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NEW GRAPHICAL APPROACH TO RAILWAY INFRASTRUCTURE CAPACITY ANALYSIS

ABSTRACT

A variety of methodologies are being used across Europe for the estimation of railway infrastructure capacity. This paper introduces the basic principles of the methodologies used – analytical methodology (e.g. Slovak railways), UIC methodology, and the graphically developed methodology of the Department of Railway Transport, University of Žilina (KŽD). On the basis of these new approaches, the occupation time estimation is researched. This new method is based on a graphic approach that uses operational time intervals as part of occupation time in accordance with the Slovak methodology. The new methodology concerns graphic capacity estimation and is a conceptual framework developed by the authors for easier evaluation of occupation time in train traffic diagrams.

KEY WORDS

capacity estimation; train traffic diagram; occupation time; detection path; indicators;

1. INTRODUCTION

The determination of railway line capacity has undergone considerable development since the beginning of railway transportation. They have changed with the changes in technology, then taking into consideration the minimum necessary time for maintenance, as well as by insuring enough time for achieving greater reliability and stability of the operation of trains. Generally, the railway line capacity means the maximal number of trains or train pairs that can pass through in a time unit (day or hour) depending on the infrastructure (number of main tracks, signalling and safety devices, and telecommunication), type and power of the locomotives (i.e. multiple units), mass and properties of the trains, as well as the management of traffic (graph type). Usually, railway line capacity is calculated as the number of trains or pairs of trains that can pass along a railway line in one day or 24 hours, but nowadays it appears to be appropriate to move forward from this method. For railway line with intensive passenger traffic (urban and suburban with clock-face timetable) or great unbalance during the day, the railway line capacity is determined not only for one day but also for the peak hour load.

Today, a number of methodologies are used for determining railway infrastructure capacity all over the globe. According to the approach the railway line capacity can be calculated, i.e. methodologies can be classified as analytical, graphical and simulation ones [1]. The aim of this paper is to propose a new methodology for railway infrastructure capacity detection based on the knowledge and analysis of the existing methodologies that are based on the graphic principle. A new approach is based on a simple graphical determination of occupation time, which comes from the analytical methods used to determine the occupation time in Central and Eastern Europe. It seems to be appropriate to follow the existing non-obligatory methodology of the International Union of Railways (UIC), which is introduced in the Leaflet UIC Code 406 "Capacity" [2]. The reason for the new approach is the diversity of capacity consumption results and the need for flexibility within the changing train mix on the railway infrastructure [3].

2. CAPACITY DETECTION

2.1 Analytical approaches

The analytical methodologies are based on deterministic understanding of the traffic operation generally, thus not taking into consideration various operational measures or transport disruptions. Thus, disturbances may have various characters and usually it is impossible to predict them.

Operating performance can be determined based on the throughput capacity of the least productive infrastructure equipment (bottlenecks) within the deterministic operating conditions [4]. In stochastic operating conditions it is necessary to solve this problem on the basis of the queuing theory knowledge as a cascade of queue systems. In doing so, it is concluded that the operating performance will be lower than the performance of the least productive equipment [1].

A type of this methodology is the approach used by the infrastructure managers in Croatia [5], Slovakia [3] or the Czech Republic [6].

According to Čičak et al. [5] one of the efficient uses of analytical approaches is using coefficient of elimination. The coefficient of elimination shows how many freight trains must be eliminated from the graph for passenger train running. Coefficients of elimination are influenced by the following factors: relation between the starting speed of the freight and passenger trains, defined schedule of the passenger trains that limit the possibility of matching the train routes into the graph, number and schedule of passenger trains in the graph, lack of uniformity of the section distances and type of train traffic graph.

The Railways of the Slovak Republic (ŽSR) in the role of infrastructure manager in its methodology under regulation ŽSR D24 [7] uses the average train paths and looks for limiting the inter-stationary section as a system bottleneck. The final result, the so-called practical throughput capacity of a critical section, is then declared as a summary of the entire track-line section, namely in absolute terms, the number of trains within a certain time span (usually 24 hours). However, it does not consider the train paths that do not pass through the limiting section.

