Keywords: working capacity; queuing system; railway line; batch coefficient; removal coefficient

Halyna NESTERENKO, **Mykhailo MUZYKIN***, **Volodymyr HOROBETS**,
Svetlana AVRAMENKO
Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan
Lazaryana, 2, 49010, Dnipro, Ukraine
**Corresponding author*. E-mail: mihailmuzykin@gmail.com

WORKING CAPACITY RESEARCH OF TRACK SECTIONS

Abstract. The paper identifies the problems and ways to implement the measures to increase the working and carrying capacity of railway lines. The analysis of this problem shows that for Ukrainian rail network there is no holistic approach to formalize procedures for calculating the working capacity of track sections taking into account technological features of passage of individual car traffic volumes. In addition, there are few studies of factors that influence the level of working capacity use. This necessitates research in this area, which can be a basis for calculating working capacity of sections depending on the influence of various factors. The main ways to increase the working and carrying capacity of railway lines are to increase the weight and length of the trains. But it is a difficult complex task. When solving this task it should be considered restrictions on the useful length of station tracks, restrictions on the traction force of locomotives, possible reduction of train service speed, and many other additional factors. Increase of the train weight makes it possible to increase the carrying capacity of railway lines on the average by 10-30%. But the problem of train weight is closely connected with analysis of the length of existing receiving and departure tracks on the main directions of train movement of OJSC "Ukrainian Railways." Having analyzed the working capacity reserve at all the existing lines of Dnipropetrovsk Management of Rail Transportations we can conclude that the available working capacity exceeds the required one (the reserve is sufficient).

1. INTRODUCTION

For railway section it is distinguished the available, required and effective working capacity. The need for strengthening the capacity arises when the required capacity is approaching the available one. When solving this problem one should analyze whether all the technical means are used efficiently and whether it is possible to reduce the required working capacity by eliminating non-optimal transportations.

Railway line capacity is influenced by many factors such as the number of main tracks; communications, operating at the railway line; type and power of locomotives; way of the train movement organizations; structure of train traffic volume on the line; train movement speed; intervals between the trains; duration of free periods meant for track repair; the features of plan and profile of railway line sections; coefficients of train removal of different categories; track development of separate points of the railway line; type of schedules and others.

2. LITERATURE REVIEW AND DEFINING THE PROBLEM

Many scientists around the world studied the problem of working capacity research. Recent developments on this issue are presented below.

The article [1] studies the process of train movement in the direction (double-track line with marshalling yard) under extreme conditions when the periods for track overhaul are offered. When researching this process it was calculated the time to restore normal movement after the repair period. In this process there are no organizational interventions aimed at changing certain parameters. The study found that the main capacity losses during the repair period are formed in the schedule as a result of disturbances caused by movement interruption, not the interruption itself. One can reduce the working capacity losses of properly influencing this process.

The article [2] formed a mathematical model determining the schemes of locomotive circulation. The model takes into account a set of technical and technological factors inherent in the transportation process at the railway network in Ukraine. This allows efficient use of the section working capacity taking into account individual approach to the choice of traction provision at the tactical level of transportations.

The work [3] proposes the method of working capacity calculating based on parametric models, which allows defining rational relationship between intensity and density of train traffic volumes at the section. It should be noted that the use of found dependences to determine the working capacity is limited by the conditions of the section under study. In addition, the dependences are valid only under conditions of constant operating mode of the station.

Analysis of the railway functioning in a competitive rail market has shown that the process of distribution of the railway infrastructure capacity becomes important. In the work [4] it is justified the necessity of developing new methods of management of railway infrastructure capacity in terms of reforming the railway transport of Ukraine.

In the article [5] on the basis of the analysis of methods for calculating the working capacity of railways infrastructure the advantages and disadvantages of each method were identified. Analytical methods are simple in calculation and are usually used to estimate the theoretical (available) working capacity, but it does not account for the stochastic nature of the train movement and the impossibility of accounting characteristics of the train traffic volumes. Simulation methods make it possible to describe the random nature of transportation process in dynamic perspective. The disadvantage of this approach is the difficulty of practical adaptation of the developed simulation model to the existing railroad infrastructure and time-consuming. The most common in the EU is optimization method. Moreover it provides better solution accuracy than calculations using analytical methods.

International Union of Railways in 2004 developed the UIC 406 R standard [6] concerning the working capacity research. The basis of this legal document is the market oriented approach to determine working capacity. Special attention in the UIC 406 R deserves the calculation of practical capacity using optimization method, called the method of schedule compaction.

