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A. I. Korobko, I. V. Semenov
Kharkiv National Automobile and Highway University, Kharkiv, Ukraine

A MODEL FOR DETERMINING THE EFFICIENCY OF A TRANSPORT SYSTEM BASED ON THE RISK OF FUNCTIONAL STABILITY

The objective of this study is to enhance the efficiency of transport systems by refining their evaluation model through a risk-oriented approach. To achieve this objective, the following tasks were addressed: identifying the primary factors influencing the functional stability of vehicles within transport systems, and substantiating a model for evaluating the operational efficiency of transport systems based on vehicle functional stability and a risk-oriented approach. Functional stability is a complex, multifactorial characteristic that defines the ability of rolling stock to perform its transport function reliably, safely, and efficiently under real-world operating conditions. This level is determined by the interplay between a vehicle's inherent technical properties and a wide range of external factors related to the transport system, infrastructure, environment, logistics, and management. This approach allows functional stability to be viewed not as a passive property of a vehicle, but as a manageable foundation for the operational efficiency of transport systems. The proposed model for evaluating transport system efficiency demonstrates that: the efficiency of its operation is proportional to the functional stability of its constituent vehicles, which, in turn, declines exponentially; the rate of this decline is determined by the risk of external factors impacting the vehicle: the higher the risk, the more rapidly functional stability diminishes; and the model accounts for the cumulative effect of external factors over time.

Keywords: transport system, transport, systems approach, operational stability, external factor, risk, efficiency.

INTRODUCTION

The current stage of development in the transport industry is characterized by a significant increase in the complexity of vehicle design, growing intensity of traffic flows, expansion of operating conditions, and heightened requirements for the safety, reliability, and operational efficiency of transport systems. Under these conditions, ensuring the functional stability of vehicles-defined as the ability to maintain specified operational, technical, and safety characteristics over a given period and under varying environmental conditions has become particularly urgent.

The operation of a vehicle within a transport system is a complex, multifactorial process simultaneously influenced by design parameters, technical condition, traffic modes, road and climatic conditions, the level of information support, as well as the actions of the operator or driver. A decline in any of a vehicle's functional circuits-namely traction-dynamic, braking, handling, stability, power, information, or ergonomic-below regulatory standards may lead to reduced transportation efficiency, increased operating costs, compromised traffic safety, and the destabilization of the entire transport system.

ANALYSIS OF LITERATURE DATA AND FORMULATION OF THE PROBLEM

The efficiency of a transport system is largely determined by the ability of its technical components to ensure the consistent performance of specified functions under varying operating conditions. Among these components, the vehicle plays a key role, as it is the vehicle that directly carries out the transport process and determines the level of its productivity, safety, reliability and resource efficiency.

An analysis of the literature [1-10] shows that in contemporary scientific literature, the efficiency of transport systems and freight transport is considered a multi-criteria category, assessed not by a single indicator but through several groups of factors and indicators. In particular, works [1-3] focus on service-economic and operational indicators: timeliness of delivery, reliability of transport services, cost of transport, productivity, level of resource utilisation, quality of logistics services, as well as environmental and social impacts. This approach demonstrates that the efficiency of the transport process is shaped not only by direct costs and outcomes, but also by broader characteristics of the transport system’s functioning.

Another group of studies [4-7] examines efficiency at the level of methodology, evaluation models, and organisational and managerial factors. These analyses focus on approaches to measuring the efficiency of transport systems, the sustainability of urban logistics, barriers to the transformation of transport processes, and the potential for using big data to describe and forecast the behaviour of freight flows. These studies confirm that, in practical assessment, structural-organisational, information-analytical, infrastructural and managerial factors are typically identified as determining the effectiveness of transport operations.

A separate line of research [8-10] focuses on the spatial-network and transport-technological aspects of efficiency. The authors of these studies link efficiency to changes in freight flows, the location of loading and unloading zones, the dynamics of freight transport movement, the interaction of transport network participants, and the optimisation of decisions solely at the level of urban logistics. Thus, the literature provides a fairly comprehensive account of the external conditions governing the transport process: route organisation, infrastructure constraints, demand distribution, transport policy, digitalisation, and the interaction of elements within the logistics network.

