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Application of advanced big data analytics technologies to enhance urban transport system reliability

Rohov A.[1], Abramova L.[2], Ptytsia H.[2]

[1] V. N. Karazin Kharkiv National University, Ukraine
[2] Kharkiv National Automobile and Highway University, Ukraine

Abstract. Problem. *Rapid urbanization, increasing traffic flows, and a high rate of road accidents create critical challenges for Ukraine's transport systems. Existing approaches to traffic analysis are unable to process large volumes of data in real time, which reduces prediction accuracy, complicates decision-making, and hinders progress toward sustainable development goals.* ***Goal.*** *The study aims to develop approaches for improving traffic management efficiency through the application of cloud computing and Big Traffic Data analytics, enabling the formation of intelligent systems for adaptive transport control.* ***Methodology.*** *A structural-functional architecture for cloud-based transport analytics is proposed, comprising three interrelated layers: data collection from heterogeneous sources, cloud-based processing using parallel computing technologies and machine-learning algorithms, and visual representation of analytical results through monitoring dashboards to support decision-making. The methodology is further enhanced by incorporating fractal analysis to detect critical states of the transport system and improve predictive modelling accuracy.* ***Results.*** *The research substantiates the potential to reduce data-processing time by 10–20 times and increase the accuracy of traffic flow forecasting by 25–30%. The proposed system can perform adaptive traffic management, automatic accident detection, route optimization, and environmental monitoring.* ***Originality.*** *The study integrates cloud technologies, machine learning, and fractal analysis into a multidisciplinary framework for digital transport analytics. A method for evaluating transport infrastructure performance is introduced, incorporating technical, economic, social, and environmental criteria.* ***Practical value.*** *The findings are valuable for shaping the national digital mobility strategy, developing Smart City infrastructure, enhancing road-safety management, and advancing Sustainable Development Goals. The implementation of the proposed system contributes to increasing the reliability and adaptability of urban transport governance.*

Keywords: *cloud computing, big data, road safety, intelligent transport systems, machine learning, fractal analysis, Smart City, sustainable development.*

Introduction

In modern urban agglomerations, rapid growth in population mobility, traffic intensity, and building density creates critical challenges for urban transport systems. Congested road networks, declining average travel speeds, longer trip durations, uneven traffic flows, and worsening environmental conditions are becoming systemic issues that directly influence quality of life, urban competitiveness, and regional economic productivity. Intensifying traffic also increases the likelihood of critical infrastructure states – precursors of road accidents, sudden congestion, abrupt speed changes, and disruptions to traffic safety.

At the same time, urbanization and the rising spatiotemporal complexity of transport flows require a shift from conventional planning and control approaches. Existing monitoring systems, based on fragmented data, localized observation, and limited computational capacity, cannot support rapid analysis of large infor-

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mation volumes or provide decision-making assistance in real time. Consequently, there is a lack of reliable analytics, which restricts effective traffic management, road-safety improvement, and optimization of urban mobility.

The need to account for the interdependence of technical, social, economic, and environmental factors further complicates decision-making in transport policy. This necessitates the adoption of intelligent, adaptive, and interdisciplinary analytical methods capable of integrating heterogeneous data sources – from sensor networks and video surveillance to GPS tracking, mobile applications, and information derived from road safety audits.

Under these conditions, the use of advanced Big Data processing technologies and cloud computing becomes increasingly relevant, as they provide scalable data handling, rapid analytical output, and the ability to model transport scenarios in real time. Integrating such technologies into traffic management systems enables the development of intelligent transport solutions that enhance network reliability, facilitate proactive risk detection, contribute to reducing accident rates, and support the achievement of urban sustainable development goals.

Analysis of publications

Annually, road traffic accidents lead to losses of up to 3% of GDP, indicating a significant negative impact on the national economy.

The study [1] estimates the macroeconomic burden of road injury across 166 countries and shows that road traffic injuries will cost the global economy USD 1.8 trillion over 2015–2030, due to redirected resources: health-care expenditures that would otherwise support savings and investment, and the loss of labor caused by mortality and morbidity.

International practice demonstrates growing use of cloud services in transport analytics within programs such as EU Smart Mobility, Intelligent Transport Systems (ITS Europe), and the Cloud4Cities initiative [2]. For example, in Singapore, the Smart Mobility 2030 system [3] employs AWS computing clusters to process GPS and video data in real time, reducing emergency response times to as little as three minutes. Similar solutions have been implemented in Barcelona and Helsinki, where cloud analytics is applied for adaptive traffic signal control and CO_2 emission assessment.