The conducted in the work [7] analysis of the bases for determining railway infrastructure capacity within a market-oriented approach confirms the imperfection of existing methods of capacity calculation at the railways of Ukraine. It is proposed the approach, in which to specify the value of working capacity it is necessary to take account the reliability of train schedule performance.

According to the work [8], the following definitions of working capacity are distinguished: theoretical capacity, practical capacity, used capacity and available capacity. According to the studies [9], the practical capacity (which takes into account the reliability of schedule performance and depends on the level of use of the working capacity) is about 60%-75% of the theoretical, which is determined in advance. In order to represent the relationship between the parameters of working capacity, it is proposed it included the number of trains, average speed, heterogeneity and stability of schedules – the quality model working capacity balancing is proposed [10].

The work [11] describes the importance of correct choosing the length of the section of line under study and the correct way to study the lines with double-track sections. This article provides a method of research of expected carrying capacity using the future schedule.

One of the approaches [12] offers to assess the schedule stability depending on the complexity of operations. The more conflicts (disagreements) in schedule, the lower stability and, thus, the reliability of such train schedule.

New systems of train movement control improve the work of station operators controlling the movement of trains [13]. Using such global navigation systems and radio communication systems GSM-R, the train can be stopped from the traffic control center if the train movement system failed or there is an abrupt detraction of the locomotive driver.

The article [14] considers the statement and implementation algorithm of the mathematical model of empty cars distribution for loading in the rail transportation hub. It takes into account the use requirements of car owners, operational level of loading the railway stations of the hub and the possibility to include the groups of empty cars to the transmission and clean-up trains. This not only accelerates the train circulation, but also improves the use of working capacity of adjacent stations of the railway hub.

One of the main types of unproductive downtime during railway cargo transportations is the downtime at marshalling yards waiting for performing the technological operations because of the system load [15]. Reducing this figure is possible with the rational use of working capacity of marshalling yards provided rational distribution of car and train traffic volumes between the basic marshalling yards of OJSC "Ukrainian Railways."

The work [16] considers the method of scheduling theory, on the basis of this method the train schedule is developed. It was also paid attention to the algorithm for calculating the working capacity: the principle of this algorithm is based on searching the most completed schedule under condition of minimum costs for train movement within the section.

The above mentioned analysis shows that for Ukrainian rail network there is no holistic approach to formalize the procedure for calculating the working capacity of track sections taking into account technological features of passage of individual car traffic volumes. In addition, there are few studies of factors that influence the level of working capacity use. This necessitates research in this area, which can be the basis for calculating working capacity of stations depending on the influence of various factors.

3. METHODOLOGY

The ways of strengthening the carrying and working capacity are divided into two groups:

organizational and technical ones, which do not require significant financial cost, but make it possible to increase the capacity due to the better use of equipment and improving the technology;

reconstructive ones related to the technical re-equipment of the lines and large investments (see Tab. 1).

The main condition of taking all the measures to increase the carrying and working capacity of the lines is the adherence to the principles of completeness and phasing the works. The principle of phasing involves performing the priority works at the most loaded elements of the lines with increasing capacities.

The measures to increase the working capacity as a result should provide: security of the train movement; the given amount of traffic; operation reliability; improvement of the quality of operational performance and reducing the costs of transportation.

Since the railway line is a complex, dynamic, stochastic, ergatic system, it can be represented as a complex queuing system, the traffic volumes of which come along the tracks, stations and interstations.

Tab. 1

Tasks and ways to perform the measures to increase the carrying and working capacity of railway line

Measures	Tasks		Ways to implement
	Increasing the amount of train traffic	Increasing the train weight	
Reconstructive	- double-track inserts and second tracks laying; - opening new interstations; - electric centralization of switch points; - the transfer of the section to automatic blocking and centralized traffic control.	- increase of the lifting force of cars; - the use of more powerful locomotives; - modified grading.	Equipment of railway haul and sections with automatic blocking devices improves their capacity, allowing batch train movement in both directions. Especially effective is to equip the double-track lines with automatic blocking. Real capacity of the sections on the hauls, which is available in the 6-minute interval is 240 trains of the parallel schedule. The most radical way to increase working capacity during trackage reconstruction is laying the second tracks. The capacity of double-track line as compared to a single-track one ceteris paribus is 2.2 – 2.5 times higher. The service-speed is higher at the double-track lines too. The main reconstructive measure today is the electrification of railway lines. Further reconstruction is to create DC and AC double-way feed electric locomotive of third generation.
Organizational and technical	- reducing the station intervals; - reduction of removal coefficient; - introduction of more effective types of graphs.	- organization of pushing the trains; - use of divisible traction; - doubling the trains.	Reducing the intervals between trains in the sections with automatic blocking is possible by adding and permutation of intermediate signals, transition to the train traffic plan with delimitation of two block sections instead of three ones, implementation of four-aspect system, increase of movement speeds due to electric traction. In the double-track sections it is possible to organize the batch movement of passenger trains with the same speeds, not separate movement. This will reduce removal coefficient and free up additional time for freight trains pass. To organize the batch movement of passenger trains it is needed the running of these trains with the speeds within two or three gradations, and the batches should contain the trains with one gradation of the same duration and number of stops.

