 33–43, doi: 10.35774/econa2019.02.033.

25. Wang, N. and Guo, J. (2021), "Modeling and optimization of multiaction dynamic dispatching problem for shared autonomous electric vehicles", Journal of Advanced Transportation, Edited by Z. Yao, Vol. 2021, pp. 1–19, doi: 10.1155/2021/1368286.

26. Nykl, J., Hrncir, J. and Jakob, M. (2015), "Achieving full plan multimodality by integrating multiple incomplete journey planners", in 2015 IEEE 18th International Conference on Intelligent Transportation Systems, IEEE, doi: 10.1109/itsc.2015.234.

27. Kaneti, V.R., Yamini, B., Nagarajan, S., Adaikkammai, A., Anto Gracious, L.A., Siva Subramanian, R. and Girija, P. (2025), "Smart transportation systems and sustainable urban mobility", in Revolutionizing Urban Development and Governance with Emerging Technologies, IGI Global, pp. 261–288, doi: 10.4018/979-8-3373-1375-7.ch009.

28. Pan, Z., Liang, Y., Wang, W., Yu, Y., Zheng, Y. and Zhang, J. (2019), "Urban traffic prediction from spatio-temporal data using deep meta learning", in Proceedings of the 25th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining, ACM (KDD ’19), pp. 1720–1730, doi: 10.1145/3292500.3330884.

29. Gomes, G., Ugirumurera, J. and Li, X.S. (2020), "Distributed macroscopic traffic simulation with open traffic models", in 2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC), IEEE, pp. 1–6, doi: 10.1109/itsc45102.2020.9294316.

30. Mnushka, O. and Savchenko, V. (2019), "Security model of an information system based on IoT technologies", Bulletin of the National Technical University “KhPI” A Series of “Information and Modeling”, No. 28 (1353), doi: 10.20998/2411-0558.2019.28.09.

31. Mnushka, O. and Savchenko, V. (2020), "Security model of IOT-based systems", in 2020 IEEE 15th International Conference on Advanced Trends in Radioelectronics, Telecommunications and Computer Engineering (TCSET), IEEE, pp. 398–401, doi: 10.1109/tcset49122.2020.235462.

32. Brahmi, Z., Mezni, H., Elmannai, H. and Alkanhel, R. (2025), "Multi-modal vaas selection in smart mobility networks via spectral hyper-graph clustering and quantum-driven optimization", Concurrency and Computation: Practice and Experience, Vol. 37, No. 23–24, doi: 10.1002/cpe.70260.

Статтю представив доктор техн. наук, професор професор кафедри "Системи автоматизованого проектування" Інституту комп'ютерних наук та інформаційних технологій (ІКНІ) НУ "Львівська Політехніка" Щербовських Сергій Володимирови

Надійшла (received) 10.11.2025
Стаття прийнята до друку 15.12.2025
Опублікована 27.03.2026

Mnushka Oksana, Senior Lecturer, M.S. (Computer. Science)
National Technical University "Kharkiv Polytechnic Institute"
2, Kyrpychova str., Kharkiv, Ukraine, 61002
Tel.:(050)2428846, e-mail: mnushka.ov@gmail.com
ORCID ID: 0000-0001-7756-9260

Savchenko Volodymyr, Cand. Sc. (Engineering),
National Technical University "Kharkiv Polytechnic Institute"
2, Kyrpychova str., Kharkiv, Ukraine, 61002
Tel.:(067)5767884, e-mail: savchenko@live.com
ORCID ID: 0000-0001-6548-0891

Povoroznyuk Anatoly, Dr. Sc. (Engineering), Professor
National Technical University "Kharkiv Polytechnic Institute"
2, Kyrpychova str., Kharkiv, Ukraine, 61002
Tel.: +38 (067) 90-21-372, e-mail: anatolii.povorozniuk@khpi.edu.ua
ORCID ID ORCID:0000-0003-2499-2350

УДК 004.056:656.1

Моделювання розподілених транспортних систем на основі метаграфів: моделі, політики та безпека / Мнушка О.В., Савченко В.М. Поворознюк А.І. // Вісник НТУ "ХПІ". Серія: Інформатика та моделювання. – Харків: НТУ "ХПІ". – 2026. – № 2 (16). – С. 126 – 140.

Розподілені транспортні системи (РТС) перетворюються на великомасштабні кіберфізичні платформи, які забезпечують розподілення обробки даних, ухвалення рішень і керування між транспортними засобами, інфраструктурою та хмарними сервісами. Попри зростання масштабованости та стійкости, це ускладнює координацію, інтеграцію й забезпечення безпеки. Узагальнено основні класи моделей, зокрема на основі IoT/edge-технологій: моніторинг, прогнозування, оптимізація, керування та мульти-модальне планування. Поперечний аналіз виявляє прогалини у формалізації. Як уніфікований підхід запропоновано використання метаграфів — математичного апарату для моделювання структурних і процесуальних залежностей, політик і перевірки у розподілених середовищах. Іл.: 1. Бібліогр.: 32 назв.

Ключові слова: розподілені транспортні системи; інтелектуальні транспортні системи; периферійні обчислення; Інтернет речей; оптимізація та керування; навчання на графах; метаграф; політики безпеки

UDC 004.056:656.1

Metagraph-Based Modeling of Distributed Transportation Systems: Models, Policies, And Security / Mnushka O.V., Savchenko V.M., Povoroznyuk A.I. // Herald of NTU "KhPI". Series: Informatics and modeling. – Kharkov: NTU "KhPI" – 2026. – № 2. – P. 126 – 140.

Distributed transportation systems (DTS) are evolving into large-scale cyber-physical platforms that distribute data processing, decision-making, and control across vehicles, infrastructure, and cloud services. While this evolution improves scalability and resilience, it also complicates coordination, integration, and security assurance. Several key classes of models are generalized, including IoT/edge-based monitoring, forecasting, optimization, control, and multimodal planning. Cross-sectional analysis reveals gaps in formalization. As a unifying approach, metagraphs are proposed – a mathematical apparatus for modeling structural and process dependencies, policies, and verification in distributed environments. Figs.: 1. Refs.: 32 titles.

Keywords: distributed transportation systems; intelligent transportation systems; edge computing; Internet of Things; optimization and control; graph learning; metagraph; security policies