The calculation of the practical throughput capacity takes into account not only the need for maintenance of infrastructure equipment but also the fact that the equipment is also used to carry out activities other than those it primarily serves and for which it has been intended. The calculation includes the necessary buffer time (to remove possible disorders or irregularities in the transport operation). The formula for practical throughput performance is [7]:

$$n = \frac{T - (T_{vyl} + T_{stal})}{t_{obs} + t_{dod} + t_{rus}} \qquad (1)$$

where:

- n – practical throughput performance (capacity) [vl.T^{-1}];
- T – time window [min];
- T_{vyl} – total time in which the operating device within the computing time is barred from operation for prescribed inspections, repairs and maintenance [min];
- T_{stal} – total time of permanent manipulations, i.e. the time in which the operating device is occupied by other actions than those for which throughput capacity is calculated [min];
- t_{obs} – technological time of occupation by one train (or act) in which the throughput capacity is calculated [min];
- t_{dod} – average backup time which extends occupation time and equalizes irregularities in transport operation [min];
- t_{rus} – average time of likely mutual train track interference, emerging in locations of potential threat due to the inability of existing parallel journeys in the rail infrastructure [min];
- vl.T^{-1} – derived physical unit for expressing absolute capacity (trains per computing time).

The key question is how to estimate the occupation time. The average occupation times per train in principle consist of the travel time in the boundary section and the operation interval time [1]. The operating interval is the shortest time interval between the arrival, through running or departure of two trains in order to meet the conditions for their safe operation. The operating interval standards are defined separately for each station and for each direction of adjunct tracks in cases where the simultaneous running of such trains is not allowed. Depending on the collision points, the operating intervals are divided into station intervals and track intervals [7]. Examples of these intervals are shown in *Figure 2*.

2.2 Graphical and simulation approaches

The International Union of Railways (UIC) enforces a uniform method of capacity calculation, which is contained in the Leaflet UIC Code 406 “Capacity”. This methodology is based on the graphical compression of train paths within defined compression sections for detecting the occupation time. This compression considers the minimum headways, which depend on the signalling system and train characteristics (*Figure 1*).

The capacity consumption is characterized by the value of infrastructure occupation (percentage of the time window). UIC Code 406 gives typical values corresponding to the type of track [2]. If the infrastructure occupation is higher than or equal to this certain

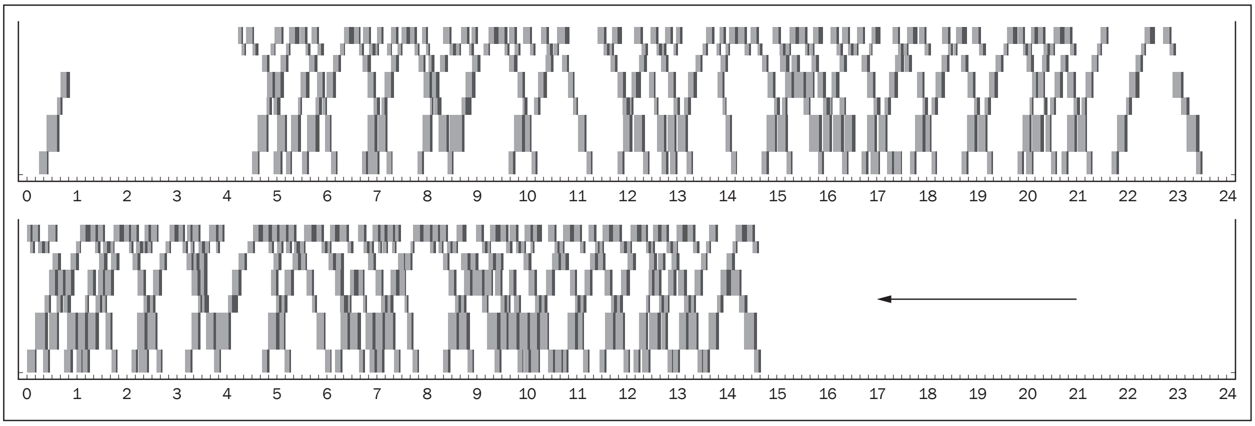

Figure 1 – Travel time and interval time occupation and its compression procedure in train traffic diagram [8]

typical value, the analysed line section should be considered a congested infrastructure, and no further additional train paths can be added to the timetable. If the occupation is lower than the typical value the capacity analysis must be further developed, and this procedure can be repeated until the infrastructure occupation reaches the congestion level.