Entering a station the traffic volume is served with corresponding parameters (there can be several channels and several phases of service), and thus it comes out the traffic volume with other parameters, which in turn influence capacity of the railway line Np. The system is aimed to provide transportation of cargo and train traffic volumes with a given average speed and minimal operating costs and unconditional movement safety performance.

The railway line subsystems are the train stations and railway sections, the elements are the haul tracks, receiving-departure and marshalling yards of stations, yard necks, trains, locomotives, cars, involved workers, etc. Complexity, multicriteriality, and high dynamism of behavior are peculiar to railway lines as a system.

Dynamics of train weight increase was observed more than a century in the Ukrainian railways development: over the last 50 years increase in the average weight of trains occurred from 500 tons to 4000 tons. Clearly, the weight increase occurred with the development of traction rolling stock, the power of which was gradually increased. Accordingly, the axle load of cars was increased too. It reached the limit of 25 tones/axle. Increased train weight is almost certainly causes increase in the train length. Therefore, to increase the carrying capacity of railway lines prerequisite is to increase the weight and length of trains. According to the results of studies of the main directions of rail transportations in some sections during the weight increase to 4500 tones it is necessary to use the pusher or double heading locomotives.

This increases the resource consumption for passage of trains. Dependence of the resource consumption on the train weight at the basic directions taking into account the costs for additional locomotive traction is shown in the Figure 1 (on the X axis it is presented − Q, t, and on the axis У − E, kW).

