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The impact of road infrastructure wear on the safety and efficiency of freight transportation

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Abstract Problem. *The growing intensity of freight transportation in the Almaty region, combined with frequent vehicle overloading and insufficient road infrastructure capacity, accelerates pavement deterioration, increases transport and logistics costs, reduces road safety, and decreases traffic efficiency.* ***Purpose:*** *This study aims to assess the influence of road infrastructure conditions and parameters on freight traffic organization in the Almaty region and to identify measures for improving the durability, safety, and efficiency of the road transport network.* ***Methodology:*** *The research is based on the analysis of scientific publications, statistical data, and regulatory-technical documents. The study examines the relationship between pavement deterioration, road capacity, traffic safety, and vehicle operating conditions. Key factors analyzed include axle loads, road category, freight traffic intensity, geometric road parameters, and seasonal maintenance quality. A comparative review of domestic and international practices was also conducted.* ***Results:*** *The study identified that overloaded heavy vehicles, insufficient pavement bearing capacity, low material quality, and adverse climatic conditions are the main causes of rutting, cracking, and surface destruction in the Almaty region. It was also found that steep grades, narrow carriageways, insufficient lane numbers, and poorly designed intersections reduce road capacity and increase freight delivery times. The research highlights the importance of automated weight-control systems, digital pavement monitoring, intelligent transport systems, and optimized traffic-distribution schemes.* ***Originality:*** *The article provides a comprehensive assessment of the combined influence of infrastructure condition, climatic factors, and freight traffic intensity on road-network performance in the Almaty region, while proposing integrated measures for sustainable freight traffic management and pavement preservation.*

Keywords: *road infrastructure, freight transport, road pavement, axle load, traffic management, freight transportation.*

Introduction

The development of road infrastructure is one of the key factors ensuring the sustainable socio-economic growth of a region. The quality and characteristics of the road network determine the level of transport accessibility, travel speed, road safety, and the efficiency of freight transport operations. In the Almaty region – one of Kazakhstan's largest transport hubs through which the international transport corridors "Western Europe – Western China," "North – South," the Trans-Kazakhstan corridor, and several other strategic routes pass – the condition of the road network directly influences the country's transit potential and the development of regional logistics.

In recent years, there has been a significant increase in transit and intra-regional freight flows, resulting in rising pressure on the road network and accelerated pavement deterioration. The proportion of heavy and high-capacity vehicles within traffic streams has grown substantially, especially during peak agricultural, processing, and industrial seasons. At the same time, certain segments of the road network do not meet modern traffic requirements in terms of geometric and structural parameters: they have insufficient pavement thickness, limited bearing capacity of the roadbed, substandard carriageway width, and outdated infrastructure elements. These factors

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collectively create risks of reduced road capacity, increased accident rates, higher operating costs, and longer freight delivery times.

Climatic conditions of the region also have a significant impact on pavement performance. Sharp temperature fluctuations, long winter periods, repeated freeze-thaw cycles, high soil moisture levels, and intensive spring thawing accelerate pavement degradation. These processes lead to the formation of cracks, potholes, subsidence, and rutting, significantly reducing pavement durability. When combined with intensive axle loads from heavy trucks, climatic stresses further shorten maintenance intervals and necessitate more frequent rehabilitation works.

The issue is particularly acute due to the uneven distribution of transport loads across the region. The highest concentration of freight traffic is observed on approaches to the Almaty metropolitan area, industrial clusters, logistics centers, warehousing zones, as well as toward international border checkpoints. The presence of bottlenecks, reduced structural capacity of certain sections, insufficient engineering infrastructure, and variable road conditions require a comprehensive assessment of factors influencing the efficiency of freight transport movement.

In this context, the aim of the present study is to analyze how the condition and parameters of road infrastructure affect the organization of freight transport in the Almaty region. The paper explores the interrelationships between axle loads, pavement structural characteristics, regulatory and technical requirements, road capacity, and traffic management elements. Special attention is given to evaluating the compliance of road conditions with actual freight demand, identifying sections with heightened vulnerability, and assessing international best practices in road network operation and modernization. The findings of the study may serve as a scientific basis for developing effective management solutions aimed at improving the sustainability, safety, and economic efficiency of the regional transport system.