The basic formula for determining the capacity consumption according to UIC Code 406 is [2]:

$$k = A + B + C + D \tag{2}$$

where:

k – total consumption time [min];
A – infrastructure occupation [min];
B – buffer time [min];
C – supplement for single-track lines [min];
D – supplement for maintenance [min].

The capacity consumption is defined as:

$$K = \frac{k}{U} \cdot 100 \tag{3}$$

where:

K – capacity consumption [%];
U – chosen time window [min].

It turned out that the problem of inserting new paths does not constitute a limiting factor of infrastructure occupation. There is almost always a possibility of inserting a train path into the timetable but only as long as the timetable stability is not affected [8]. Based on this, the standard infrastructure capacity consumption values cannot be determined. Therefore, the limiting values of infrastructure capacity utilization by trains were listed in leaflet 406 of the UIC. These must not be exceeded in order to respect the buffer time and ensure timetable stability. It is worth adding also that the typical values still need to be adjusted in accordance with various operating factors. For example, for normal traffic train mix a recommended value of 60% is given [2].

With the development of computer technology, new possibilities for timetable construction and evaluation, particularly by simulation tools, have opened up [9]. In the last two decades a number of different software solutions for railway infrastructure, hub planning and timetable evaluation have been developed. Simulation models reproduce the real object, i.e. the system as a whole, into a model through which the conducting of many processes on the basis of fixed data inputs and variables that represent stochastically behaving processes can be examined [10]. Based on examination of the results it may be possible to make adjustments to the model that will meet all the requirements. Therefore, the simulation models play an important role in the project and design stages of the complex system's implementation and they can help to avoid hidden defects through very early detection [11] while respecting the parameters that may affect the track capacity and quality of transportation services [12, 13].

2.3 Original graphical methodology of the Department of Railway Transport KŽD

A graphical methodology for determining the occupation time and time window (certain computing time) via surface geometric shapes in a timetable diagram (usually rectangles) was established in the Department of Railway Transport at the University of Žilina (KŽD) in the period from 2008 to 2009. The methodology offered a new dimension to the perception of capacity. It is based on the requirements of UIC 406 methodology and it also uses some elements of the analytical methodology of ŽSR. It also covers the determination of single-track line capacity, eliminating the shortcomings of the UIC methodology. It also puts forward the essential requirements for a new software module for the information system of ŽSR [3].

This proposed methodology does not require compression by simulation procedures. The new approach to the determination of occupation time is based on a graphical principle. It defines the occupation surfaces (areas) in a constructed timetable, which are given by multiplication of the time and distance in a timetable diagram. The share of all the occupation surfaces on the total surface of the train diagram graphic (time window) identifies the occupation rate (capacity consumption). The railway infrastructure capacity is expressed as the percentage level of capacity utilization S_v, which corresponds comparably to the capacity consumption K by the UIC 406 methodology, while taking the maximum (limiting) value of capacity utilization level in accordance with UIC 406 [8].

Additional train paths are inserted into the timetable until the moment when the occupation level is exceeded (recommended value). The capacity of the line section is then expressed as the sum of the initially and additionally inserted paths in the timetable. The formula for the capacity utilization rate becomes [3]:

$$S_v = \frac{\sum_{i=1}^{n} S_{obsi} + \sum_{j=1}^{m} S_{PVj}}{S_T} \cdot 100 \quad (4)$$

where:

S_v – capacity utilization level [%];

ΣS_{obsi} – sum of blocking section occupation surfaces (travel times) [min·km];

ΣS_{PVj} – sum of operational time interval surfaces [min·km];

S_T – time window surface (peak or day-long) [min·km];

i – 1...n, where n is the number of blocking section occupation surfaces;

j – 1...m, where m is the number of operational time interval surfaces.

The so-called occupation surface S_{obsi} is the result of the multiplication of the time slot and the blocking section length. However, the result is a dimensionless number and thus provides an appropriate informational value of the total railway infrastructure occupancy; namely, its percentage of usage. According to Gašparík, Zitrický [3], the simplicity of this methodology predetermines its relatively easy incorporation into an existing software product for timetable construction, and also into software for simulating traffic operations. Despite many disagreements about multiplying the time and the distance, claimed many times by scientists, this methodology has been the starting element for further research and has been subsequently developed through research and several tests, resulting in a proposal for a new (modified) methodology.