However, despite the breadth of coverage, most of the works considered share one significant limitation: the object of assessment is predominantly the transport system, the transport process or the logistics network, but not the transport vehicle itself, in particular the motor vehicle (MV), as the functional carrier of transport. Even when reliability, stability or transport performance are mentioned, these characteristics are usually interpreted solely at the level of service, operations, flows or organisational decisions, rather than at the level of the technical condition, operational capability and functional stability of a specific motor vehicle.

To further highlight the relevance of considering the functional stability of vehicles as a factor that significantly influences the functioning of transport systems, it is advisable to examine scientific works in research areas where the efficiency of transport operations is linked not only to the organisation of the process itself but also to the influence of the environmental conditions in which this process takes place. Among such works, [11-15] can be highlighted. These publications broaden the scope of analysis by taking into account environmental, infrastructural, climatic, and logistical conditions.

In a number of studies, the efficiency of transport operations is examined through the parameters of the transport process and the logistical organisation of delivery. Thus, in [11], the efficiency of the supply chain is analysed depending on the parameters of the transport process: the duration of operations, the coordination of movement stages, the regularity of transport services, the distribution of time costs, and logistical coordination. The authors effectively demonstrate that even with an identical delivery structure, changes in transport and service parameters can significantly alter the overall performance of the entire system. A similar line of reasoning is demonstrated in [12], where the impact of logistics management practices on the operational performance of road transport companies is linked to the quality of route management, the organisation of interaction, resource planning and the management of transport operations. These studies clearly demonstrate an understanding that transport efficiency is a function of the external organisation of the process – its planning, coordination, and manageability.

The vast majority of authors emphasise the need for sustainable development of transport systems in their work. They examine efficiency through the prism of environmental sustainability, resource efficiency, economic sustainability and systemic balance. For instance, Stephen Nkesah [13] conducted a systematic review of the sustainability of road freight transport and concluded that modern approaches to improving the efficiency of road freight include reducing emissions, optimising routes, increasing energy efficiency, reducing empty runs, digitalisation, fostering cooperation and changing transport policy. A similar multidimensionality of assessment is demonstrated in [14], where sustainability is evaluated through the impact of lorry routing strategies on economic, environmental and operational indicators, as well as in [15], in which multimodal transport is considered as a means of ensuring sustainable development.

The analysis of the literature shows that existing approaches to studying the operational efficiency of transport systems do not sufficiently account for the impact of a vehicle's internal condition on the overall efficiency of the transport process. Nevertheless, it is precisely the technical condition of components and systems, the reliability of units, remaining service life, the stability of adjustable parameters, failure probability, and the ability to maintain operational properties under various operating modes and conditions that directly determine whether a motor vehicle can ensure the necessary productivity, regularity, safety and cost-effectiveness of transport. In other words, the efficiency of the transport system is most often assessed in the literature as a function of the external organisation of transport, but not as the result of the combined effect of external conditions and the internal functional stability of the vehicle.

PURPOSE AND OBJECTIVES OF THE STUDY

The aim of the study is to improve the efficiency of transport systems by refining the model for their assessment based on a risk-oriented approach. To achieve this objective, the following tasks must be addressed:

– to identify the main factors influencing the operational stability of vehicles within the context of transport system operations;

– to develop a model for assessing the operational efficiency of transport systems based on the operational stability of vehicles and utilising a risk-oriented approach.

RESEARCH RESULTS

Factors influencing the operation of transport systems from the perspective of a vehicle's functional stability

A systems analysis [16] shows that most factors traditionally regarded as determinants of transport system efficiency are, in fact, realised through changes in the level of a vehicle's functional stability. This means that there is an intermediate systemic link between the external and internal operating conditions of the transport system and its output indicators – the functional stability of the vehicle (Fig. 1).

Fig. 1 – A prerequisite for the effective functioning of the transport system

This approach allows us to formulate a cause-and-effect model: the efficiency of the transport system is not viewed as a direct consequence of the availability of equipment, routes, etc., but is determined by the extent to which a vehicle is capable of performing its transport function consistently within a specific operating environment.