Analysis of Scientific and Regulatory Sources

The relationship between road infrastructure and freight transport is widely examined in both international and domestic research. According to the findings presented in [2], the intensity of freight transportation directly affects pavement durability and must be taken into account during the design, reconstruction, and maintenance of highways. It is noted that the impact of heavy vehicles on pavement structures significantly exceeds that of passenger cars, as pavement damage increases proportionally with higher axle loads and vehicle weight.

Similar conclusions are offered in study [5], which states that heavy vehicles are the primary factor in pavement degradation and the accelerated emergence of defects such as rutting, shear deformations, cracking, and the deterioration of the asphalt concrete surface layer. The authors emphasize that traditional methodologies for calculating pavement bearing capacity require modernization to reflect increased loads and changing operating conditions.

Study [3] establishes that exceeding axle load limits by 10–15% accelerates pavement destruction by a factor of 3–4, a result consistent with the findings of research [4] conducted on the transport network of Bosnia and Herzegovina. International experience shows that the introduction of automated weigh-in-motion (WIM) systems significantly reduces the number of violations, thereby lowering road repair costs.

Research [5] also examines the concept of infrastructure resilience as the ability of a transport network to maintain functionality under changing operating conditions, elevated loading, climatic influences, and seasonal variations in traffic intensity. The resilience of road infrastructure is determined by a combination of factors, including design quality, road maintenance standards, availability of bypass routes, development of logistics terminals and distribution centers, and the effectiveness of intelligent transport systems.

Publications [6, 7] analyze approaches to establishing resilient transport corridors and optimizing routes in consideration of dynamic road conditions, risks of corridor overloading, CO_2 emissions, and logistics costs. According to these studies, effective management of freight flows requires the use of transport network modeling and geographic information systems to assess capacity, pavement condition, and projected deterioration over a 5–10-year horizon. The authors highlight the importance of adaptive route planning and redistribution of freight flows to reduce stress on the most vulnerable segments of the network.

In the domestic regulatory framework, the key documents include the Standards for Axle Loads of Vehicles [8] and sector-specific road design standards [9]. These documents define the permissible parameters of heavy vehicles, requirements for structural strength of pavements, design loads, and rules for designing highways of various categories. Compliance with these standards ensures the necessary durability of roads and prevents premature deterioration; however, practical observations indicate that actual loads on several regional road sections exceed the regulatory limits.

According to the National Report on the Condition of Kazakhstan's Highways [10], about 38% of regional roads in the Almaty region are in unsatisfactory condition. This results in restrictions on heavy-vehicle movement, increased freight delivery times, higher fuel consumption, rising logistics costs, and reduced competitiveness of the region's transport sector. Several sections require reconstruction or major repair, a finding confirmed by instrumental assessments that include measurements of pavement strength, rut depth, and skid resistance.

Purpose and Objectives

The purpose of this study is to comprehensively assess the impact of road infrastructure conditions and parameters on the organization of freight traffic in the Almaty region, as well as to substantiate measures aimed at improving the durability, safety, and efficiency of the road transport system under increasing traffic intensity and axle loads.

Research Objectives:

1. To analyze the influence of freight traffic intensity, vehicle overloading, climatic factors, and road infrastructure parameters on accelerated pavement deterioration and reduced network capacity.
2. To evaluate the current condition of the road network in the Almaty region and, based on regulatory requirements and international experience, to justify directions for its modernization and improvement of freight traffic management, including the implementation of intelligent transport systems and axle load control.

Methodological Framework of the Study

The methodological framework of this study includes a set of analytical, statistical, and instrumental methods aimed at assessing the impact of road infrastructure parameters on the organization of freight traffic. The foundation of the methodological approach is systems analysis, which enables the road network to be viewed as a multi-component system whose functioning is determined by a combination of technical, economic, and operational factors. This approach provides a comprehensive understanding of the cause–effect relationships between pavement condition, characteristics of traffic flows, and the level of transport safety.

The study employed methods of comparative analysis of regulatory requirements, a review of scientific publications on transport infrastructure, as well as processing of data obtained from road condition surveys. Official statistical data from the Committee for Highways of the MIIR of the Republic of Kazakhstan were used, along with instrumental pavement diagnostics, information on actual traffic intensity, and axle load distribution. To refine spatial characteristics, geographic information technologies were applied, enabling a detailed cartographic assessment of network conditions, visualization of traffic intensity, and identification of sections with elevated vulnerability. This toolkit allows for modeling load-development scenarios, forecasting pavement deterioration under different freight-flow levels, and evaluating the effectiveness of modernization measures.