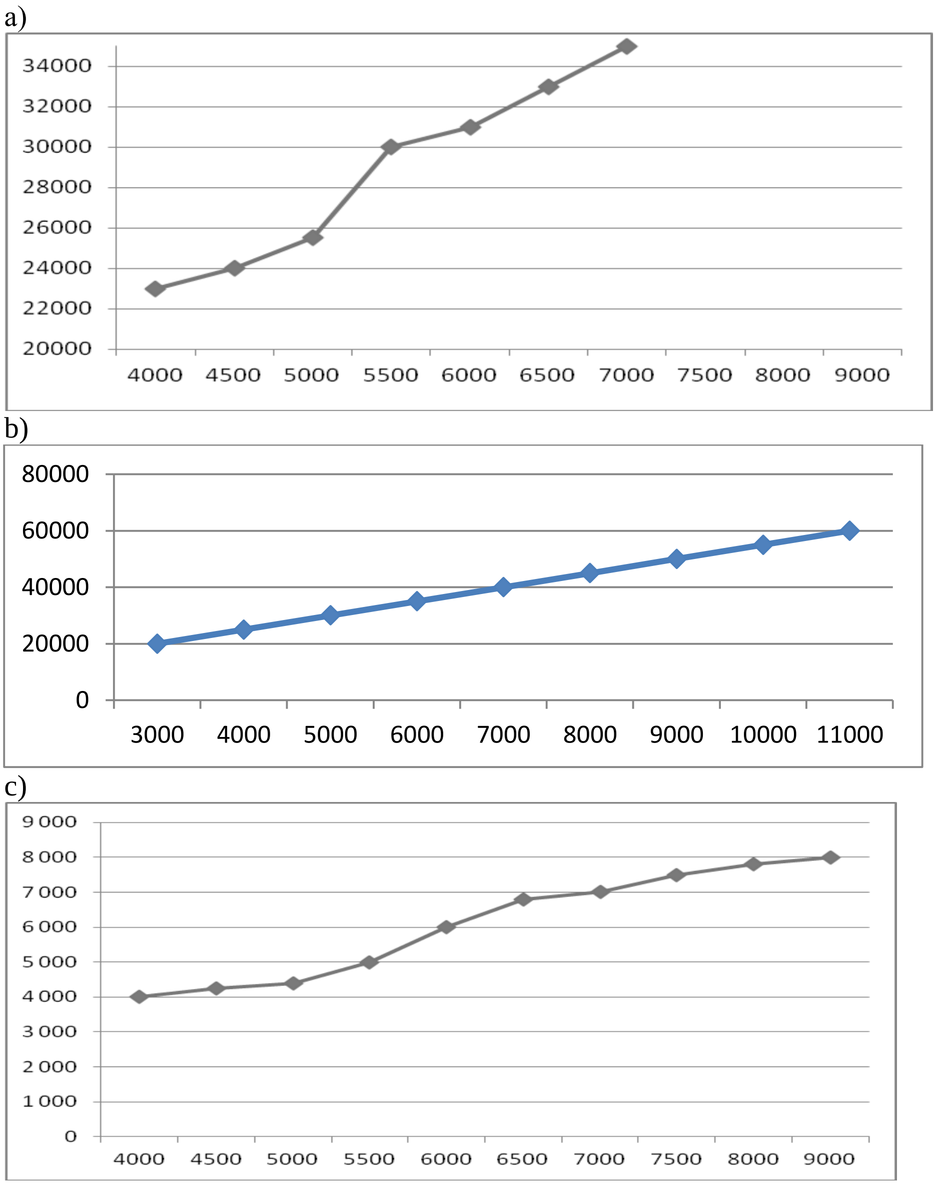

Fig. 1. Dependence of fuel equivalent coonsupmtion (kW) on the train weight at the main railway directoins: a) Verkhivtsevo section; b) Vuzlove section; c) Synelnykove section

The train weight increase at these directions can increase the carrying capacity of lines by an average of 10-30%. But it is necessary to consider some limitations. Increased train weight is almost certainly increases the length of trains. In terms of limiting the train length the standard length of receiving and departure tracks is 850 m. Further increase of the train weight is impossible, because the average static loading of cars within 65-75 t/car makes it possible to take trains weighing 3700-4300 tons. Therefore, the problem of train weight increase is closely connected with the analysis of the length of existing receiving and departure tracks at the basic directions of train movement of Ukrzaliznytsia. Moreover, the power of locomotives in some sections is used as much as possible, but given the age of locomotives and their wear it can cause additional problems.

The removal coefficient for high-speed passenger trains and other long-distance and local passenger and suburban trains, which have a net time of movement less than that of freight trains is determined for the calculated section, which is equipped with automatic block system (centralized traffic control) as follows:

$$\varepsilon_{pas} = 1 + 0,06\alpha_{batch} - \frac{20 \cdot C_s^f}{N_{pas}}, \qquad (1)$$

where α_{batch} – batch coefficient;

$C_s^f = C_f / \Sigma C$ – share of four-track stations in the calculation;

C_f – number of four-track stations;

ΣC – total number of intermediate interstations in the calculated section

N_{pas} – the total number of passenger and suburban trains.

ε_{pas} cannot be less than 1.

Let us perform corresponding calculations of the removal coefficient for high-speed passenger trains:

– with changed batch coefficient from 0.1 to 1 and construct a dependence graph (see. Figure 2).

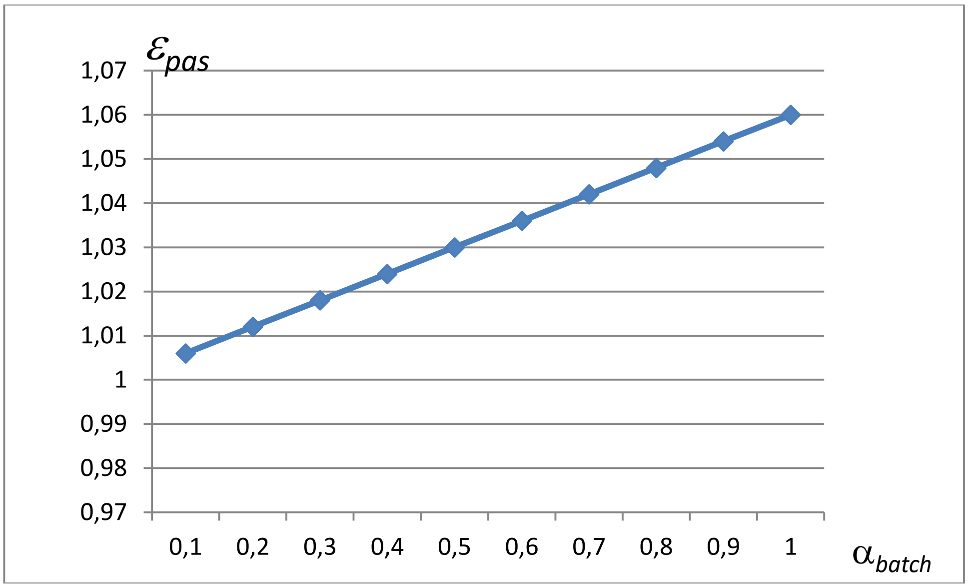

Fig. 2. Dependence of the removal coefficient of passenger trains on the batch coefficient

