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S. V. Panchenko, Dr. Sci. (Tech.), Professor,
T. V. Butko, Dr. Sci. (Tech.), Professor,
A. V. Prokhorchenko, Cand. Sci. (Tech.), Associate Professor,
L. O. Parkhomenko, Cand. Sci. (Tech.)

Ukrainian State University of Railway Transport, Kharkiv, Ukraine, e-mail: railwayhub@yahoo.com

FORMATION OF AN AUTOMATED TRAFFIC CAPACITY CALCULATION SYSTEM OF RAIL NETWORKS FOR FREIGHT FLOWS OF MINING AND SMELTING ENTERPRISES

С. В. Панченко, д-р техн. наук, проф.,
Т. В. Бутько, д-р техн. наук, проф.,
А. В. Прохорченко, канд. техн. наук, доц.,
Л. О. Пархоменко, канд. техн. наук

Український державний університет залізничного транспорту, м. Харків, Україна, e-mail: railwayhub@yahoo.com

ФОРМУВАННЯ АВТОМАТИЗОВАНОЇ СИСТЕМИ РОЗРАХУНКУ ПРОПУСКНОЇ СПРОМОЖНОСТІ ЗАЛІЗНИЧНИХ МЕРЕЖ ДЛЯ ПРОСУВАННЯ ВАНТАЖОПОТОКІВ ПІДПРИЄМСТВ ГІРНИЧО-МЕТАЛУРГІЙНОГО КОМПЛЕКСУ

Purpose. The article deals with a higher accuracy estimation of traffic capacity of rail networks intended for transportation of raw materials and finished products of mining and smelting industries, which is based on the automated analysis.

Methodology. The methods of comparative analysis, mathematic modelling and forecasting have been employed.

Findings. The article deals with the development of the method that allows taking into consideration the operating reliability of a transportation system while forming an automated traffic capacity calculation system for rail networks. The authors have proposed statistical evaluation of operating reliability of a section using simulation modelling of primary and secondary train delays in the section timetable. The instantaneous availability of the system has been proposed as an evaluation ratio of operating reliability of the section. The method established the foundation for consecutive automated traffic capacity calculation of a rail network for freight transportation of mining and smelting industries. The results of failure modelling on a rail section testify considerable influence of secondary delays on operating reliability of the scheduling technology. The research substantiates the importance of taking into account organizational and technological failures in a timetable while formalizing the traffic capacity calculation of rail networks. The dependencies of instantaneous availability on the number of trains and an accepted reliability level on the test rail section have been defined.

Originality. An automated traffic capacity calculation method for more accurate evaluation of rational workload limits of a rail network has been designed. This automated method, unlike existing ones, takes into consideration the operating reliability of the rail transportation system of mining and smelting industries.

Practical value. The proposed automated traffic capacity calculation system for rail networks makes it possible to increase accuracy of determining the maximum amount of trains on the section and avoid its overloading which will increase the speed of freight flows and influence the efficiency of transport logistics for raw materials and finished products of mining and smelting industries.

Keywords: *mining and smelting industries, automation, traffic capacity, rail section*

Introduction. The rail network is one of the most significant links in supply chains of Ukraine's mining and smelting industries (MSI). Rapid and timely delivery of raw materials and finished products of MSI depends on conditions in which industrial and mainline transport operates. As is known, a rail section is one of the main elements of the transportation network. The analytical method for defining traffic capacity of rail sections employed in

Ukraine's railways is not quite appropriate due to overrated values of the actual traffic capacity, which impedes determining possible traffic capacity under the given quality of services. Thus, more accurate calculation methods are required for calculation of traffic capacity for rail sections. Improved accuracy and simplicity of labour-consuming manual calculations can be attained by developing automated traffic capacity calculation systems for rail sections of mainline and industrial transport servicing MSI.