Let us identify the main groups of factors influencing the functioning of the transport system through the functional stability of the vehicle, since it is precisely through the condition and behaviour of the rolling stock that the key characteristics of the transport process are realised. These factors include technical, loading and operational, road and infrastructure, natural and climatic, organisational and logistical, human, and information and management factors (Fig. 2).

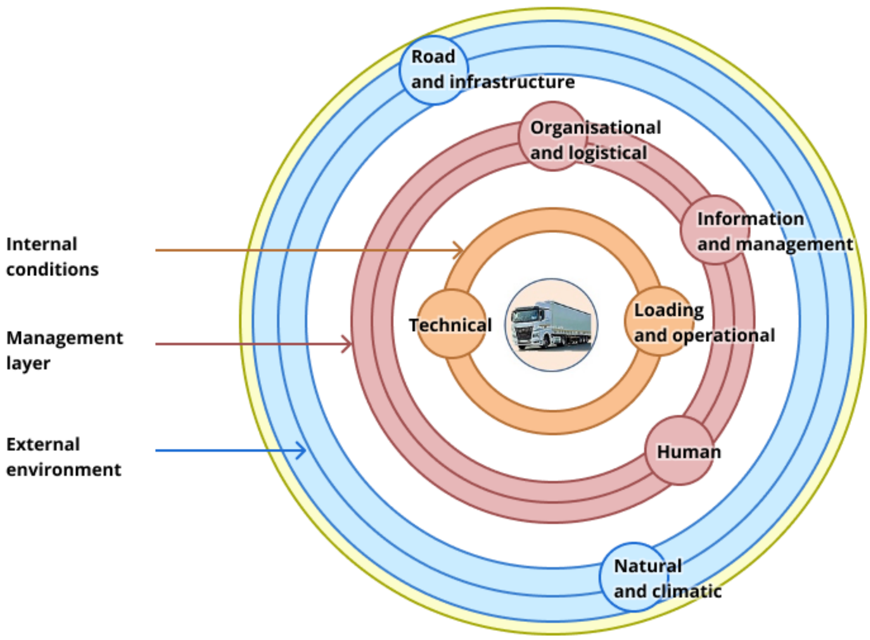

Fig. 2 – Factors affecting the functioning of the transport system through the functional stability of the vehicle

The primary basis for a vehicle's operational reliability is its technical condition, which determines its potential ability to perform its transport function consistently throughout its entire service life. Technical factors include the serviceability of assemblies and systems, their level of wear, the remaining service life of components, the reliability of the engine, transmission, braking system and chassis, the stability of settings, the presence of hidden defects, resistance to failure, and maintainability. Taken together, the influence of these factors manifests itself in the vehicle's ability to maintain a given level of performance and technical readiness over time.

As the technical condition deteriorates, systemic consequences arise, manifested in an increased probability of failures, a reduction in the technical readiness coefficient, an increase in the number of unscheduled downtimes, disruption to the regularity of journeys, increased operating costs, and a reduction in the actual productivity of the transport unit. These changes directly affect the efficiency of the entire transport system.

In view of the above, it can be stated that the technical condition of a vehicle effectively sets the upper limit of the transport system's potential efficiency. Even with a high level of transport organisation and favourable road and infrastructure conditions, it is impossible to ensure the stable operation of the system if vehicles are in a state of «accelerated deterioration». In this regard, technical factors should be regarded as the fundamental framework for establishing the functional stability of a vehicle, which ultimately determines the stability and efficiency of the transport system as a whole.