After simulation modeling of the working capacity at the section with the changed removal coefficient one can see that the larger the batch coefficient, the greater the removal coefficient (see Figure 3). Thus, the working capacity will increase.

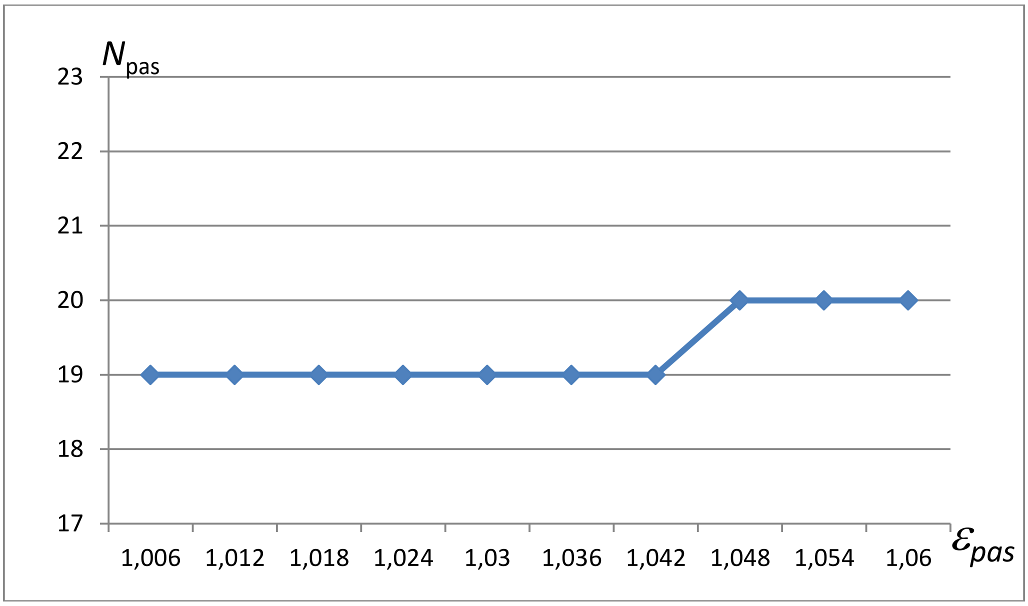

Fig. 3. Dependence of the working capacity on removal coefficient, which in turn depends on the batch coefficient

With modified share of four-rack stations in the calculated section from 1 to 10:

$$\varepsilon_{\text{pas}} = 1 + 0.06 \cdot 0.1 - \frac{20 \cdot 1}{10} = -0.999 .$$

After the first calculation one can see that εpas is less than 1, but this is impossible. Therefore, it can be concluded that the more four-track stations at the section, the lower the removal coefficient.

At the one-track stations equipped with automatic block system (centralized traffic control) mainly with freight traffic the removal coefficient for pickup trains is determined by the following formula:

$$\varepsilon_{\text{pick}} = \delta(1.2 + 0.9C_{\text{pick}}) + 0.4N_{\text{pas}}(1 - \Delta) - 0.5, \quad (2)$$

where δ – the ratio of intervals between trains in unpaired and pair directions in case of the batch schedule to the period of non-batch schedule on limiting interstation

C_{pick} – the number of stations at the section, which are served by a pickup train;

Δ – the average ratio of net time of travel for the pair of passenger (suburban) trains to the travel time of pair of freight trains in the calculated section.

After calculating the capacity at the section, it can be seen that the higher the ratio of between train intervals in unpaired and pair directions, the greater the removal coefficient. Thus, the working capacity will also be increased.

Changing the number of stations at the section, which is served by a pickup train from 1 to 10 it is obtained the dependency (see Figure 4).