Analysis of recent research and publications. Conventional approaches to calculation of traffic capacity of rail sections for MSI and rail mainline transport are similar. Some problems of higher calculation accuracy for traffic capacity of railways based on automation and application of information technologies were the point of concern of scientists and specialists among whom are V.M. Akulinichev, Ye.V. Arkhangelskyi, A.H. Bartkus, A.P. Baturin, T.V. Butko, N.A. Vorobiov, P.S. Gruntov, B. Del Rio, A.D. Karetnikov, B.S. Kozina, I.T. Kozlov, D.Yu. Lievin, A.M. Makarochkin, B.M. Maksimovich, B.Ya. Negrei, A.P. Petrov, N.V. Pravdin, V.V. Povorozhenko, N.A. Samarina, Ye.M. Tishkin I.H. Tikhomirov, K.K. Tikhonov and others.

In the mid-1960s M.S. Hrishyn was one of the first within scientific projects of the Central Scientific Research Institute who computerized traffic capacity calculation for rail sections using the Ural computer [1]. The approach proved efficient though a level of automation then did not allow disposing of manual calculations based on nomograms and tables for a section of minimal traffic. Evolution of the computer made it possible in the 1970s to computerize drawing maximal train traffic diagrams, which led to higher accuracy of traffic capacity calculations [1, 2]. Drawing maximal diagrams for a section eliminated the calculations being made only for minimal traffic sections. Among the drawbacks of the approach, one should mention considerable idealized character of designed schedules and the unjustified time-consuming nature [2].

Within the framework of recent research, study [3] gives the algorithm of automated traffic capacity calculations for single- and double-track lines used in mass calculations and substantiates the optimal development plan of rail technology. But a drawback of the automated approach is building an algorithm based on the analytical method which is applied in Ukraine's railways.

The world experience has demonstrated high efficiency in applying automated traffic capacity calculation systems for rail sections, based on the integrated approach with the use of simulation and optimization methods [4].

Unsolved aspects of the problem. The conventional method of actual traffic capacity calculation for rail sections [5] is mostly focused on the infrastructure potential and does not fully consider peculiarities and special character of train flows along the whole sections.

The functional traffic capacity calculation technique is applied for a section of minimal traffic (in section) while the actual traffic capacity is changing and depends on the character of a train flow along the whole section [1]. The conditions under which the trains run are influenced greatly by an operational technology chosen according to the train traffic schedule and dispatchers' recommendations. Reliability of the scheduling technology is directly connected with organizational and technological problems, namely, failures made by dispatchers, lack of arrival sidings at stations, failures in handling trains along the section due to other trains' delays when the section is overloaded, etc. As analytical formulas do not consider reliability of the organizational transportation technology on a calculated section, it leads to unjustified overrated values of traffic capacity and, as a consequence, more frequent train delays and increased operational charges.

Conventional methods of automated traffic capacity calculations are based on the analytical method considering only reliability of technical means of the infrastructure. Therefore, formalization of traffic capacity calculation of rail networks for mining and smelting industries is important; it will allow taking into account problems of operational reliability, i.e. organizational and technological faults in the train traffic schedule.

Objectives of the study. The main objective of the research is formation of an automated traffic capacity calculation system for rail networks intended for freight transportation of mining and smelting industries; it is based on calculation taking into account operating reliability of the transportation system, which, in turn, leads to the higher accuracy of traffic capacity calculation and elimination of labour-consuming manual calculations.

The main material of the research. The research deals with the designing of an automated traffic capacity calculation system for rail freight networks of mining and smelting industries; the method, unlike the conventional ones, considers the operating reliability of a transportation system. Formulation of basic concepts used for determining empirical dependences to verify the proposed method is important. The method considers operating reliability as the capacity of a rail section, as a system, of handling train flows according to the specified accuracy of a train traffic schedule at a given time (24 hours). Considering trouble-free operation as a character of the operating reliability one should define the concept of failure. It means an operational fault, i.e. a train delay at arrival or departure at each station of a section due to organizational and technological problems. Besides, train delays are classified into primary (caused by external random factors in transportation technology) and secondary (caused by primary delays of the first train and consequent failures in the schedules of other trains, which run on the site of the first delayed train) [6]. Fig. 1 shows the scheme of train routes on a double-track section when primary and secondary delays occur.