Loading and operational factors constitute a group of factors that determine the operating modes and intensity of a vehicle's use, since it is the operational load that dictates the conditions under which its design potential is realised and the rate at which 'functional degradation' accumulates. These factors include the vehicle's load factor, the presence and magnitude of overloads, the number of trips per shift, the average trip duration, the driving mode, the frequency of acceleration and braking, the duration of operation under load, the number of engine start-stop cycles, and the proportion of operation under severe conditions. In the context of functional stability, these parameters characterise the operational stress on the vehicle: as the intensity of operation increases, the mechanical, thermal and dynamic loads on its components and systems rise, leading to accelerated wear and an increased likelihood of failures. For the transport system as a whole, this means that operating modes affect both current productivity and the long-term sustainability of the transport process. Thus, a short-term increase in load or transport intensity may lead to an increase in the volume of transport work performed, but at the same time contributes to an accelerated decline in the functional stability of the vehicle and, consequently, a deterioration in the efficiency of the system during subsequent operating cycles. In this regard, the assessment of the transport system should be based not only on indicators of current productivity, but also take into account the cost at which this result is achieved in terms of maintaining the functional stability of the rolling stock.

Road infrastructure factors are the most important component of the operating conditions of the transport system, as the transport process always takes place within a specific infrastructure environment. Parameters such as road surface quality, the presence of unevenness, rutting and potholes, the type of road surface, the route's topography, longitudinal and transverse gradients, the geometry of bends, the condition of access roads, the capacity of individual sections, as well as the presence of traffic jams, junctions and various restrictions. The influence of these factors manifests itself through changes in rolling resistance, levels of vibration and shock loads, tyre-road contact conditions, actual speed and the frequency of manoeuvres.

The impact of road and infrastructure conditions is reflected in journey times and the reliability of a vehicle's operational condition. Deterioration in road conditions leads to increased dynamic loading on structural components, accelerated wear of the running gear and suspension, increased fuel consumption, reduced driving stability, a higher probability of technical failures, and an increase in the variation of the time parameters of the transport cycle. Thus, road and infrastructure factors should be regarded as active influences that alter the level of a vehicle's functional stability during its operation.

Natural and climatic factors significantly influence the functioning of the transport system, forming an external disturbance field that affects the vehicle during its operation. Such factors include ambient temperature, humidity, precipitation, the presence of snow, ice, mud and dust, seasonal changes in road surface conditions, wind loads, and the corrosive activity of the environment. In terms of a vehicle's operational stability, these influences manifest themselves in the performance of cooling and lubrication systems, tyre characteristics and road grip conditions, the operation of hydraulic and electrical systems, and through increased corrosion and abrasive wear.

For the transport system as a whole, this means that even with identical vehicle design characteristics and unchanging transport routes, operational efficiency can vary significantly depending on seasonal and weather conditions. This is because vehicles maintain their functional stability differently as environmental parameters change. Thus, natural and climatic factors should be regarded as important modifiers of the transport system's stability, which exert an indirect influence through changes in the functional state of the vehicle and its ability to maintain specified operational parameters under various operating conditions.

Organisational and logistical factors are reflected in the principles and methods used to organise the transport process. They determine the actual structure of loads, waiting times, the sequence of operations and the modes of vehicle utilisation. This group of factors includes the routing scheme, the coordination of timetables, the regularity of transport supply, the organisation of loading and unloading operations, the occurrence of waiting times and downtime, the duration of the turnaround cycle, the availability of reserve rolling stock, the flexibility of the dispatching system, and the level of coordination between participants in the transport process. Despite the indirect nature of their impact, these factors significantly affect the operational stability of the vehicle. For instance, prolonged idling with the engine running leads to increased wear and fuel consumption; an uneven flow of traffic leads to congestion during peak periods; the lack of reserve capacity forces vehicles to operate at the limits of their capacity; and inefficient routing increases empty runs and the overall operational load. Ultimately, the organisational and logistical structure of the transport system determines not only its immediate efficiency but also the nature of transport operating modes, and thus influences the level of their functional stability and the overall stability of the system's operation.

The human factor is the most important element in ensuring the functional stability of a vehicle, as it is the driver who operates the vehicle, monitors its technical condition and makes key decisions during operation. This group includes driver qualifications, driving style, adherence to established operating procedures, the accuracy of transport operations, the timeliness of identifying signs of malfunctions, the discipline of technical inspections, the level of training of maintenance staff, and the quality of dispatch decisions. The influence of the human factor is evident in the vehicle's current operational behaviour and in the rate at which its «functional degradation» accumulates. For example, an aggressive driving style contributes to accelerated wear of the braking system, transmission and tyres; an irrational choice of driving modes increases fuel consumption and the thermal load on the engine; and ignoring early signs of malfunctions leads to latent defects developing into overt failures. Thus, the human factor should be regarded as an active regulator of a vehicle's functional stability, upon which the stability of the transport system as a whole depends.