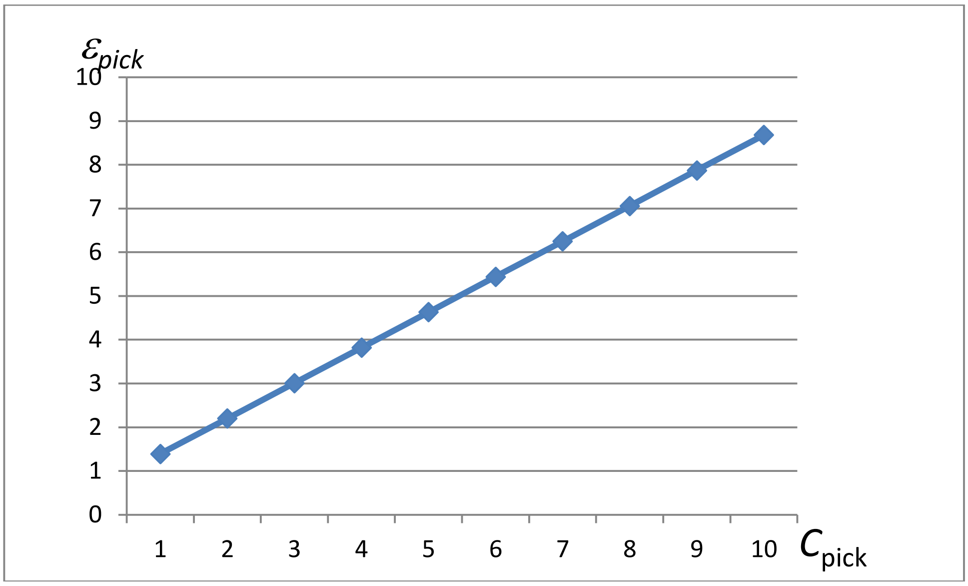

Fig. 4. Dependence of the removal coefficient on the number of stations at the section, which is served by a pickup train

After calculating the working capacity at the station one can see that the higher the ratio of stations number at the section, which is served by a pickup train the greater the removal coefficient. Thus, the required working capacity will also be increased (see Figure 5).

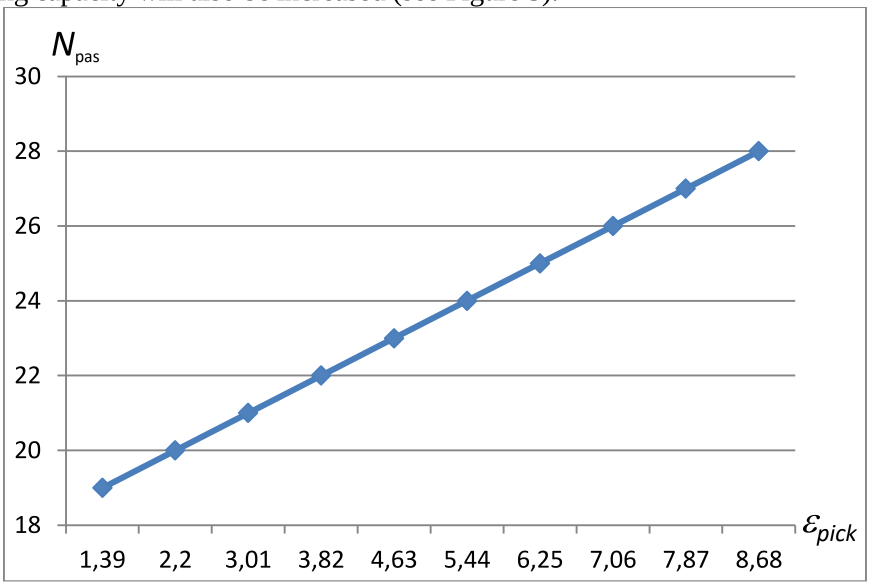

Fig. 5. Dependence of the working capacity on removal coefficient, which in turn depends on the ratio of stations number at the section served by pickup train with modified average ratio of net time of travel of pair of passenger (suburban) trains to the travel time of pair of freight trains at the calculated section from 0.1 to 1

After calculating the working capacity at the section one can see that the more the ratio of net travel time of pair of passenger (suburban) trains to the travel time of pair of freight trains, the greater the removal coefficient (see Figure 6). Thus, the capacity will also be reduced (see Figure 7).