The process of consequent delays on a section, which is described above is nonergodic. In such conditions, the analytical investigation into reliability of the system is not effective due to its complexity. Therefore, the research proposes the statistical evaluation of operating reliability of the section using the simulation modelling method for various failures.

Instantaneous availability of the system has been proposed as an operating reliability indicator; it specifies that at the t moment the system is functional [7]. The calculation of availability can statistically be determined as

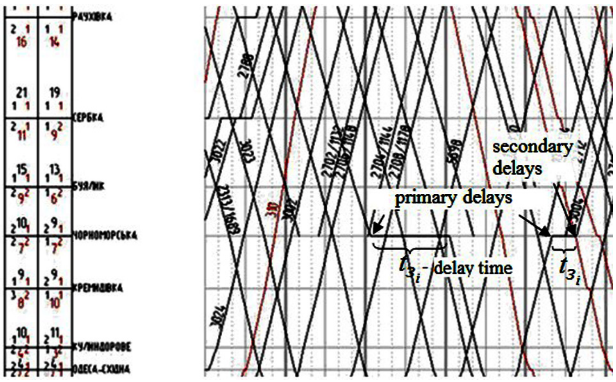

Fig. 1. Scheme of train routes on a double-track section when primary and secondary delays occur

$$\alpha_{expl} = \frac{\sum_{i=1}^{N}\sum_{j=1}^{k} t_{m_i}}{\sum_{i=1}^{N}\sum_{j=1}^{k} t_{m_i} + \sum_{i=1}^{N} t_{з_i}}, \quad (1)$$

where $\sum_{j=1}^{k} t_{m_i}$ is the stopping time of the i^{th} train according to the normative traffic schedule, hours; $t_{з_i}$ is the train delay due to organizational and technological problems at each station of the section, hours; $j = 1, k$, hours; N is the number of trains at the section. As traffic capacity of the section is defined for 24 hours, the availability should also be defined for a 24-hour period.

The authors propose to use an optimization mathematical model for designing the train traffic schedule as simulation modelling of the section operating with various delays. Considering lack of statistical investigations regarding the law of failure distribution in the traffic schedule within the rail networks of MSI, the research proposes to generate primary delays with the distribution law [8]. Taking into account research [9], according to each failure the delay time (when the train restores its running) is proposed to be modelled applying the exponential failure law with the rate of recovery $\mu = \frac{1}{t_в}$, where $t_в$ is the average recovery time.

In order to define the dependency of fulfilment of the train traffic schedule on failures rate, the authors have developed a program code in the Scilab environment, which helps to generate parameters of train delays in a normative train traffic schedule by specified factors, then, using an optimal model, to find a rational train traffic schedule considering failures, and to calculate an instantaneous availability according to (1). The optimization model for designing an optimal train traffic schedule uses a target function as a search criterion for the best train handling along the section; the function considers minimal wastes of all trains on the section and limitations regarding the number of reception and departure sidings at wayside stations of the section and wasting time over 30 min for a freight train at the section as inadmissible. The algorithm of routing for the train traffic schedule gives priority to passenger trains, followed by commuter trains, and then freight trains of all types. In order to ensure the validity of the experiment the modelling results were checked against conformity of the designed model for train traffic schedule with actual processes by the F-test (Fisher–Snedecor distribution). Fig. 2 demonstrates a segment of the train traffic schedule designed by modelling delays.

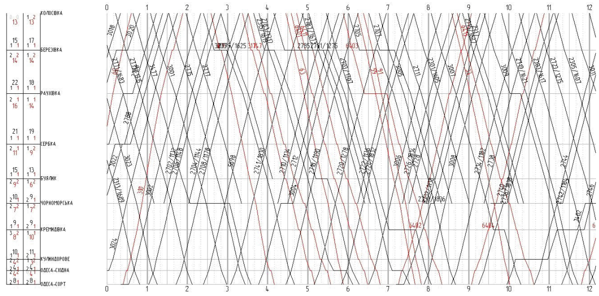

Fig. 2. A segment of the train traffic schedule on the Kolosivka – Odesa Sort. section with modelled delays on the section

For quantitative assessment of a secondary delay on the total time of organizational and technological delays the research describes experiments carried out on the Kolosivka-Odessa Sort. Section. In order to investigate mutual influence of trains under changes in operating reliability of the section it was proposed to define the availability for three workload levels, namely, for traffic volumes corresponding to a normative train traffic schedule in 2012 (N_{TTS}); the workload level of 80 % out of the maximum; the maximal workload level corresponding to the actual traffic capacity (N_{max}).