At the current stage of transport system development, information and management factors are playing an increasingly important role, as they enable the monitoring and regulation of operational processes based on data and analytics. This group includes the availability of on-board diagnostics, technical condition monitoring systems, route and operating mode control, recording of failures and deviations, the use of telemetry, digital fleet management, remaining life prediction and adaptive dispatch control. The significance of these factors stems from the fact that a vehicle's operational stability is determined not only by its initial technical condition, but also by the system's ability to detect deviations in a timely manner and adjust operating conditions.

In the absence of advanced information support, a deterioration in a vehicle's condition leads to a loss of efficiency and increased downtime. At the same time, the use of monitoring, diagnostic and telemetry systems make it possible to detect the onset of deterioration at an early stage, predict the development of failures and take preventive management decisions. Thus, information and management factors ensure control and active support for the functional stability of the vehicle.

A model for assessing the performance of a transport system based on the functional stability of vehicles and using a risk-based approach.

The efficiency of a transport system is determined by its ability to ensure the continuous, safe, timely and cost-effective execution of the transport process in a changing environment. In the field of freight transport, such efficiency is shaped by a large number of interrelated factors. The technical and operational capabilities of the vehicles directly involved in the freight delivery process play a leading role among these factors. This is why the overall performance of the transport system depends to a large extent on the extent to which a vehicle is capable of consistently maintaining the necessary properties and performance indicators under the influence of variable external and internal factors.

Let us consider the transport system as a dynamic system, the operation of which is characterised by the level of functional stability $S(t)$, where $S(t) \in [0,1]$, and:

– $S(t)=1$ – fully stable operation;

– $S(t)=0$ – complete loss of operational capability.

The efficiency of the transport system's operation $E(t)$ is linked to functional stability. This is evident in the fact that any disruptions (malfunctions, delays, failures) reduce productivity. Therefore:

$$E(t) = E_{\max} S(t). \tag{1}$$

where $E_{\max}$ is the maximum (nominal) efficiency of the system under ideal conditions.

Suppose the system is affected by external factors (weather conditions, loads, technical failures, etc.). It is convenient to describe their impact not directly, but in terms of the risk of loss of functional stability.

The risk *R*(t) is determined by the frequency of adverse events *λ*(t) and the probability that an event will lead to a reduction in stability *p*(t).

The risk can then be expressed as:

$$R(t)=\lambda(t)p(t). \tag{2}$$

External factors are heterogeneous and random in nature. To avoid describing each factor in detail, we introduce a generalised measure: risk. This is permissible because:

– the frequency *λ*(t) reflects the intensity of the environmental impact;

– the probability *p*(t) reflects the system's vulnerability.

Thus, expression (2) describes the expected intensity of the loss of functional stability, making risk a universal characteristic of the external environment's influence.

Let us assume that the rate of change in functional stability is proportional to the current level of stability and the risk of its loss:

$$\frac{dS(t)}{dt}=-R(t)S(t), \tag{3}$$

or, taking (2) into account

$$\frac{dS(t)}{dt}=-\lambda(t)p(t)S(t). \tag{4}$$

Equation (4) is a first-order equation with separate variables.

Let us divide both sides of equation (4) by *S*(t) and multiply by *d*(t)

$$\frac{dS(t)}{S(t)}=-\lambda(t)p(t)dt, \tag{5}$$

Let us integrate both sides of (5)

$$\int\frac{dS}{S}=\int-\lambda(t)p(t)dt. \tag{6}$$

The left-hand side of equation (6) is a standard integral

$$\int\frac{dS}{S}=\ln|S|, \tag{7}$$

so, we obtain

$$\ln S(t)=-\int\lambda(t)p(t)dt+C. \tag{8}$$

We omit the modulus, since $S(t)\geq 0$.