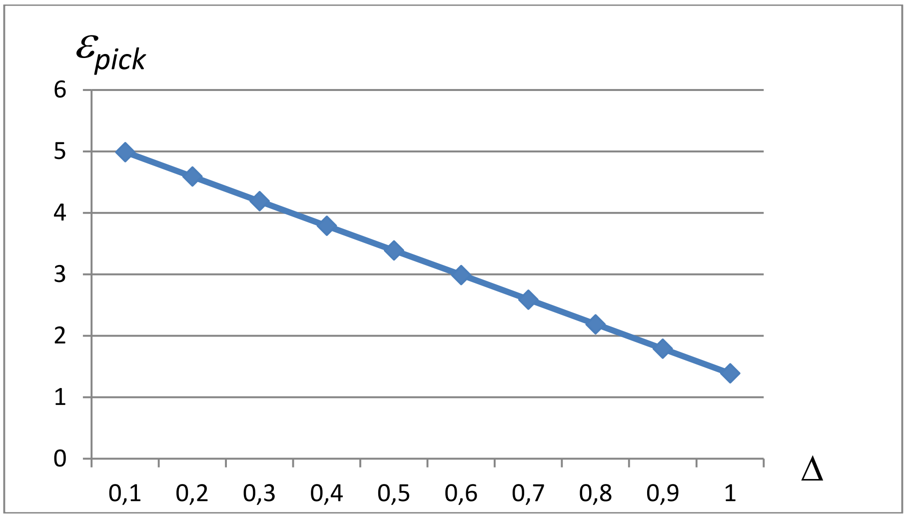

Fig. 6. Dependence of removal coefficient on the average ratio of net travel time of pair of passenger (suburban) trains to the travel time of pair of freight trains at the calculated station

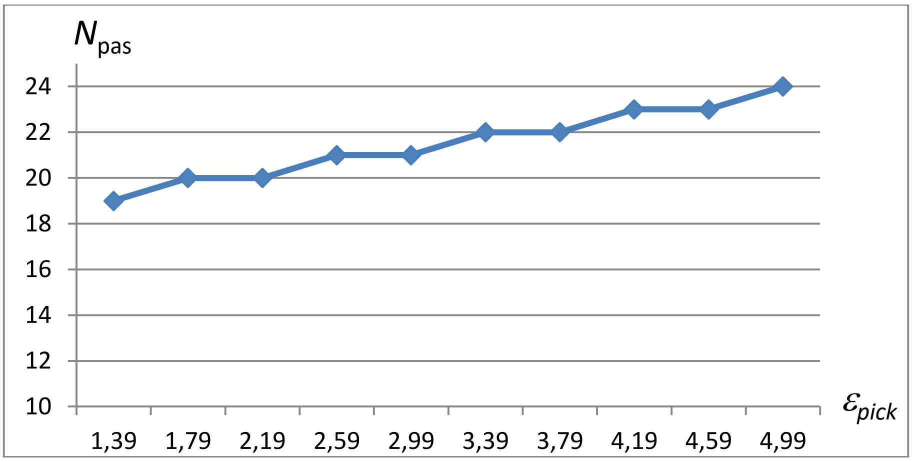

Fig. 7. Dependence of the working capacity on removal coefficient which in turn depends on the ratio of net travel time of pair of passenger (suburban)trains to travel time of pair of freight trains

4. CONCLUSIONS

The railway line capacity is influenced by many factors that depend on both, the parameters of railway line and the parameters of train servicing at the stations. It is impossible to describe their relationship using analytical methods, because when studying the factors affecting the level of working capacity use, it is advisable to use simulation and ergatic models of railway lines and stations.

The main way to increase the working and carrying capacity of railway lines is increasing the weight and length of trains. But it is a difficult complex task, when solving which it should be considered the restrictions on the useful length of station tracks, and the restrictions on the traction force of locomotives, and possible reduction in service speed of trains, and many other additional factors. Increase of train weight can increase the carrying capacity of railway lines by an average of 10-30%. But the problem of train weight increase is closely connected with the analysis of the length of the existing receiving and departure tracks at the main directions of Ukrzaliznytsia's trains.

Having analyzed the working capacity reserve at all the existing lines of Dnipropetrovsk Management of Rail Transportations we can conclude that the available working capacity exceeds the required one (reserve is sufficient).