Analysis of the condition of major highways in the Almaty region revealed that approximately 42% of national roads do not meet the international transit corridor requirements in terms of carriageway width, pavement category, and structural strength of the roadbed [10]. These deficiencies significantly limit the efficiency of freight transport operations and increase the risk of accidents, particularly on high-intensity sections. The methodological analysis included comparing regulatory requirements with the actual parameters of the road network, which allowed the identification of key inconsistencies and the determination of high-risk zones.

The most problematic sections include:

1. Almaty – Konaev – Taldykorgan road, characterized by a high degree of pavement wear, sections with loss of surface evenness, subsidence, and rutting, which reduces the speed and safety of heavy-vehicle movement;
2. Access routes to the "Khorgos" border checkpoint, where roadside infrastructure is insufficiently developed, lacking modern service areas, maintenance facilities, and parking zones for multi-axle vehicles, resulting in congestion and decreased capacity;
3. Several segments of the Almaty – Bishkek highway, which require modernization in key safety parameters and reconstruction of pavement structures in response to increased axle loads and growing international transport flows.

In addition, expert assessments from industry specialists were used within the methodological framework to provide qualitative analysis of the causes of deterioration and the factors influencing transport resilience. To assess the impact of heavy vehicles, models for calculating equivalent load and methods for evaluating the remaining pavement service life were employed.

The comprehensive methodological basis of the study enables an objective determination of the factors influencing road-network condition, identification of structural deficiencies, and development of scientifically grounded recommendations for improving freight-traffic organization in the region. This approach allows for a holistic understanding of the current state of transport infrastructure and the identification of priority directions for its modernization in line with international requirements and the future development of freight transport.

The influence of traffic loads on pavement structures was assessed using the Equivalent Single Axle Load (ESAL) method based on the modified AASHTO formula. (American Association of State Highway and Transportation Officials):

$$N = \sum_{i=1}^{k} \left(P_i \times ESAL_i \right) \qquad (1)$$

where N – is the total impact over the design period; P_i - the number of vehicles of the i-th type; $ESAL_i$ - the load equivalency factor; k - the number of vehicle categories.

For the quantitative analysis, the following parameters were used: traffic intensity – 37,500 vehicles/day; share of freight transport – 13%; average axle load of heavy trucks – 11.5 t. The calculation was performed for the Almaty – Konaev route (Category I-b).

Total impact over 10 years, taking into account a 3% annual traffic growth:

$$N = 4160341 \times 1.34 = 5.5 \text{ million ESAL}$$

The design pavement life for Category I-b roads, at a design load of N = 2.5 million ESAL (Equivalent Single Axle Load), is achieved over 12 years of operation. The actual value N_{10} = 5.5 million ESAL indicates an exceedance of the normative load by approximately 80%, which reduces the pavement service life to 7 years.

Thus, an increase in the share of heavy vehicles and the exceeding of axle loads significantly accelerate pavement deterioration, increase the frequency of maintenance, and create the need for optimization of routes and operational modes of freight transport.

Table 1. – Calculation of the total impact of the traffic flow over 10 years

Type vehicle	Share in traffic, %	Axle load, t	ESAL	Daily number of vehicle	Annual impact (×10³)
Passenger vehicles	32625	1.0	0.0004	31987	4.6
Buses	0,17	5.5	0.8	638	1 862
Medium-duty trucks	9	8.5	1.8	3375	2 217
Heavy-duty trucks	4	11.5	3.2	1 500	1 752
Total for the year	–	–	–	37500	4 160

Current State of Road Infrastructure in the Almaty Region

According to the Committee for Highways of the MIIR of the Republic of Kazakhstan, the total length of roads in the Almaty region is approximately 9,000 km, of which about 70% have asphalt-concrete pavement. A significant portion of the network was built during the Soviet period, when regulatory axle loads and traffic intensity were substantially lower than today. As a result, many structural characteristics of existing roads do not meet the requirements of heavy trucks with axle loads of up to 11.5 t. Increasing transport demand, growth in freight volumes, a rising share of multi-axle vehicles, and the use of high-capacity equipment exert substantial pressure on road infrastructure elements, accelerating both physical and functional degradation.

