THE ROLE OF INTELLIGENT SAFETY SYSTEMS IN THE TRANSPORTATION OF HAZARDOUS CHEMICALS: THE INTEGRATION OF IOT AND ARTIFICIAL INTELLIGENCE

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Abstract. The article examines the role of intelligent safety systems in the transportation of hazardous chemicals through the integration of the Internet of Things and artificial intelligence technologies. The purpose of the study is to substantiate the role of intelligent safety systems in transporting hazardous chemicals by integrating IoT and AI technologies to minimize risks, improve transportation management efficiency, and ensure environmental safety. The research employed general scientific methods of cognition, including analysis, synthesis, a systematic approach, generalization, comparison, and forecasting. The article demonstrates that sensor networks, wearable devices, and smart packaging enable timely detection of deviations in cargo conditions, environmental parameters, and personnel's physiological indicators. It has been shown that the combination of IoT with AI technologies creates a qualitatively new level of safety management. AI enhances IoT by transforming collected data into predictive models and intelligent managerial decisions. The study concludes that optimization algorithms and machine learning make it possible to design routes that take into account economic, environmental, and safety aspects, as well as to predict potential risks and quickly adapt transportation strategies to changing conditions. It has been proven that such integration facilitates the development of comprehensive decision-support systems that minimize accidents, reduce costs, and limit the negative environmental impact. The practical significance of the study lies in the possibility of implementing integrated intelligent safety systems to enhance the efficiency of hazardous cargo transportation management and to reduce environmental and social risks.

Keywords: Internet of Things, artificial intelligence, safety, chemical cargo, logistics.

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Introduction

Current trends in the transportation of hazardous chemicals require the implementation of high-tech solutions to enhance safety and reduce risks for people and the environment. According to international studies, nearly 90% of road accidents are caused by human factors [7]. This highlights the critical need for automation of transportation processes and the introduction of intelligent systems capable of minimizing human error. The development of the Internet of Things (IoT) offers new opportunities for the transport sector, as sensor networks and communication protocols enable real-time data collection and transmission. The emergence of the 5G standard, which ensures ultra-fast communication, is of particular importance [8]. In addition, the LoRa protocol allows long-distance monitoring with minimal energy consumption, creating prospects for large-scale systems that track hazardous cargo conditions during transportation [8]. At the same time, integrating IoT with artificial intelligence technologies enables not only control but also risk prediction of accidents. In the field of environmental safety, such systems can detect even minimal leaks of hazardous substances into the air, water, or soil, which is crucial for preventing catastrophic consequences [6].

Thus, the relevance of the study is driven by a combination of factors: the high accident rate caused by human factors; the emergence of new technological solutions in IoT and 5G communication; and the growing role of artificial intelligence in monitoring, forecasting, and risk management. The integration of these approaches in the transportation of hazardous chemicals provides a qualitatively new level of safety, making this topic particularly significant in both scientific and practical contexts.

Literature Review

The issue of intelligent safety systems in the transportation of hazardous chemicals through the integration of IoT and AI technologies has been widely studied in international academic literature. Significant contributions have been made in research focused on route optimization, the development of intelligent transport systems, and the application of IoT platforms and AI methods for risk minimization and emergency management. F. Chen and Q. Zhu [1] emphasized intelligent route optimization methods for transporting hazardous materials under multi-criteria constraints, allowing systems to adapt flexibly to changing transport conditions. A similar approach was developed by L. Liu, S. Sun, and S. Li [5], who applied a conditional value-at-risk model to optimize railway routes for hazardous substances, highlighting the principle of risk distribution. Meanwhile, Z. Zou and S. Kang [10] analyzed routing under variable traffic flows, providing a valuable addition to modern safe logistics solutions. Another research direction concerns the implementation of intelligent technologies for crisis management. A. Fruhling et al. [2] presented in the REaCH report an emergency communication system for HAZMAT incidents, ensuring rapid response through integrated digital communication channels. Additionally, S. Yu, Y. Li, and Z. Xuan [9] proposed the use of deep neural networks (GRU-DNN) for real-time risk assessment, integrating multi-channel sensor data. Studies focused on IoT integration in monitoring and traffic management are also of high importance. H. Karthikeyan and G. Usha [4] described a cognitive-oriented IoT architecture for intelligent transport systems, providing secure data transmission and adaptive management. Similarly, D. Witczak and S. Szymoniak [8] analyzed IoT-based monitoring systems that improve reliability in hazardous cargo transportation.

Research on monitoring environmental risks is also noteworthy. S.M. Popescu et al. [6] examined the synergy of IoT and AI for pollution tracking, directly related to hazardous material transport safety. In their report, M. Hollifield, P. Blanton, and B. Barnett [3] developed the concept of “smart packaging” for energy cargo, showing how sensor systems can be combined with transport infrastructure to increase transparency and safety in logistics. An important foundational source is the UNECE report [7], which outlines key directions for developing intelligent transport systems to ensure sustainable and safe hazardous material transportation globally.