3. HYPOTHESES FOR CAPACITY RESEARCH

The main aim of the research was to resolve the issue of finding a universal indicator of railway infrastructure capacity that can be posted online within the marketing of train paths. Based on the partial objectives of the research, three hypotheses have been compiled and these were verified by research tools during the testing processes. The validity of the hypotheses was proven by the test phase results of the simulation model and by an analytical comparison of the analysed methodologies [8]. Based on our assumptions, the following research *hypotheses* have been established before the research and testing begun:

1) The dependence of railway infrastructure capacity utilization and the number of incorporated train paths are not linearly related.
2) Railway infrastructure capacity may be characterized as a dimension of time while the spatial dimension of distance does not affect the determination of its value.
3) Railway infrastructure capacity utilization can be directly and accurately assessed only at every particular blocking section in a certain time frame.

An important finding is that the incorporation of the spatial dimension into the infrastructure capacity calculation by the determination of occupation surfaces does not produce sufficient results. It is necessary to distinguish the capacity of each blocking section, namely, each inter-station section (open line intermediate blocking section).

As the basis of a new methodology for capacity detection the following postulates have been defined after the research had been carried out:

- capacity consumption does not have a linearly related dependence on the number of train paths, so the capacity cannot be expressed in absolute value of trains per time period,
- capacity consumption depends notably, among the range of transport operations, on the individual train paths' character and their mutual mix,
- implementation of a graphical compression of paths, namely, any additional insertion of train type paths and detection of their added number, is not justified,
- railway infrastructure capacity consists of the character of time elements only,
- capacity as a proportion of time element consumption is expressed in percentage,
- capacity consumption affects occupation time consisting of train movement t_j, indirect occupation time by operational intervals t_{PI} and non-utilizable time t_x (Chapter 4.2),
- spare (free) capacity is the remaining rate of overall (total) capacity after the deduction of consumed capacity,
- capacity expression for the track line section that consists of several blocking sections is possible as the arithmetic average of these sections' values only.

These principles respect the simplicity of perception and implementation of the methodology by various railway infrastructure managers and the result respects fair and non-discriminatory access for all railway undertakings.

4. MODIFIED METHODOLOGY OF DEPARTMENT OF RAILWAY TRANSPORT KŽD

The modified methodology has to respect the diversity of train paths given by the diversity of customer demands. Capacity determination steps enable wide flexibility of track section selection and a varying number of blocking sections within inter-station sections in accordance with the travel direction (unidirectional track interlocking, different position of block signals and so on).

4.1 Step procedure of railway infrastructure capacity detection

The determination of capacity can be performed in all day time windows (24 hours) or in a peak time window. This proposed methodology also assumes capacity utilization limits of the UIC methodology in order to respect the timetable stability. However, in contrast to previous methodologies, this methodology does not use train path compression or additional train path insertion. It considers operational determination of the capacity and also the immediate publication of results right after each new path is inserted. This creates prerequisites for new software application design that evaluates all limiting factors based on the input parameters and other selected procedures when inserting paths.

The proposed methodology uses a graphical approach for determining the capacity consumption either by directly specifying the occupation time or determining the occupation surface within a computing framework in the same blocking section. This way causes the exact elimination of the spatial factor of distance only. The proposed capacity utilization indicator C_S is defined as a percentage rate of the sum of time consumptions (t_j, t_{Pl}, t_x) to time window T. These consumption time elements give a separate partial capacity consumption imaging (see the definition in Chapter 4.2).

On a single-track line it is most common to see directionally opposite train paths. In this case, the station operational time intervals are used. In the case of sequent trains in the same direction in the blocking section, the track (line) operational time intervals are used. For details about operational time interval determination see also [7, 3].

The double-track line capacity is determined for each track separately (one-direction operation). The point is to determine capacity consumption time elements for each blocking section. For triple-track lines (and more) it is important to very specifically separate directional operation as much as possible while different traffic conditions may be specific for each line track. In an absolute implementation of the methodology, the capacity is determined by direct calculation from actual transport operation volume and its character. The capacity is significantly influenced by a clock-face timetable construction.