International experience confirms that the implementation of cloud analytics in the transport sector not only improves traffic efficiency but also supports road-safety policy, which is a key urban development priority within sustainable cities. Results from international projects indicate that deploying cloud-based analytical platforms in the transport domain [4] helps reduce traffic delays and mitigate the risk of accidents. Similar approaches may be adapted to Ukraine, taking into account regional characteristics of the national transport network.

Modern transport systems represent one of the most dynamic areas of the digital economy, generating massive volumes of data from sensor networks, video-surveillance cameras, GPS trackers, mobile applications, and intelligent transport systems (ITS). These datasets capture spatiotemporal movement parameters, road-user behavior, infrastructure conditions, and environmental indicators. However, traditional computing environments are increasingly inadequate for processing such information flows due to limited local resources, high hardware costs, and latency in obtaining analytical outputs. This creates barriers to timely decision-making and road-safety improvement, especially under accelerating urbanization and rising pressure on the transport infrastructure of Ukrainian cities.

The 2030 Agenda for Sustainable Development sets an ambitious target to reduce road traffic fatalities and injuries by 50% by 2030. The Sustainable Development Goals (SDGs) [5–6] identify transport reliability as a key component of sustainable progress, including in Ukraine, through direct contributions to the achievement of [7]:

- SDG 3 “Good Health and Well-being”, specifically SDG 3.6, which aims to reduce road traffic injuries and fatalities;
- SDG 9 “Industry, Innovation and Infrastructure”, as the development of digital transport analytics promotes innovative infrastructure solutions;
- SDG 11 “Sustainable Cities and Communities”, since increasing the throughput of transport networks by reducing congestion enhances the efficiency of passenger and freight mobility;
- SDG 13 “Climate Action”, because route optimization and reduced CO_2 emissions from the transport sector help lower environmental pollution.

Purpose and Tasks

Addressing this challenge requires improving traffic management efficiency through the application of cloud computing technologies for designing adaptive traffic control systems capable of ensuring both technical road safety and social effectiveness, alongside economic feasibility, through the use of modern information technologies.

The purpose of this study is to enhance traffic management efficiency by applying cloud computing technologies for Big Traffic Data analytics.

Achieving this goal involves developing a structural-functional data architecture for an intelligent transport system capable of integrating heterogeneous information sources, supporting real-time stream processing, and enabling the formation of predictive models of network conditions.

The implementation of this objective relies on integrating cloud platforms, machine-learning algorithms, and fractal analysis into a unified analytical framework. This approach enables the identification of critical system states, early detection of instability within traffic flows, and the development of adaptive traffic-control strategies. Such integration facilitates accident reduction, improved network resilience, and more efficient mobility planning. In addition, it supports the transition toward digital Smart-mobility models that are resistant to cyber threats, capable of learning from incoming data, and aligned with the achievement of sustainable development goals.

Adaptive Traffic Flow Management Under Urban Digital Transformation

In the context of the digital transformation of urban transport systems, the need to introduce innovative approaches to traffic flow management becomes increasingly evident. Growing complexity of the road environment and traffic instability require a shift from static regulation models toward adaptive systems capable of responding to changing conditions in real time. The selection of appropriate management technologies becomes a key factor in ensuring network reliability, as it determines the system's ability to maintain flow stability, prevent overloads, minimize congestion, and enhance road safety.

The use of cloud platforms and Big Data analytics expands the capabilities of adaptive management by enabling the integration of heterogeneous information sources, prediction of traffic behavior, and decision-making based on high-precision analytical insights. This establishes the foundation for socially oriented and environmentally responsible transport policies that help reduce accident rates, lower emissions, and improve mobility quality for road users.

The application of adaptive traffic management in cities involves addressing several priority tasks:

– improving the efficiency of urban transport network operation;

– maintaining the required level of road safety as an essential condition within traffic management processes;

– increasing transport network reliability, where failure is understood as the loss of the system's ability to perform its core function – ensuring continuous vehicle movement along established routes;

– enhancing environmental safety.