The results of failure modelling obtained testify considerable influence of secondary delays on operating reliability of scheduling technology. It has been established that even for free train traffic flows (the normative train traffic schedule) by variants of the average delay of 10, 20 and 30 minutes, part of primary delays accounts for approximate 40 % out of the total delay time, while part of secondary delays accounts for 60 % on the average. The dependency of duration of primary and secondary delays on the number of delayed trains in the normative train traffic schedule on the section Kolosivka – Odesa Sort. in both directions with various average times of primary delays is demonstrated in Fig. 3.

The dependencies obtained (Fig. 3) testify low response of the train traffic schedule to failures. Thus, up to 20 % of delayed trains out of the total number in the train traffic schedule do not influence the general operational situation on the section at all. Under conditions of high congestion in the section the situation is changing according to similar variants of the average delays of 10, 20 and 30 minutes; part of primary delays accounts for just 10 % out of the total delay time in the train schedule, while part of secondary delay time is 90 % on average. The results of modelling show a strong response of the operation under conditions of high congestion, thus the primary delay time of 5 minutes in the maximum train traffic schedule leads to a secondary delay, the total time of which is 507 minutes.

The dependency of the primary and secondary delay time on the number of delayed trains in the train traffic schedule corresponding to the actual traffic capacity on the Kolosivka – Odesa Sort. section in both directions with various average primary delay times is given in Fig. 4.

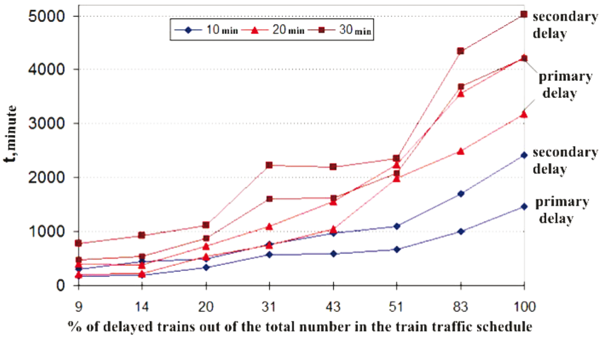

Fig. 3. The dependency of duration (t) of the primary and secondary delays on the number of delayed trains in the normative train traffic schedule on the Kolosivka – Odesa Sort. section in both directions with various average times of primary delays

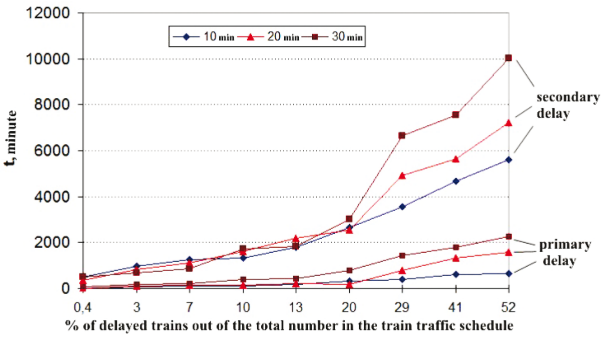

Fig. 4. The dependency of primary and secondary delay time (t) on the number of delayed trains in the train traffic schedule corresponding to the actual traffic capacity on the Kolosivka – Odesa Sort. section with various average primary delay times