Let at time *t*=0

$$S(0)=S_0. \tag{9}$$

Substitute (9) into (8)

$$\ln S(0)=C. \tag{10}$$

We substitute the constant term (10) into (8)

$$\ln S(t)=-\int_o^t\lambda(\tau)p(\tau)d\tau+\ln S_0. \tag{11}$$

We take the logarithm of (11)

$$S(t)=e^{\left(\ln S_0-\int_o^t \lambda(\tau)p(\tau)d\tau\right)}. \qquad (12)$$

Taking into account the properties of the exponential, we obtain in final form

$$S(t)=S_0 e^{\left(\int_o^t \lambda(\tau)p(\tau)d\tau\right)}. \qquad (13)$$

If $\lambda(t) = \lambda$ and $p(t) = p$ are constants, then

$$\int_o^t \lambda p d\tau=\lambda pt, \qquad (14)$$

and the solution simplifies to

$$S(t)=S_0 e^{-\lambda pt}. \qquad (15)$$

Substituting expression (13) into (1) gives

$$E(t)=E_{\max} S_0 e^{\left(\int_o^t \lambda(\tau)p(\tau)d\tau\right)}, \qquad (16)$$

or, for constant parameters

$$E(t)=E_{\max} S_0 e^{-\lambda pt}. \qquad (17)$$

DISCUSSION OF THE RESULTS OF THE STUDY

The functional stability of a vehicle is an integral property that characterises its ability to perform its transport function with a specified level of performance, whilst maintaining the necessary level of technical readiness throughout its entire service life. This manifests itself in the stability of traction, speed and braking characteristics, ensuring the predictability of the vehicle's behaviour under various road and operating conditions. An important component of functional stability is also ensuring operation without a critical reduction in safety levels, even under the influence of external and internal disruptive factors. Furthermore, the vehicle must be capable of adapting to varying loads, driving modes and operating conditions, whilst maintaining the reliability of its main assemblies and systems. A key aspect is limiting the probability of failures and minimising unscheduled downtime, which directly affects the efficiency of the transport process. Taken together, these properties ensure the maintenance of an acceptable level of energy and operational efficiency and determine the vehicle's ability to consistently fulfil its functional capabilities within the transport system.

From the perspective of the transport system, this means that the functional stability of a vehicle is an internal regulatory factor regarding the continuity of the transport process. The higher the level of this stability, the more predictable and controllable the operation of the transport system becomes. Conversely, a reduction in the functional stability of one or more vehicles leads to increased variability in operational parameters, disruption of timetables, reduced throughput capacity and a deterioration in the overall efficiency of the system.

Consequently, the transport system must be viewed as a system in which macro-level performance indicators are determined by the micro-level capacity of transport vehicles to carry out transport operations (Fig. 3).