The study also relied on expert literature, including publications in contemporary online editions, covering relevant aspects of AI solutions in logistics and IoT applications in risk monitoring. Despite the abundance of scientific sources, there is still a lack of systematized material on the comprehensive integration of intelligent safety systems in hazardous chemical transportation. For this reason, information was analyzed, grouped, and presented in line with the study's theme using various scientific methods.

Methodology and Methods

The methodology is based on a systemic and interdisciplinary approach combining transport safety, information technologies, and environmental risk analysis. To achieve the study's purpose, methods applied included content analysis of academic publications and international reports, comparative analysis of route optimization models and risk management systems, and generalization of IoT and AI implementation experience in transportation. Classification and systematization methods were also used to identify key directions of intelligent safety system integration, as well as a predictive approach for evaluating future technological development in hazardous chemical transportation.

The purpose of the study is to substantiate the role of intelligent safety systems in hazardous chemical transportation through IoT and AI integration in order to minimize risks, improve transportation management efficiency, and ensure environmental safety. *The research tasks* include analyzing current scientific approaches to route optimization and risk assessment; examining IoT and sensor network applications for monitoring cargo conditions and transport infrastructure; identifying the potential of artificial intelligence in accident prediction and response; and summarizing international experience of intelligent transport system implementation to form a comprehensive safe logistics model for hazardous substances.

Research Results

Intelligent safety systems in the transportation of hazardous chemicals represent comprehensive technological solutions that integrate automation tools, artificial intelligence, and the Internet of Things. Their primary task is to ensure safe and controlled movement of vehicles carrying dangerous cargo, minimize accident risks, prevent leaks, and reduce harm to people and the environment. At their core, such systems develop the concept of Intelligent Transport Systems (ITS), seen as an extended format of Vehicular Ad Hoc Networks (VANET), which enable automated, cooperative, and connected mobility management. By integrating cognitive science mechanisms to distinguish legitimate users from potentially malicious actors, they enhance the level of information security and data protection in IoT-ITS environments [4].

Several key groups of intelligent safety systems can be distinguished. First are IoT-based monitoring and control systems, which use sensors and communication protocols to collect and transmit real-time data. These include solutions based on wireless technologies such as Wi-Fi, Bluetooth, Zigbee, GSM, as well as modern mobile standards, particularly 5G, which provides low latency and high bandwidth. The LoRa protocol is also widely used, allowing long-distance data transmission with minimal energy consumption [8]. Second are predictive maintenance subsystems, where sensors collect data on vehicle conditions and machine learning algorithms analyze these parameters to forecast failures or accidents. Third are environmental monitoring systems, which, by combining IoT and AI, detect hazardous emissions into air, water, or soil. These approaches employ a wide range of sensors – from photoionization to ultrasonic – and can identify even minimal deviations in real time [6].

In practice, intelligent safety systems are being widely implemented in the transport sector at the global level. For example, under United Nations initiatives, international ITS standards are being developed and adopted, covering automated, connected, and cooperative transport technologies. Modern solutions include features such as automatic emergency braking, stability control systems, lane-keeping assistants, and collision warning systems. An important area is the use of sensor technologies to detect and respond to transport events, ranging from lidars and radars to cameras and inertial measurement units. With these technologies, vehicles can perceive their surroundings, classify objects, and perform dynamic responses without direct human intervention [7].

Thus, intelligent safety systems can be defined as interdisciplinary technological complexes that combine sensor networks, AI algorithms, and communication platforms for monitoring, forecasting, and preventing incidents in hazardous chemical transportation. They are based on IoT integration principles, provide automated control and decision-making, address both cyber risks and environmental safety, and today are becoming one of the key tools for enhancing the resilience and safety of transport systems worldwide.

The Internet of Things (IoT) in the transportation of hazardous chemicals in the United States is regarded as a key tool for improving safety, monitoring cargo conditions, and protecting people involved in transportation. Its applications cover both monitoring the health and condition of first responders during emergencies and controlling packaging and movement of hazardous materials. For instance, within the REaCH project (Real-Time Emergency Communication System for HAZMAT Incidents), a system was developed and tested that integrates various IoT sensors to track rescuers' health and physiological indicators during hazardous chemical incident response [2]. A crucial component is wearable technologies, which allow real-time monitoring of parameters such as body temperature, heart rate, blood pressure, oxygen saturation, and other physiological indicators. Examples include telemetry capsules for measuring core body temperature, Zero Heat-Flux sensors for non-invasive temperature monitoring, AliveCor Kardiaband smart bracelets for ECG recording, and multifunctional Zephyr sensor modules that gather and transmit data on heart rate, respiration, temperature, and even responder location [2]. These technologies are particularly important in conditions where personal protective equipment (PPE) creates risks of heat stress and serious health complications for first responders. In this case, IoT sensors become a tool for risk prevention and improving HAZMAT incident response efficiency.