4.2 The mathematical model of capacity determination

Capacity consumption in a certain blocking section is estimated as follows:

$$C^S = \frac{\sum_{y=1}^{n} t_y}{T} \cdot 100 \qquad (5)$$

where:

C^S – capacity consumption in a blocking section [%];

t – occupation time of element (t_j, t_{Pl}, t_x) [min];

y – 1...n, where n is the number of occupation time elements;

T – computing time (i.e. pure occupation time T_c) [min].

Consequently, an indicator of free railway infrastructure capacity can be established as the difference between the total theoretical capacity and the consumed capacity in each blocking section.

Time elements of capacity occupation consist of three elements:

t_j – travel time of train in a blocking section;

t_{Pl} – operational time interval corresponding to a train path within a blocking section;

t_x – inapplicable time (lost and unavailable for added path) in a blocking section.

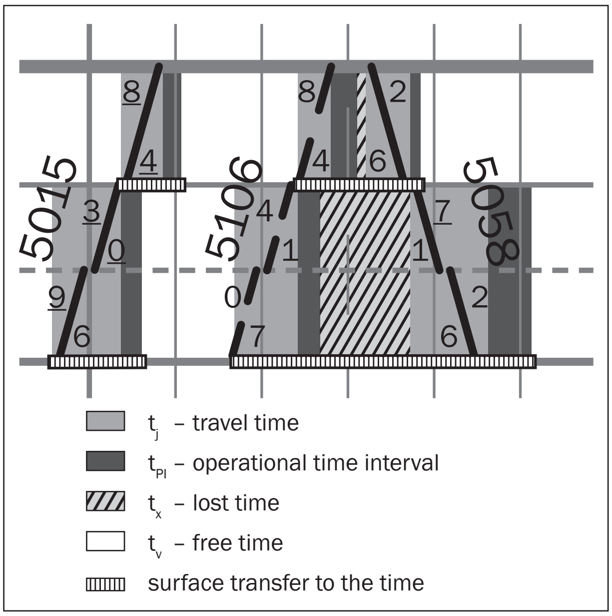

Figure 2 – Example of graphical capacity determination and surface transfer to the time

The occupation time determination by train paths t_j is a simple projection of the diagonal expression of a mass point motion in a blocking section to the base line of the station (or another operational point) in a timetable diagram (*Figure 2*).

Indirect occupation time element transfer of operational time intervals t_{PI} will be carried out as well as the identifying and assigning of their time duration to the underlying station (base line) within each blocking section.

The main principles of the identification of operational time intervals evaluated and taken over in terms of ŽSR methodology are as follows:

- for each train path in each blocking section, the operational time interval *PI* is closed,
- determination of a particular interval *PI* (station or track) is provided by the following train path; inserting a new path may change and update interval *PI*,
- in inter-station sections with multiple blocking sections where intervals *PI* cannot be directly assigned according to the following path (for example, impossible train crossing at certain operational points), these intervals are determined by a suitable opposite train path,
- the last path in a time window as the next closest path is also considered the first path in the time window (making a circle),
- various cases of banned mutual train movements by crossing the longer operational interval are taken into account.

The transfer of the lost time t_x is also performed as relating to the graphical lower base line (underlying – to the operational point closing the blocking section – i.e. station). The occurrence of lost time is assessed by an analysis of the timetable, subject to the following principles:

- it is necessary to determine the fastest path (bidirectional) for each blocking section, the so-called detection path,
- by inserting the detection path into the timetable diagram all the operational intervals are respected and also updated with respect to the train path layout,
- if it is not possible to add the detection route, the time between adjoining paths is declared as unavailable (lost) time.

5. THE CASE STUDY

The procedures of the modified KŽD methodology have been verified in a graphical analysis of the timetable diagram as the primary basis for overall analysis within this research. The single-track line ŽSR 140/141 in the length of 35.4 km from Leopoldov to Nitra (Slovakia) with various train mixes was selected. Taken together, 81 train paths with a proportion of 88% of passenger trains were inserted (9 long-distance fast passenger trains, 62 local passenger trains, 8 long-distance freight trains and 2 local freight trains).

In the first step the train paths were transferred to graphic occupation time elements t_j (travel times) and subsequently the operational time intervals t_{PI} were identified. The second step was to search for the lost time t_x by insertion of the detection path.