Adaptive traffic management methods [8] encompass both software-based and software-adaptive approaches that enable flexible system responses to changing road conditions. The primary objective of such systems is the dynamic optimization of traffic flows at intersections within the road network, based on real-time situation analysis and future condition forecasting. The formalization of adaptive control relies on a management function that automatically adjusts in real time. This function considers current traffic intensity, time of day, weather conditions, incident occurrences, and the load level of each intersection approach. Unlike conventional systems with fixed signal cycles, adaptive management allows rapid adjustment of signal timings in response to traffic fluctuations. Traditional traffic-control systems do not always ensure sufficient network throughput, which is why innovative approaches based on smart technologies, artificial intelligence algorithms, and real-time regulation are capable of transforming the traffic-management paradigm.

Cloud-Based Technologies and Intelligent Transport Analytics in the Smart City Framework

The Smart City concept aims to enhance the efficiency of urban infrastructure management, reduce environmental pressures, and improve citizens' quality of life through digital technologies. One of its core components is the development of transport infrastructure that integrates intelligent control systems, sustainable mobility, and environmentally oriented solutions.

Innovative approaches to managing emergency situations on road networks – based on smart technologies such as AI, IoT, edge computing, V2I/V2V communication, and intelligent modelling – enable a new level of safety and responsiveness. Instead of reacting after incidents occur, systems can transition toward a predictive mode in which hazardous scenarios are anticipated and addressed before fully materializing. Although significant economic, technical, organizational, and security barriers exist, prospects for overcoming them are realistic and strategically important. In this context, cloud computing technologies play a crucial enabling role.

Cloud computing technologies open new opportunities for Big Traffic Data analytics by providing scalable, flexible, and accessible computational capacities in real time. Cloud platforms enable the integration of heterogeneous information sources, distributed processing of data streams, and the development of intelligent traffic management models.

Overall, the digitalization of transport data carries not only technological but also socio-environmental priorities. Thus, integrating cloud computing into urban transport systems represents an essential step in the digital transformation of transport infrastructure aimed at enhancing safety, environmental resilience, and alignment with global sustainable development goals.

Cloud computing is defined by the U.S. National Institute of Standards and Technology (NIST) as a model for convenient network-based access to shared computing resources with minimal management effort [9]. This technology relies on principles of virtualization, distributed processing, and service orientation. In the transport domain, cloud platforms support the integration of distributed data sources, enabling a unified environment for processing streaming information [10]. The Big Data concept encompasses not only data volume but also analytical methods that transform unstructured information into actionable knowledge. For transport systems, this includes time-series analysis, route clustering, anomaly detection, and traffic flow optimization [11–12].

In general, cloud computing is viewed as a model for accessing computing resources over the Internet, implemented on an on-demand basis and encompassing three service layers – Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS). For the transport sector, this enables scalable real-time data processing without the need to maintain local data centers. In combination with the Big Data concept, cloud technologies provide the foundation for intelligent transport systems capable of analyzing traffic flows in real time, forecasting changes, and optimizing road infrastructure. With the advancement of artificial intelligence tools, cloud technologies extend beyond classical analytics by providing intelligent prediction of traffic conditions.

Big Traffic Data is characterized by high levels of Volume, Velocity, Variety, and Veracity, which necessitate the use of parallel and distributed computing methods. At this stage, technologies such as Hadoop, Apache Spark, and MapReduce operate effectively, enabling multithreaded processing of data streams.

A significant and promising direction is the integration of cloud infrastructure with artificial intelligence tools. To forecast traffic intensity, recurrent neural networks such as Long Short-Term Memory (LSTM) models are useful, as they can capture temporal dependencies. Meanwhile, convolutional neural networks (CNNs) support automated analysis of video streams from surveillance cameras, including object detection and anomaly recognition. Therefore, embedding artificial intelligence into transport data analytics forms the basis of next-generation predictive systems.

The study introduces a structural–functional architecture for a cloud-based transport data analytics system aimed at improving urban traffic management efficiency. The proposed approach is grounded in the need to consolidate fragmented information streams into a unified analytical environment capable of supporting real-time situational awareness and informed decision-making. By integrating heterogeneous data sources – from sensor grids and video analytics to mobile applications and safety audits – the system enables a shift from reactive to predictive traffic control. The architecture is conceptualized as a multilayer analytical framework in which each level performs a distinct function while contributing to a continuous information cycle that spans data collection, preprocessing, modelling, visual interpretation, and managerial action:

1. Data Collection Layer. At this stage, the initial dataset is formed from diverse sources, including sensor networks, GPS trackers, urban video-surveillance systems, mobile applications, and traffic monitoring platforms. A significant contribution to this layer comes from road safety audit results, which provide information on deficiencies and violations in traffic organization.