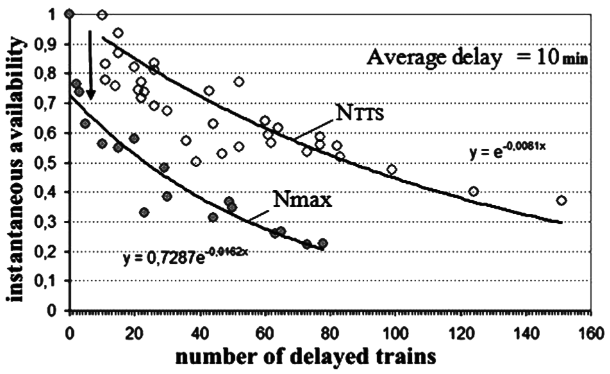

Fig. 5. The dependency of instantaneous availability on the number of delayed trains on the Kolosivka – Odesa Sort. section in both directions by various levels of the section loading: N_{TTS} – normative train traffic schedule; $N_{\max}$ – maximal workload level corresponding to train traffic schedule

The modelling results made it possible to define the dependencies of an instantaneous availability on the number of delayed trains on the Kolosivka – Odesa Sort. section in both directions by different levels of station workload, which demonstrate rapid transition from a free train flow to synchronized movement and then to a holdup at the congested section (Fig. 5).

On the base of the above-mentioned research the authors propose the following sequence of automated carrying capacity calculation for the railway infrastructure which takes into account the operating reliability of the transportation system:

1. The calculation of the actual carrying capacity of the rail section according to the Instruction [5]. The calculated maximum number of freight trains n_{fr} while determining the actual carrying capacity of the section with a constant interval timetable and the previously specified number of trains of all other types (n_{pas} stands for passenger trains, n_{com} stands for commuter trains, n_{as} stands for assorted trains) are taken as the total number of trains ($n_{actual} = n_{fr} + n_{pas} + n_{com} + n_{as}$) corresponding to the maximal workload level of the station. All other types of station workload for modelling delays are calculated according to a specified maximum workload level at the station.

2. Statistical investigation into the impact of organizational and technical failures are to be conducted (a one-year period is desirable for the analysis). The laws of failure distribution and traffic recovery time on the section and their characteristics are to be established. Due to lack of statistics primary delays are described with the Poisson distribution law, and according to each failure the recovery time is described by the exponential failure law.

3. Primary delays are modelled according to the given parameters of the distribution law, then the rational train traffic schedule is searched, which takes into account failures; and the instantaneous availability is defined according to formula (1). Fulfilment of the following conditions regarding failure modelling and regulations on experimental data processing is important:

- for double-track sections the instantaneous availability is calculated for each direction separately whereas for single-track ones it is estimated for both directions simultaneously;
- the calculation should be made for three workload levels, especially for traffic volumes which correspond to a free train traffic mode (the normative train traffic schedule); the workload level of 80 % of the maximum workload; the maximum workload level corresponding to the actual carrying capacity of the rail section or close to it;
- while modelling each workload level one should accept similar operating conditions along the section for all trains, in which the high-speed mode differs from the speed of a train and which are taken for defining the actual carrying capacity (n_{pas}, n_{com}, n_{as}). A specified departure time and the normative stoppage mode of these categories remain the same for each of the accepted workload levels;
- for each loading level the availability factor is calculated for the number of delays, accepted in accordance with fulfilment of the train traffic schedule $p(n)$ $\forall$ (90, 80, 70, 60 %) depending on the total number of trains according to a section workload level and a specified average delay time (10 and 20 minutes);
- the modelling results are stored in the database; nomograms are automatically built searching for analytical dependencies of the instantaneous availability α_{expl} on the number of trains, an accepted reliability level at the sec-