Another area of development is Smart Packaging (SP), introduced under the SPaCES project (Smart Packaging for Critical Energy Shipments). The concept transforms packaging of hazardous cargo, including radioactive materials, into a "smart" platform equipped with sensors and communication modules [3]. Unlike traditional monitoring systems relying on external devices that can be easily damaged or disconnected, SPaCES integrates sensors directly into container structures. This enables real-time monitoring of temperature, pressure, vibration, gas levels, packaging condition, and geolocation during transportation. IoT technologies within SP provide remote data access and generate alerts in cases of packaging damage or critical events (fire, mechanical impacts, flooding, etc.).

Two technologies combining AI methods with practical risk management tasks are actively applied today in hazardous chemical transportation. The first is GRU-DNN with multimodal feature embedding, described by Yu et al. (2022) [9]. It is used for real-time risk assessment during hazardous material transport and integrates GPS data, onboard camera video, vehicle sensor readings, and driver behavior characteristics. This approach enables detection of potential threats in dynamic conditions, prediction of accidents, and provision of actionable information to transport administrations for rapid intervention. In practice, the technology is already employed in China's road transport systems, where equipping tankers with GPS trackers and cameras is mandatory, allowing integration of data into AI-based monitoring systems. The second technology is Conditional Value-at-Risk (CVaR) with risk equity principles, presented by Liu et al. (2025) [5]. It is applied in rail transport of hazardous cargo, where accident probability is relatively low but consequences are catastrophic. CVaR accounts not only for average risks but also worst-case scenarios, helping minimize extreme outcomes. Additionally, it incorporates the principle of equitable risk distribution, ensuring risks are fairly spread across regions and communities potentially affected by accidents. This makes transport planning more socially responsible and aligned with modern environmental and social safety requirements.

A significant contribution to innovative approaches was made by Tamara Kovryzhenko, author of the "SafeAgroLogistics" methodology, which proposes a multi-level model of preventive safety in transporting agrochemicals and other hazardous cargo. Its essence lies in comprehensive use of:

IoT sensors for real-time monitoring of physicochemical parameters (temperature, pressure, vibration, container tightness);

AI predictive analytics algorithms capable of identifying deviations from regulatory indicators and forecasting accident probability before occurrence;

intelligent routing that considers population density, environmentally vulnerable areas, and road infrastructure condition;

the "smart emergency" automated response system, which provides instant notification of emergency services and stakeholders when threats are detected.

In the scientific context, this methodology serves as an example of an integrated transport safety approach that addresses several tasks simultaneously:

improving transportation safety levels through continuous monitoring of key parameters and predicting potential incidents;

protecting the environment by enabling rapid response and preventing the spread of toxic substances;

optimizing economic processes by reducing accident-related costs and improving routes, lowering expenses by 15–20%;

enhancing personnel training through specialized programs focused on handling agrochemicals and high-risk hazardous substances.

Thus, the "SafeAgroLogistics" methodology (author – Tamara Kovryzhenko) demonstrates that IoT and AI integration in transport safety is moving from conceptual solutions to practical implementation. It confirms the key thesis of the study: the role of intelligent safety systems lies not only in event recording but also in active prediction and prevention, which has strategic importance for national and environmental security.

Table 1 – Integration of IoT and AI in the "SafeAgroLogistics" intelligent safety system

Stage / Component	IoT technology	AI algorithms	Result / Value for safety
Cargo condition monitoring	temperature, pressure, vibration, and container tightness sensors	real-time big data analysis	detection of deviations from the norm, early warning
Risk assessment	data transmission to a central platform	predictive analytics (machine learning, neural networks)	forecasting of accidents before their occurrence
Transportation routing	GPS trackers, motion sensors	route optimization considering population density and eco-zones	minimization of social and environmental risks
Incident	"smart emergency"	critical event	instant notification of

response	system (automatic notification)	recognition algorithms	emergency services and clients
Personnel control	biometric sensors, surveillance cameras	AI-based driver condition analysis (fatigue, focus, reactions)	prevention of accidents caused by human factors
Environmental monitoring	emission and leakage sensors	modeling of pollution spread scenarios	rapid reduction of environmental damage
Economic optimization	container load sensors	logistics process optimization algorithms	15–20% cost reduction, decrease in empty runs

Thanks to IoT solutions within SPaCES, situational awareness of operators and safety services is significantly improved, allowing timely response to deviations from normal transportation conditions. For instance, in cases of lost or damaged hazardous cargo, such as the 20-pound package of radioactive materials in the USA in 2010 or the lost cesium-137 capsule in Australia in 2023, the integration of sensor technologies into packaging would have enabled rapid problem detection and risk localization [3].