2. Cloud Processing Layer. The collected data are transmitted to cloud infrastructure (AWS, Azure, Google Cloud, etc.), where preliminary cleansing, filtering, aggregation, and analytical processing take place. This stage employs tools for parallel and distributed computing (Hadoop, Apache Spark) and machine-learning algorithms (TensorFlow, PyTorch). It ensures scalability, high performance, and the capability to handle streaming data in real time.

3. Visualization and Decision-Making Layer. Analytical results are integrated into visualization systems (Power BI, Grafana, Google Data Studio), which generate interactive dashboards displaying indicators such as traffic volume, average speed, congestion index, CO_2 emissions, and accident hotspots. This layer serves as the interface between the analytical system and end users – dispatchers, analysts, and traffic authorities – supporting the development of measures to improve road safety management.

At the practical level, the system can perform functions such as congestion forecasting and optimization of public transport routing; automatic accident detection and real-time monitoring of video streams; assessment of traffic organization effectiveness with respect to temporal and spatial patterns; and environmental monitoring of transport flows within the context of sustainable development. Expected outcomes of cloud-based analytics implementation include:

– a 10–20-fold reduction in data-processing time;

– a 25–30% increase in the accuracy of traffic flow forecasting;

– reduced accident rates through proactive risk identification;

– enhanced assessment of traffic conditions to support improved road-safety management.

Cybersecurity and Information Resilience in Intelligent Transport Systems

The integration of artificial intelligence technologies into transport infrastructure requires consideration of cybersecurity and comprehensive protection of information flows. Since intelligent systems rely on the processing, analysis, transmission, and storage of large data volumes in distributed environments, their vulnerability to risks such as unauthorized access, data manipulation, targeted attacks, and disruption of control algorithms increases. Consequently, ensuring the reliability of digital infrastructure becomes a critical factor for the effective functioning of adaptive traffic management systems.

Robust data protection, encrypted communication channels, network segmentation, and access control mechanisms are essential not only from a technical but also from a social perspective. These safeguards maintain the operational stability of integrated transport systems, prevent manipulation of traffic indicators, minimize the risk of interference with signal control or dispatching services, and protect user privacy. Preserving trust among road users and transport authorities is a key condition for successful mobility digitalization, as data security directly influences the perceived legitimacy of intelligent systems and societal readiness to adopt them.

Thus, the development of cyber-resilient Smart solutions in the transport sector must be accompanied by technical, administrative, and regulatory measures, including security audits, continuous monitoring of network risks, standardization of access procedures, and responsible application of machine-learning tools. This approach not only preserves system reliability but also supports its evolution toward greater safety, transparency, and accountability within urban mobility.

Thus, the comprehensive modernization of infrastructure, deployment of intelligent technologies, development of digital services, and ensuring data security form the basis for effective operation of integrated systems in contemporary cities. However, increasing technological complexity and the digitalization of traffic management create the need to address emerging threats arising in cyber, information, and technical domains.

Cyber threats may manifest as unauthorized access, malware attacks, distributed denial-of-service (DDoS) assaults, or data interception and substitution. Information threats include theft or falsification of telemetry data and manipulation of statistics to influence decision-making.

Cybersecurity is a central component of safety within automated traffic control systems (ATCS) and begins with system architecture. All ATCS components are segregated into isolated segments: the sensor network, transport network, control layer, and analytical center, each with distinct access policies and network rules. Firewalls, security gateways, and traffic-control mechanisms operate between segments to prevent attack propagation in the event of local intrusion. Data transmission between sensors, controllers, and central nodes relies on modern protocols such as TLS 1.3 and PKI-based certification. Each device possesses its own digital key to verify authenticity. The Zero Trust principle (no implicit trust) enables detection of internal threats, for instance when a device is compromised or replaced.

Furthermore, ATCS incorporate monitoring and incident response mechanisms. Specialized SIEM platforms collect event logs, analyze anomalies, and generate alerts for operators. If an intrusion attempt affects traffic control on a specific section, the system can be temporarily switched to local mode. Finally, cybersecurity includes secure software updates: patches are tested in a digital twin of the city and then deployed to the operational system through signed over-the-air (OTA) packages.

Information security and data protection are grounded in three fundamental principles: confidentiality, integrity, and availability (the CIA model). Any distortion of or unauthorized access to ATCS data can lead to technical failures and erroneous managerial decisions. Confidentiality is ensured through encrypted communication channels, access control mechanisms, and user authentication. Integrity guarantees that no data packet can be altered or substituted without detection – this is achieved using hash checks, digital signatures, and audit logs. Availability implies that critical data must be accessible when required, which is ensured through backup systems, geographically distributed servers, and cloud storage.