Pavement diagnostics indicate that the International Roughness Index (IRI) on several road sections exceeds acceptable values (3.5–4.0 dm/km), reducing driving comfort and safety. Many regional and local roads exhibit rutting, shear deformations, cracking, and surface-layer deterioration. These defects are particularly pronounced on sections with a high share of heavy vehicles transporting agricultural products, aggregates, or industrial cargo. On secondary roads, the situation is aggravated by insufficient repair funding, limited pavement bearing capacity, and the absence of modern monitoring systems, leading to reduced speeds, route deviations, and increased operational costs for carriers.

According to the report “Almaty Region: Transport Development Strategy 2030”, priority directions for modernizing the road network include strengthening pavement structural capacity, reconstructing highways to accommodate modern axle loads, and widening the carriageway on key high-load sections. The document highlights the importance of implementing Intelligent Transport Systems (ITS): automated traffic signal control, comprehensive traffic-flow monitoring, weigh-in-motion (WIM) technologies, and driver-information displays. The adoption of such systems improves traffic distribution, enhances capacity, and reduces incidents associated with network overloading.

The organization of freight traffic is directly linked to the physical characteristics of vehicles, their operational parameters, and the structure of traffic flows. Specifically:

- The increasing dimensions and weight of heavy trucks require widening traffic lanes, reinforcing shoulders, strengthening bridges, and using more durable materials in pavement construction;
- A high share of heavy vehicles reduces average travel speeds, increases cargo delivery time, and lowers overall capacity, leading to congestion and reduced logistics efficiency;
- Non-compliance with axle-load regulations accelerates pavement deterioration, increases repair frequency, and raises road maintenance costs, intensifying pressure on regional budgets.
- Effective traffic organization requires separating freight and passenger flows, introducing temporal restrictions on heavy-vehicle movement in urban areas, and redistributing freight flows to alternative routes with higher bearing capacity.

Another challenge is the insufficient development of roadside service infrastructure. In many areas, there is a lack of modern truck parking facilities, logistics hubs, service zones, and maintenance points. This reduces service quality, creates risks related to driver rest violations, and increases the likelihood of accidents caused by fatigue or forced roadside stops. Given the growing volume of international transit through the Almaty region, this issue becomes strategically significant, affecting corridor attractiveness, service quality, and the region’s competitiveness in international freight transport.

Overall, the current state of the Almaty region’s road infrastructure is characterized by high transport loads, limited load-bearing capacity on several sections, inadequate roadside services, and the non-compliance of certain highways with modern regulatory requirements. These factors underscore the need for a comprehensive approach to road-network development, including structural pavement strengthening, implementation of intelligent traffic management systems, improved weight control, and expansion of freight-service infrastructure. The implementation of these measures will enhance the resilience and efficiency of the regional transport system, increase transit potential, and improve conditions for the safe movement of freight flows.

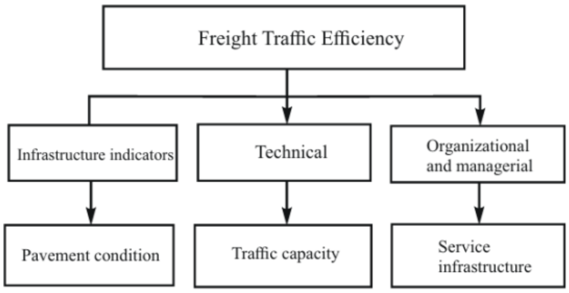

Fig. 1. Hierarchical model of the influence of road infrastructure factors on freight traffic efficiency

Additional studies confirm that the low quality of road infrastructure has a multifactorial impact on the operational performance of freight transport. In particular, reduced pavement smoothness leads to increased vertical vehicle vibrations, which not only heighten dynamic loading on the pavement structure but also significantly increase fuel consumption. According to estimates by international transport organizations, an increase of just 1 m/km in the IRI index may lead to a 6–10% rise in fuel consumption, depending on vehicle type and cargo characteristics. For the Almaty region, where freight volumes continue to grow annually, such deviations result in substantial economic losses for both carriers and the regional economy as a whole.

Furthermore, deterioration of road surface conditions affects the technical state of freight vehicles, increasing the frequency of failures in the chassis, tires, and suspension systems. This leads to higher maintenance costs and reduces the reliability of supply chains. For regions with a significant share of transit flows–such as the transport corridors of the Almaty region–this factor becomes critical, as it raises the risk of delays and disruptions in international logistics processes.