Artificial intelligence in hazardous chemical logistics plays a crucial role in solving the problem of optimizing transport routes, which are characterized by multi-criteria requirements and high risk levels. The complexity of such transportation lies in the need to simultaneously account for economic, safety, and environmental factors, as well as dynamic changes in the transport environment. In the study by Chen & Zhu (2025), an intelligent route optimization method was proposed for multimodal transport networks under multi-criteria constraints [1]. The authors developed a three-objective integer programming model, solved using an enhanced multi-criteria algorithm. Thus, AI ensures balanced consideration of multiple criteria (cost, safety, number of transshipments) and creates a foundation for automated decision-making in complex transport environments.

Another approach is presented in the work of Zou & Kang (2024), which focuses on route optimization for hazardous chemical transportation under time-varying conditions [10]. The authors note that China's transport system has a high number of accidents: from January to October 2021 alone, 344 incidents involving hazardous chemical transport were recorded, and a tanker explosion in 2020 caused 20 deaths, 175 injuries, and direct damages amounting to 94.78 million yuan. In response to these risks, they proposed a multi-objective vehicle routing problem (MOVRP) model that considers transport costs, accident risks, and CO_2 emissions. The problem is solved using an improved algorithm that integrates time-varying data (traffic, population density, road conditions). This approach allows simultaneous minimization of costs, accident risks, and environmental impacts, aligning with global sustainable development requirements.

Therefore, the role of AI lies not only in mathematical route optimization but also in building comprehensive decision-support systems that balance economic efficiency, safety, and environmental responsibility.

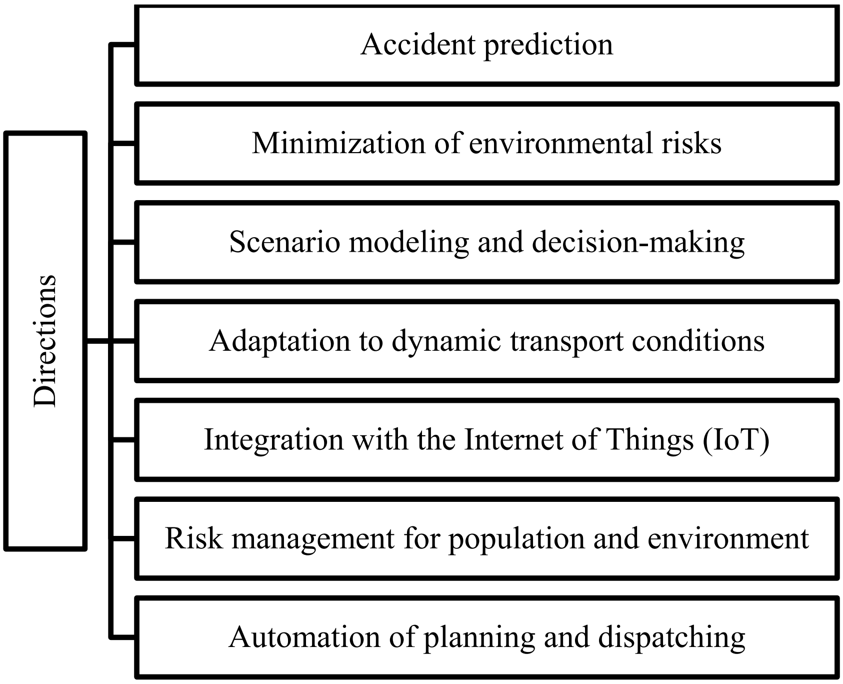

Fig.1. Directions of AI application in hazardous material transportation

Conclusions

The Internet of Things (IoT) in hazardous chemical transportation forms a new safety paradigm based on continuous monitoring, real-time data collection, and processing. The use of sensor networks, wearable devices, and smart packaging enables timely tracking of cargo condition, environmental parameters, and personnel's physiological indicators. This not only allows early detection of deviations but also prevents the development of accidents, improving responsiveness and ensuring the protection of both people and the environment. IoT integrates transportation into a unified information ecosystem that helps reduce risks and ensures transparency of logistics processes.

Artificial intelligence complements IoT by transforming collected data into predictive models and intelligent decisions. With optimization algorithms and machine learning, AI enables the design of routes that consider economic, environmental, and safety criteria, predicts risks, and adapts transportation strategies to dynamic conditions. This makes it possible to create comprehensive decision-support systems that reduce accident likelihood, optimize costs, and minimize environmental consequences. Combined with IoT, AI technologies ensure the transition from reactive to proactive models of transport safety management, meeting modern requirements of sustainable development and global logistics.

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