An important task is the protection of personal data in accordance with anonymization policies and storage requirements under GDPR and the Law of Ukraine "On Personal Data Protection" [14]. Another priority is securing analytical systems and databases, which is achieved through multi-factor authentication, role-based access control (RBAC), access logging, and automatic detection of suspicious requests.

Achieving high accuracy in traffic forecasting requires combining analytical and neural network approaches. In particular, alongside algorithmic methods, a fractal approach is proposed for describing traffic flows as self-organizing structures. Fractal analysis in transport research is based on principles of nonlinear dynamics, wherein traffic flows are viewed as self-organized systems exhibiting scale invariance. The fractal dimension *Df* enables quantitative assessment of system complexity and its tendency toward chaotic behavior [15]. Changes in this indicator may signify a transition from stable to critical states, such as prior to congestion formation. Combining fractal geometry with chaos-based modelling allows researchers to describe transport dynamics that do not adhere to linear patterns.

In Ukraine, cybersecurity regulation is governed by the Law "On the Basic Principles of Ensuring Cybersecurity of Ukraine" [16] and a range of subordinate acts establishing requirements for critical infrastructure. As automated traffic control systems (ATCS) directly influence road safety, they are classified as critical infrastructure objects, meaning their components must undergo mandatory cybersecurity certification. Compliance with international standards is essential not only from a legal standpoint but also from a practical perspective. The use of certified encryption algorithms, implementation of information security policies aligned with ISO 27001, and development of update protocols collectively strengthen system credibility and support its integration into international transport infrastructure.

The security of automated traffic control systems in contemporary conditions represents a synthesis of technology, organizational maturity, and a culture of accountability. ATCS are no longer isolated local networks – they interact with cloud services, vehicles, mobile applications, artificial intelligence solutions, and even individual citizens through digital mobility services. Therefore, trust built through transparency, verification, and controlled access becomes a fundamental principle for their future development.

In the coming years, traffic management platforms will increasingly integrate artificial intelligence, autonomous decision-making capabilities, and vehicle-to-infrastructure communication (V2I/I2V). This evolution requires a significantly higher level of protection – not merely reactive, but predictive in nature. Security models will be trained alongside operational control models, forming adaptive defense environments capable of independently detecting risks, modifying access policies, and responding to emerging threats without human intervention.

Thus, ATCS security is an integral component of the evolving digital transport ecosystem. Its sustainability depends on the integration of cybersecurity practices, standardization of data exchange, and continuous monitoring of system integrity. These measures ensure the stability of smart transport solutions and enhance the reliability, resilience, and safety of urban mobility.

Conclusions

In the context of Ukraine's development, particularly in the post-war period, the implementation of modern information technologies is a necessary step to minimize losses caused by road traffic accidents and to ensure the adaptability of transport infrastructure to emerging challenges.

Therefore, the use of cloud computing within the transport system constitutes a key direction of the digital transformation of road infrastructure. The combination of cloud technologies, neural networks and fractal analysis not only improves traffic management efficiency but also enables the creation of an intelligent environment for adaptive traffic regulation. The real-time deployment of such systems is expected to enhance road safety, reduce infrastructural stress and support the transition towards resilient models of urban mobility.

The conducted research demonstrates that the integration of cloud technologies and big traffic data analytics enables a shift from reactive to proactive traffic management, increasing predictive capability and improving the reliability of transport networks. This technological model aligns with Sustainable Development priorities, contributing to the achievement of SDGs 3, 9, 11 and 13 by supporting road safety, infrastructure innovation, environmental resilience and overall quality of urban life. This confirms that the digital transformation of transport analytics has not only technological but also social significance.

The research findings may be applied to the development of a national digital mobility strategy and Ukraine's integration into the European ITS framework. In the long term, the establishment of a national cloud-based traffic management platform can be proposed, which would integrate data from regional systems, enable a unified analytical center and reinforce Smart City principles.

Future research should focus on refining methodological approaches to evaluating the effectiveness of intelligent transport systems, developing adaptive control models for various urban environments, and identifying mechanisms for integrating big data technologies into public policy for urban mobility.