Reduced capacity at transport nodes exacerbates spatial–temporal imbalances in traffic flows. The issue is most evident in suburban areas of major cities–Almaty, Konaev, and Taldykorgan–where morning and evening peaks create severe congestion. In the absence of dedicated lanes for trucks, average travel speeds decrease by 25–40%. Considering that a large portion of freight operations involves the delivery of construction materials, food products, and industrial goods, such delays increase logistics costs and disrupt enterprise supply schedules.

Modern research in transport planning emphasizes the need for comprehensive adaptation of road infrastructure to the characteristics of heavy vehicles. This involves not only strengthening pavement structures but also modernizing planning solutions. For example, the creation of bypass routes around urban agglomerations reduces the share of heavy trucks in urban street networks. For the Almaty region, the development of bypass routes around Almaty and construction of additional connecting corridors between major logistics hubs – including the "Khorgos" dry port, Zhetyzhe, and distribution centers in the Almaty industrial zone –is particularly important.

Intelligent Transport Systems (ITS) can significantly enhance the efficiency of freight-flow management. The application of automatic vehicle identification technologies, real-time overload-control systems, and adaptive traffic-management algorithms allows more accurate prediction of traffic conditions and redistribution of flows based on road situations. The use of machine-learning algorithms to analyze data collected from connected vehicles enables predictive road maintenance, where potential defects are identified before they appear.

Equally important is the development of roadside service infrastructure. A shortage of modern rest areas for drivers, inspection stations, parking facilities for heavy trucks, and logistics terminals leads to suboptimal distribution of transport along highways and contributes to chaotic stopping behavior, reducing overall safety. With the growth of transit freight flows, this problem becomes a risk factor, increasing the probability of accidents, especially on narrow or congested road sections.

A key direction in modernizing transport infrastructure is the integration of environmental criteria into planning systems. Freight transport is a major source of CO_2 emissions, and its contribution to the region's carbon footprint is increasing. Route optimization based on pavement conditions, time of day, and network congestion allows reductions in fuel consumption and greenhouse-gas emissions. For the Almaty region, this practice is especially relevant given the strategic goal of improving the sustainability of the logistics system within the framework of national transport policy.

Taken together, the proposed measures provide a foundation for developing a more resilient and efficient regional transport system. Implementing a comprehensive approach will increase network capacity, reduce operational and environmental costs, and improve the safety and durability of road infrastructure.

To improve the efficiency of freight traffic management in the region, it is advisable to implement the following measures:

1. Strengthen the weight-control system through the use of automated complexes;
2. Implement intelligent traffic management systems at key transport nodes;
3. Develop logistics hubs and bypass routes to optimize traffic flow distribution;
4. Conduct regular monitoring of pavement conditions using data collected from connected vehicles;
5. Integrate road planning with environmental and economic sustainability criteria, including CO_2 emissions reduction and optimization of freight transport routes.

The adoption of a comprehensive approach will not only reduce the load on vulnerable road sections but also increase the overall network capacity, enhance traffic safety, and lower operational costs.

Conclusion

The condition of the road infrastructure in the Almaty region has a significant impact on the organization of freight traffic and the functioning of the regional logistics system. The conducted analysis revealed that a substantial portion of the road network does not meet modern requirements in terms of load-bearing capacity, geometric parameters, and pavement quality, creating a complex set of systemic issues. Insufficient structural strength of roadways leads to accelerated pavement degradation under the influence of heavy trucks, which constitute a significant share of traffic on highways supporting international and interregional transport. High levels of network wear, excessive IRI values, and limited capacity on certain sections create conditions for reduced average travel speeds, increased operational costs for carriers, and higher risks of traffic accidents.

Analysis of international and domestic studies indicates that effective freight traffic management is only possible through a comprehensive approach that combines engineering, organizational, and information-analytical methods. A key element is the optimization of routes based on actual infrastructure conditions, time of day, traffic intensity, and the distribution of transport flows. The application of dynamic planning algorithms allows reducing loads on the most worn sections, redistributing traffic, and minimizing delays at city entry points.

Axle load and vehicle weight control play a crucial role. With growing transit traffic and the active development of international corridors, the weight-control system must provide objective and continuous monitoring of freight vehicles. The implementation of automated Weigh-in-Motion (WIM) systems will significantly reduce violations, minimize pavement damage, and ensure fair allocation of maintenance costs. Such measures enhance the efficiency of the road network and contribute to its durability.