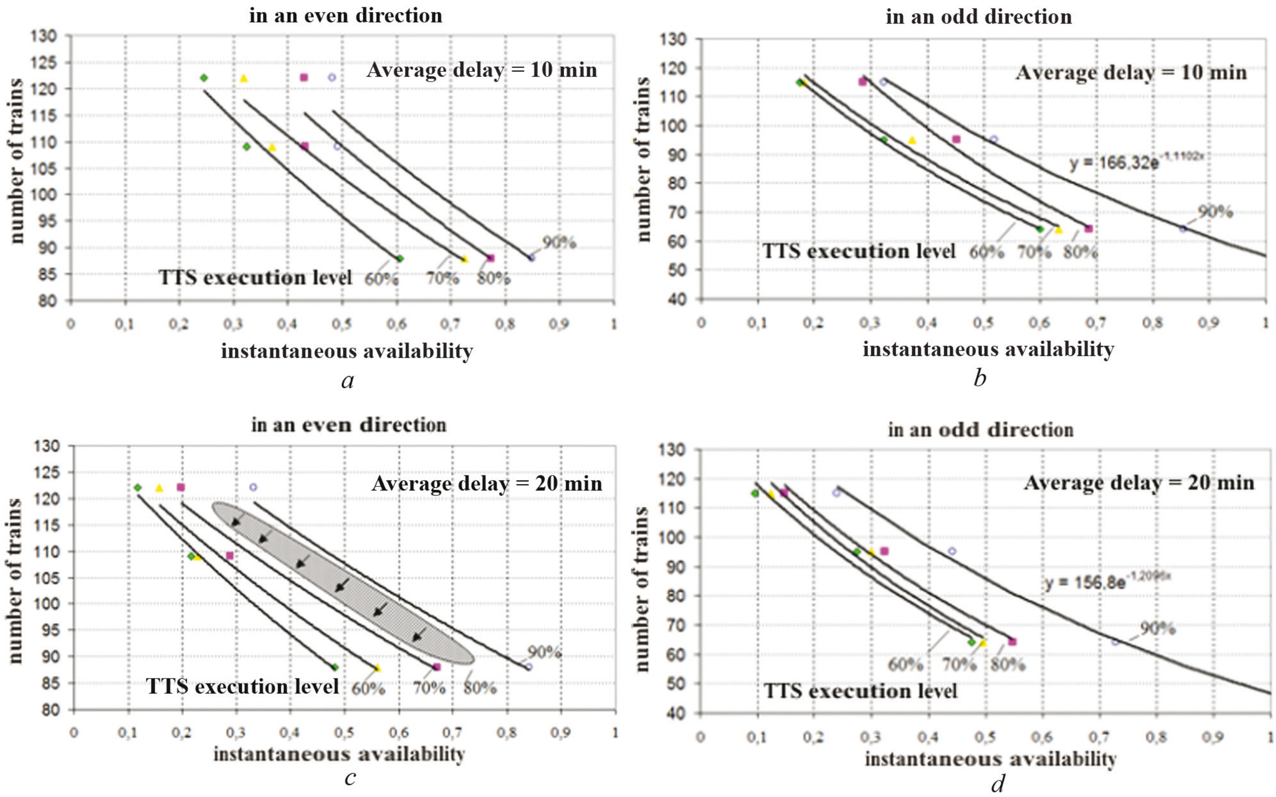

Fig. 6. Dependency of the instantaneous availability on the number of trains and accepted level of reliability of scheduling technology on the Kolosivka–Odesa Sort.: *a – in an even direction with an average delay time of 10 minutes*; *b – in an odd direction with an average delay time of 10 minutes, c – in an even direction with an average delay time of 20 minutes*; *d – in an odd direction with an average delay time of 20 minutes*

tion and given average delay time $t_в$. These analytical dependences are defined by the least square method.

4. The calculation of the maximum possible number of trains on the section during the fulfilment of the train traffic schedule in both directions at the given reliability level $p(n)\ \forall$ (90, 80, 70, 60 %), the accepted availability of trains $\alpha_{expl}^{normative}$ and the given average delay time $t_в$ is made according to the defined exponentially lowering dependency

$$n^{practical} = a \cdot e^{-b \cdot \alpha_{expl}^{normative}}, \qquad (2)$$

where a, b are parameters of the function defined by the least square method while analysing dependencies of the instantaneous availability α_{expl} on the number of trains and the accepted reliability level on the section; $\alpha_{expl}^{normative}$ is the instantaneous availability α_{expl} defined by norms according to an accepted operational mode of the rail infrastructure operation for a freight year; $n^{practical}$ is the maximum number of trains in the train traffic schedule which will run along the section observing the set reliability level regarding the train traffic schedule $p(n)$, the accepted instantaneous availability $\alpha_{expl}^{normative}$ and the defined average delay time $t_в$.