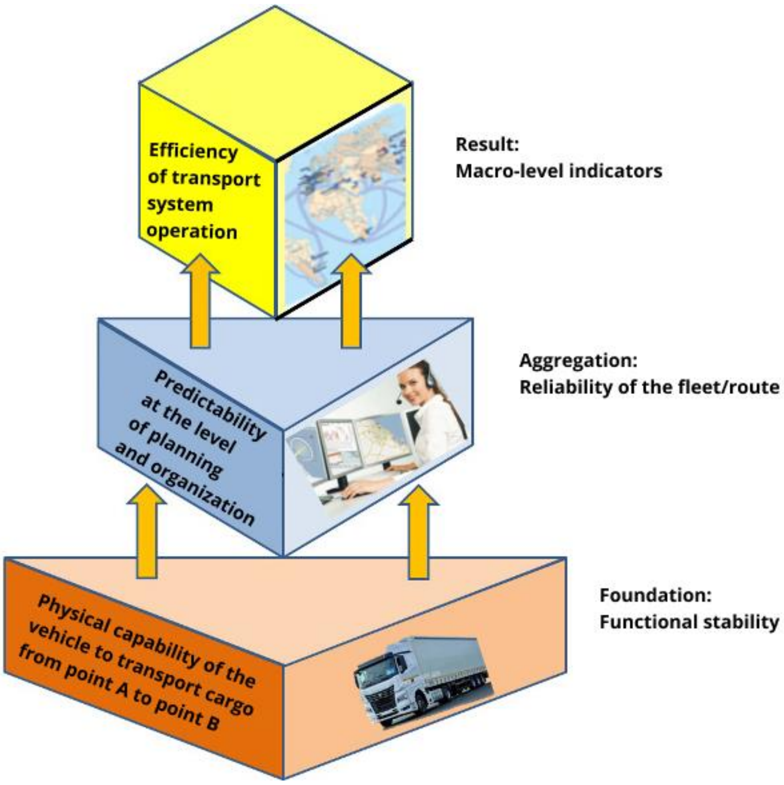

Fig. 3 – The relationship between the macro-level of the Customs Union and the macro-level indicators of the Customs Union's functioning

CONCLUSIONS

The operational reliability of vehicles is a complex, multifactorial characteristic that determines the ability of rolling stock to perform its transport function reliably, safely and efficiently under real-world operating conditions. Its level is shaped by the vehicle's internal technical properties and a wide range of external factors related to the transport system, infrastructure, environment, transport organisation and management. This approach allows functional stability to be viewed not as a passive property of a vehicle, but as a controllable basis for the effective functioning of transport systems.

The proposed model for assessing the efficiency of a transport system shows that:

– the efficiency of its operation is proportional to the functional stability of the vehicles comprising it, which, in turn, decreases (diminishes) according to an exponential relationship;

– the rate of decline is determined by the risk of external factors affecting the vehicle: the greater the risk, the faster the functional stability decreases;

– the model takes into account the cumulative effect of external factors over time.

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***А. Коробко, І. Семенов*. Модель визначення ефективності транспортної системи на основі ризику втрати функціональної стабільності**

Метою дослідження є підвищення ефективності функціонування транспортних систем за рахунок удосконалення моделі її оцінювання на основі ризик-орієнтованого підходу. Для досягнення поставленої мети необхідно вирішено задачі: виявлено основні фактори, що впливають на функціональну стабільність транспортних засобів в умовах функціонування транспортних систем; обгрунтовано модель оцінювання ефективності функціонування транспортної системи на основі функціональної стабільності транспортних засобів та з використанням ризик орієнтованого підходу. Функціональна стабільність транспортних засобів є складною багатофакторною характеристикою, що визначає здатність рухомого складу надійно, безпечно та ефективно виконувати транспортну функцію у реальних умовах експлуатації. Її рівень формується під впливом внутрішніх технічних властивостей машини та широкого спектру зовнішніх факторів, пов'язаних із транспортною системою, інфраструктурою, середовищем, організацією перевезень та керуванням. Такий підхід дозволяє розглядати функціональну стабільність не як пасивну властивість транспортного засобу, а як керовану основу ефективності функціонування транспортних систем. Запропонована модель оцінювання ефективності транспортної системи показує, що: ефективність її функціонування пропорційна функціональній стабільності транспортних засобів, що в неї входять, яка, в свою чергу, зменшується (убуває) за експоненціальною залежністю; швидкість убування визначається ризиком впливу на транспортний засіб зовнішніх факторів: чим більший ризик, тим швидше зменшується функціональна стабільність; модель враховує накопичену дію зовнішніх факторів з часом.

Ключові слова: транспортна система, перевезення, системний підхід, функціональна стабільність, зовнішній фактор, ризик, ефективність.

Andrii KOROBKO, Doctor of Technical Sciences, Associate Professor, Kharkiv National Automobile and Highway University, e-mail: ak82andrey@gmail.com. https://orcid.org/0000-0002-6618-7790

Illia SEMENOV, PhD student, Head of the Laboratory, [1]Kharkiv National Automobile and Highway University, [2]Kharkiv branch of the State Scientific Organization «L.Pohorilyi Ukrainian Scientific Research Institute of Forecasting and Testing of Machinery and Technologies», e-mail: illia.semenov@outlook.com. https://orcid.org/0009-0007-2571-309X

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