Conflict of interests

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

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Rohov Andrii [1], CSc (Eng.), Assoc. Prof., Department of Information Technologies and Mathematical Modeling, ESI «Karazin Banking Institute»
e-mail: a.v.rogov@karazin.ua,
Phone.: +38 (099) 440-54-70,
ORCID: http://orcid.org/0009-0009-3972-4931
Abramova Liudmyla [2], DSc (Eng.), Prof., Department of Traffic Management and Road Safety,
e-mail: abramova_ls@ukr.net,
Phone.: +38 (097) 465-35-43,
ORCID: https://orcid.org/0000-0003-1182-9618
Ptytsia Hennadii [2], CSc (Eng.), Assoc. Prof., Department of Traffic Management and Road Safety,
e-mail: gennadij.ptitsa@ukr.net,
Phone.: +38 (050) 633-58-93,
ORCID: http://orcid.org/0000-0002-5061-0144

[1] V. N. Karazin Kharkiv National University, Svobody Sq., 4, Kharkiv, Ukraine, 61022
[2] Kharkiv National Automobile and Highway University, Yaroslava Mudrogo str., 25, Kharkiv, Ukraine, 61002

Застосування новітніх технологій аналізу великих даних для підвищення надійності транспортної системи міста

Анотація. Проблема. *Стрімка урбанізація, зростання транспортних потоків і високий рівень аварійності формують критичні виклики для транспортних систем України. Наявні методи аналізу дорожнього руху не здатні оперативно обробляти великі обсяги даних, що знижує точність прогнозів, ускладнює ухвалення управлінських рішень і перешкоджає досягненню цілей сталого розвитку.* ***Мета.*** *Розроблення підходів до підвищення ефективності управління дорожнім рухом через застосування хмарних обчислень і аналітики великих транспортних даних для формування інтелектуальних систем адаптованого управління транспортним потоком.* ***Методологія****. Запропоновано структурно-функціональну архітектуру хмарної транспортної аналітики, що охоплює три взаємопов'язані рівні: збір даних з різнорідних джерел, їх обробку в хмарних платформах із застосуванням технологій паралельних обчислень і машинного навчання, а також візуалізацію результатів у системах моніторингу для підтримки рішень. Методологію доповнено пропозицією використання фрактального аналізу для виявлення кризових станів транспортної системи та покращення прогнозних моделей.* ***Результати****. Обґрунтовано потенціал скорочення часу обробки даних у 10–20 разів і підвищення точності прогнозування інтенсивності руху на 25–30%. Система здатна виконувати функції адаптивного управління трафіком, автоматичного виявлення ДТП, оптимізації маршрутів і моніторингу екологічних показників.* ***Оригінальність****. Дослідження поєднує хмарні технології, машинне навчання та фрактальний підхід, створюючи міждисциплінарну модель цифрової транспортної аналітики. Запропоновано метод оцінювання транспортної інфраструктури з урахуванням технічних, економічних, соціальних і екологічних критеріїв.* ***Практичне значення****. Результати є корисними для формування національної стратегії цифрової мобільності, розвитку Smart City, удосконалення управління безпекою дорожнього руху та реалізації Цілей сталого розвитку. Впровадження системи сприятиме підвищенню надійності та адаптивності управління транспортною мережею.*

Ключові слова: *хмарні обчислення, великі дані, безпека дорожнього руху, інтелектуальні транспортні системи, машинне навчання, фрактальний аналіз, Smart City, сталий розвиток.*

Рогов Андрій Володимирович [1], к.т.н., доцент кафедри інформаційних технологій та математичного моделювання ННІ «Каразінський банківський інститут»
e-mail: a.v.rogov@karazin.ua,
тел.: +38 (099) 440-54-70,
ORCID: http://orcid.org/0009-0009-3972-4931
Абрамова Людмила Сергіївна [2], д.т.н., професор кафедри організації та безпеки дорожнього руху,
e-mail: abramova_ls@ukr.net,
тел.: +38 (097) 465-35-43,
ORCID: https://orcid.org/0000-0003-1182-9618
Птиця Геннадій Григорович [2], к.т.н., доцент кафедри організації та безпеки дорожнього руху,
e-mail: gennadij.ptitsa@ukr.net,
тел.: +38 (050)633-58-93,
ORCID: http://orcid.org/0000-0002-5061-0144

[1] Харківський національний університет імені В. Н. Каразіна, пл. Свободи, 4, м. Харків, Україна, 61022
[2] Харківський національний автомобільно-дорожній університет, вул. Ярослава Мудрого, 25, м. Харків, Україна, 61002