5. The calculation of the number of freight trains on sections of mainly freight traffic with a constant interval timetable corresponding to the accepted execution level of train traffic schedule is defined by the formula

$$n_{fr}^{practical} = n^{practical} - (n_{pas} + n_{com} + n_{as}), \qquad (3)$$

where n_{pas}, n_{com}, n_{as} stand for the number of trains (pairs of trains) of different types according to the accepted conditions of railway operation (the given number of trains should correspond to the initial delay modelling conditions).

Formulas (2–3) are calculated for a double-track section separately according to traffic directions, for a single-track section – for both directions simultaneously. The outcome obtained by (2–3) is rounded up to the integral number.

As an example, the research calculates dependencies of the instantaneous availability α_{expl} on the number of trains and accepted reliability level $p(n)$ on the Kolosivka–Odesa Sort. section. Taking into account that the Kolosivka – Odesa Sort. section is a double track, the calculations were made for each direction separately. The nomograms of dependencies obtained are given in Fig. 6, *a–d*. In order to investigate the influence of a primary delay on the reliability of the section operation it was proposed to make calculations in two variants of an average delay time: 10 and 20 minutes.

The analysis of the nomograms in Fig. 6, *a–d* testifies the existence of phase transition between modes of train traffic flows on the section. Thus, the nomograms in Fig. 6, *c–d* demonstrate a break between the given reliability of 90 % with lower levels (a shaded area in Fig. 6, *c*) that testifies an abrupt transition from free train traffic to a synchronized flow and a holdup. Various stability of the train traffic schedule in modelling primary delays of an average time of 10 and 20 minutes testifies a considerable influence of both the number of primary delays and their times on reliability of train flows across the section.

Conclusions and prospects of further development of the research. The proposed automated traffic capacity calculation system for rail networks will make it possible to improve accuracy in calculation of maximum number of trains on a section and avoid its overloading contributing, thus, to more efficient transportation of freight flows and effective logistics services in transportation of raw materials and finished products of MSI. In prospect, the proposed automated information system enables the system of a new generation, which is part of the decision-making system – that is an interactive computer system designed to support decision-making regarding the management of carrying capacity of the railway network encompassing mainline transport and MSI.

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Мета. Робота присвячена питанню підвищення точності оцінювання пропускної спроможності залізничних мереж для перевезення сировини та готової продукції підприємств гірничо-металургійного комплексу на основі автоматизації розрахунків.

Методика. Використано методи порівняльного аналізу, математичного моделювання, прогнозування.

Результати. Для формування автоматизованої системи розрахунку пропускної спроможності залізничних мереж у роботі розроблено метод, що дозволяє врахувати експлуатаційну надійність системи перевезень. Запропоновано статистично оцінити експлуатаційну надійність роботи дільниці за допомогою застосування імітаційного моделювання первинних та вторинних затримок поїздів у графіку руху на дільниці. В якості показника оцінки експлуатаційної надійності роботи дільниці запропоновано використати нестаціонарний коефіцієнт готовності системи. На основі даного методу розроблена послідовність проведення автоматизованого розрахунку пропускної спроможності залізничної мережі для просування вантажів підприємств гірничо-металургійного комплексу. Обґрунтована важливість обліку збоїв у графіку руху поїздів, пов'язаних з організаційно-технологічними причинами при формалізації розрахунку пропускної спроможності залізничних мереж. Знайдені залежності нестаціонарного коефіцієнта готовності від кількості поїздів та прийнятого рівня надійності на експериментальній залізничній дільниці.

Наукова новизна. Розроблено автоматизований метод розрахунку пропускної спроможності залізничних мереж для підвищення точності оцінки їх раціональних меж завантаження, що, на відміну від існуючих, дозволяє врахувати експлуатаційну надійність системи перевезень вантажів підприємств гірничо-металургійного комплексу на основі автоматизації.

Практична значимість. Запропонована автоматизована система розрахунку пропускної спроможності залізничних мереж дозволить підвищити точність визначення максимальної кількості поїздів на дільниці та уникати її перевантаження, що, у свою чергу, підвищить швидкість просування вантажопотоків та вплине на ефективність формування логістики перевезень сировини та готової продукції підприємств гірничо-металургійного комплексу

Ключові слова: *підприємства гірничо-металургійного комплексу, автоматизація, пропускна спроможність, залізнична дільниця*

Цель. Работа посвящена вопросу повышения точности оценки пропускной способности железнодорожных сетей для перевозки сырья и готовой продукции предприятий горно-металлургического комплекса на основе автоматизации расчетов.