References

1. Музикін, М. І. & Нестеренко, Г. І. Вплив «вікон» на пропускну спроможність залізничного напрямку. *Наука та прогрес транспорту. Вісник Дніпропетровського національного університету залізничного транспорту ім. акад. В. Лазаряна*. 2014. No. 3 (51). P. 24-33. [In Ukrainian: Muzykin, M.I. & Nesterenko, H. I. Influence of maintenance windows on the working capacity of railway route. *Science and Transport Progress. Bulletin of Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan*]
2. Butko, T. & Prokhorchenko, A. & Muzykin , M. An improved method of determining the schemes of locomotive circulation with regard to the technological peculiarities of railcar traffic. *Eastern-European Journal of Enterprise Technologies*. 2016. Vol. 5, Issue 3 (83). P. 47-55. doi: 10.15587/1729-4061.2016.80471
3. Прохорченко, А. В. & Тревогін, О. І. & Болкун, О. Дослідження пропускної спроможності залізничної дільниці на основі побудови параметричних функцій залежності інтенсивності від щільності поїздопотоків. *Збірник наукових праць Української державної академії залізничного транспорту*. 2013. No. 140. P. 44-48. [In Ukrainian: Prokhorchenko, A. V. & Tre-vohin, A. I. & Bolkun, A. Research capacity railway plots on the basis of constructing parametric functions depending on the intensity of the density flow train. *Proceedings of the Ukrainian State Academy of Railway Transport*]
4. Прохорченко, А. В. Передумови розроблення нових методів управління пропускною спроможністю залізничної інфраструктури в умовах реформування залізничного транспорту України. *Збірник наукових праць Української державної академії залізничного транспорту*. 2015. No. 156. P. 82-87. [In Ukrainian: Prokhorchenko, A. V. Background develop new methods of management of railway infrastructure throughput in restructuring railway Ukraine. *Proceedings of the Ukrainian State Academy of Railway Transport*]
5. Прохорченко, А. В. & Огієнко, В. А. Аналіз методів розрахунку пропускної спроможності залізничних дільниць. *Збірник наукових праць Української державної академії залізничного транспорту*. 2014. No. 150. P. 66-73. [In Ukrainian: Prokhorchenko, A. V. & Ohienko, V. A. Analysis of the methods of calculating the capacity of the railways lines. *Proceedings of the Ukrainian State Academy of Railway Transport*]
6. UIC leaflet 406 R, Capacity. UIC International Union of Railways, France, 2004.
7. Прохорченко, А. В. Проблеми розрахунку пропускної спроможності залізничної інфраструктури в умовах ринкових відносин. *Інформаційно-керуючі системи на залізничному транспорті*. 2014. No. 4. P. 36-41. [In Ukrainian: Prokhorchenko, A. V. Problems of calculation of railway infrastructure capacity in market conditions. *Information management systems for rail*]
8. Kontaxi, E. & Ricci, S. Railway capacity analysis: methodological framework and harmonization perspectives. *12th WCTR*. July 11-15, 2010. Lisbon, Portugal. 21 p.
9. Kraft, E.R. Jam Capacity of Single Track Rail Lines. *Proceedings of the Transportation Research Forum*. 1982. Vol. 23 (1). P. 461-671.
10. Abril, M. & Barber, F. & Ingolotti, L. & Salido, M. A. & Tormos, P. & Lova, A. An assessment of railway capacity. *Transportation Research Part*. 2008. Vol. 44. P. 774-806.
11. Landex, A. & Kaas, A. H. & Schittenhelm, B. & Schneider-Tilli, J. Evaluation of railway capacity. *Trafikdage på Aalborg Universitet*. 2006. 22 p.
12. Delorme, X. & Gandibleux, X. & Rodriguez, J. Stability evaluation of a railway timetable at station level. *European Journal of Operational Research*. 2009. Vol. 195 (Issue 3). P. 780-790.
13. Liudvinavicius, L. & Dailydka, S. & Sładkowski, A. New possibilities of railway traffic control systems. *Transport problems*. 2016. Vol. 11. Issue 2. P. 133-142. DOI: 10.20858/tp.2016.11.2.13
14. Rakhmangulov, A. & Kolga, A. & Osintsev, N. & Stolpovskikh, I. & Sładkowski, A. Mathematical model of optimal empty rail car distribution at railway transport nodes. *Transport problems*. 2014. Vol. 9. Issue 3. P. 125-132.
15. Nesterenko, G. I. & Muzykin, M. I. & Horobets, V. L. & Muzykina, S. I. Study of car traffic flow structure on arrival and departure at the marshalling yard X. *Наука та прогрес транспорту. Вісник Дніпропетровського національного університету залізничного транспорту ім. акад.*

В. Лазаряна. 2016. No 1(61). P. 85-99. doi 10.15802/stp2016/60986 [In Ukrainian: *Science and Transport Progress. Bulletin of Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan*]

16. Oliveira, E. & Smith, B.M. A Job-Shop Scheduling Model for the Single-Track Railway Scheduling Problem. *Research Report University of Leeds*. 2000. 21 p.