A critical factor in improving infrastructure quality is the modernization of the road network, including strengthening structural layers, widening carriageways, reinforcing shoulders, improving curve geometry, and enhancing safety. For the Almaty region, where a substantial portion of roads was constructed several decades ago and was not designed for current high-intensity traffic, upgrading transport infrastructure is a strategic necessity. Increasing the load-bearing capacity of pavement structures will ensure stable movement of heavy vehicles, improve highway throughput, and reduce routine maintenance costs.

The implementation of intelligent transport systems and road condition monitoring is a key element in developing the transport system. The use of digital diagnostics, vibration and deformation sensors, telematics data, and satellite observation systems enables early detection of pavement defects and prompt planning of maintenance activities. Intelligent transport systems provide adaptive traffic management, timely driver information, congestion reduction, and optimization of freight routes.

The implementation of the Almaty Region Transport Strategy through 2030 creates opportunities for systematic modernization of road infrastructure based on sustainable development principles. A comprehensive set of measures—including reconstruction of key highways, construction of bypass roads, development of logistics hubs, strengthening of international transport corridors, and the introduction of modern digital technologies–will ensure safe and efficient freight movement. Reducing logistics costs, shortening delivery times, minimizing environmental impact, and enhancing the competitiveness of the regional transport system will be significant outcomes of these strategic initiatives.

In the long term, modernization of road infrastructure and improvement of freight traffic management will contribute to sustainable economic development in the Almaty region. Enhancing road quality, increasing transport speed and reliability, and creating a modern logistics ecosystem will strengthen the region's position in international transport corridors and ensure stable growth of transit flows. Thus, a comprehensive approach that integrates infrastructure, organizational, and intelligent solutions is a key factor in increasing the efficiency and safety of the region's transport system.

Conflict of interests

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

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Вплив зношення дорожньої інфраструктури на безпеку та ефективність вантажних перевезень.

Анотація. Проблема: *Зростання інтенсивності вантажних перевезень в Алматинському регіоні у поєднанні з частими випадками перевантаження транспортних засобів і недостатньою пропускною здатністю дорожньої інфраструктури прискорює руйнування дорожнього покриття, збільшує транспортно-логістичні витрати, знижує рівень безпеки дорожнього руху та ефективність перевезень.* ***Мета:*** *Метою дослідження є оцінювання впливу стану та параметрів дорожньої інфраструктури на організацію вантажного руху в Алматинському регіоні, а також визначення заходів щодо підвищення довговічності, безпеки та ефективності дорожньо-транспортної мережі.* ***Методологія:*** *Дослідження ґрунтується на аналізі наукових публікацій, статистичних даних і нормативно-технічної документації. Розглянуто взаємозв'язок між руйнуванням дорожнього покриття, пропускною здатністю доріг, безпекою руху та експлуатаційними характеристиками транспортних засобів. Проаналізовано такі ключові чинники, як осьове навантаження, категорія дороги, інтенсивність вантажного руху, геометричні параметри доріг і якість сезонного утримання. Також проведено порівняльний аналіз вітчизняного та міжнародного досвіду.* ***Результати:*** *Встановлено, що перевантажені великовантажні транспортні засоби, недостатня несуча здатність дорожнього покриття, низька якість матеріалів і несприятливі кліматичні умови є основними причинами колійності, тріщиноутворення та руйнування покриття в Алматинському регіоні. Також визначено, що значні поздовжні ухили, вузька проїзна частина, недостатня кількість смуг руху та нераціонально спроєктовані перехрестя знижують пропускну здатність доріг і збільшують час доставки вантажів. Підкреслено важливість автоматизованих систем вагового контролю, цифрового моніторингу стану покриття, інтелектуальних транспортних систем та оптимізації схем розподілу транспортних потоків.* ***Оригінальність:*** *У статті надано комплексну оцінку сукупного впливу стану інфраструктури, кліматичних чинників та інтенсивності вантажного руху на функціонування дорожньої мережі Алматинського регіону, а також запропоновано інтегровані заходи для забезпечення сталого управління вантажними перевезеннями та збереження дорожнього покриття.*

Ключові слова: *дорожня інфраструктура, вантажний транспорт, дорожнє покриття, осьове навантаження, організація дорожнього руху, вантажні перевезення.*

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