Методика. Использованы методы сравнительного анализа, математического моделирования, прогнозирования.

Результаты. Для формирования автоматизированной системы расчета пропускной способности железнодорожных сетей в работе разработан метод, который позволяет учесть эксплуатационную надежность системы перевозок. Предложено статистически оценить эксплуатационную надежность работы участка с помощью применения имитационного моделирования первичных и вторичных задержек поездов в графике движения на участке. В качестве показателя оценки эксплуатационной надежности работы участка предложено использовать нестационарный коэффициент готовности системы. На основе данного метода разработана последовательность проведения автоматизированного расчета пропускной способности железнодорожной сети для продвижения грузов предприятий горно-металлургического комплекса. Обоснована важность учета сбоев в графике движения поездов, связанных с организационно-технологическими причинами, при формализации расчета пропускной способности железнодорожных сетей. Найдены зависимости нестационарного коэффициента готовности от количества поездов и принятого уровня надежности на экспериментальном железнодорожном участке.

Научная новизна. Разработан автоматизированный метод расчета пропускной способности железнодорожных сетей для повышения точности оценки их рациональных границ загрузки, которая, в отличие от существующих, позволяет учесть эксплуатационную надежность системы перевозок грузов предприятий горно-металлургического комплекса на основе автоматизации.

Практическая значимость. Предложенная автоматизированная система расчета пропускной способности железнодорожных сетей позволит повысить точность определения максимального количества поездов на участке и избегать ее перегрузки, что в свою очередь, повысит скорость продвижения грузопотоков и повлияет на эффективность формирования логистики перевозок сырья и готовой продукции предприятий горно-металлургического комплекса.

Ключевые слова: *предприятия горно-металлургического комплекса, автоматизация, пропускная способность, железнодорожный участок*

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Ou Ye,
Zhanli Li

Xi'an University of Science and Technology, Xi'an, China

SIMILARITY DISTANCE BASED APPROACH FOR OUTLIER DETECTION BY MATRIX CALCULATION

Оу Є,
Чжаньлі Лі

Сіаньський науково-технічний університет, м. Сіань, КНР

ПІДХІД ДО ВИЯВЛЕННЯ ВИКИДІВ ЗА ДОПОМОГОЮ МАТРИЧНИХ ОБЧИСЛЕНЬ, ЗАСНОВАНИЙ НА МІРІ СХОЖОСТІ

Purpose. In client information, string outliers need to be detected and cleaned. At present, many outlier detection algorithms only focus on the semantics of data, and ignore the structure, so it is difficult to ensure the accuracy of outlier detection. In order to address this issue, outlier detection method based on similarity distance is suggested in this paper.

Methodology. We formulated the similarity calculation model of string data by combining with semantic and structure factors. According to the outlier detection theory in data cleansing, one-dimensional string data were projected to two-dimensional space and string outlier data were detected by using a new similarity measurement mechanism in the two-dimensional space.

Findings. We first got the word frequency of string data by using the matrix calculation. Then the semantic similarity and structure similarity were calculated by using word frequency. After the string data mapping from one-dimensional to two-dimensional space, we obtained the outlier data by using the similarity distance.

Originality. We made a study of string outlier detection in data cleansing. Firstly, we formulated the similarity calculation model by considering the semantic factor and structure factor. Secondly, by constructing the similarity cell to project the string data, we fulfilled the similarity distance measurement in the similarity cell.

Practical value. The method can be used to clean the outlier string data in client information for any enterprise so that to ensure the data quality of client information, and reduce the costs of data maintenance. Extensive simulation experiments have been conducted to prove the feasibility and rationality of this method. The results showed that this method allows improving the accuracy of string outlier detection.

Keywords: *data quality, data cleansing, outlier detection, matrix calculation, semantic similarity, structure similarity, similarity cell, similarity distance*