The results of the capacity analysis, which are expressed in percentage, are shown in *Figure 3*. The results are graphically shown for each blocking section. Directly consumed capacity consists of travel time t_j and operational intervals t_{PI}. Free capacity is expressed as the difference between time window *T* and consumed capacity, reduced by the lost time t_x.

This lost time also causes the capacity consumption (indirect) and may be included in the economic indicators in the context of train path marketing. By this, an emphasis on effective train path input and its adherence with regard to *ex post* timetable evaluation can be achieved.

The case study also points out the inappropriate expression of capacity value as an arithmetic average for the entire line section, where it is possible to express the capacity more in detail (for each blocking section). In the examined section there is an average consumption capacity of 34.2%. Every further added train path causes a change in the consumption as a whole, but the exact impact on the individual blocking sections is unknown (*Table 1*). If the infrastructure

Table 1 – Different expressions of capacity indicators

Blocking section	Capacity [%]					
	Consumed (t_j+t_{PI}+t_x)			Free (t_v)		
	A	B	C	A	B	C
Nitra – Mlynárce	55.19	48.75	34.19	44.81	51.25	65.81
Mlynárce – Lužianky	42.31			57.69		
Lužianky – Zbehy	23.88	28.36		76.12	71.64	
Zbehy – Alekšince	31.00			69.00		
Alekšince – Rišňovce	22.65			77.35		
Rišňovce – Hlohovec	38.46			61.54		
Hlohovec – Leopoldov	25.81			74.19		

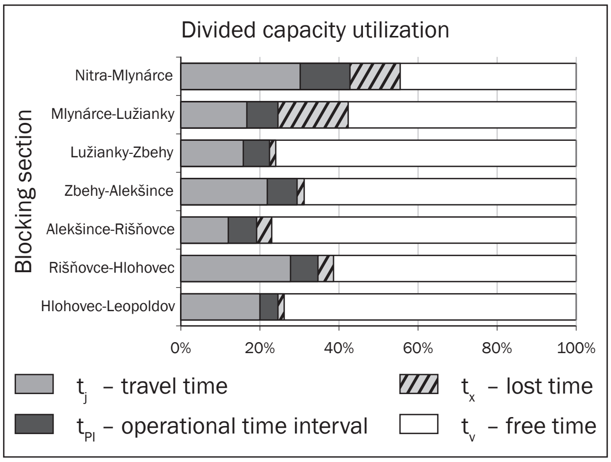

Figure 3 – Results of the capacity analysis of the railway line Nitra – Leopoldov

manager (IM) requires that for different reasons (as ŽSR do), then it is possible to use this way of making an average value, but it should be strictly noted that this way is inaccurate!

There is a comparison of the ways in which the capacity indicators can be expressed. The most accurate and effective expression is given by the modified KŽD methodology proposal (column *A*), so the capacity is shown for each blocking section. The second way (columns *B* and *C*) of expressing capacity is calculated as an average value (values of blocking section cells from column *A*, which graphically belong to the merged cells of column *B* or *C*, are used for calculation) in the conditions of any methodology that is based on fixed line sections that cannot be changed. This method is very imprecise and does not give exact values of changes in capacity indicators after insertion of the train path. Column *B* represents a merged line section in conditions of real ŽSR lines (ŽSR 122/123). Column *C* is a more merged line section in conditions of ŽSR but under the isolating terms of the research, so whole blocking sections were merged into one common line section. As mentioned, taking an average value is inaccurate and it was done just to make a comparison to the ŽSR D24 and UIC 406 methodologies in result.

6. DISCUSSION

A comparison of capacity analysis results according to the methodology of ŽSR D24, UIC 406 and the modified methodology KŽD is shown in *Figure 4*. The modified KŽD methodology gives the lowest values from the rest of the methodologies in use due to different steps and procedures of the capacity detection. But there is a way different capacity detection procedure is used in every one. The UIC 406 methodology uses train path compression, which means that this step is used for overall line length without any restrictions of the chosen length. With this knowledge we have got compressed 81 train paths which give the capacity consumption of 58.5%. While using analytical methodology ŽSR D24 a bottleneck is found, the restrictive inter-station section in which the capacity is calculated. However, the difference is that we do not take into consideration all train paths, but only train paths that are set in this section. This means 39 train paths which give the capacity consumption of 38.0%. Using the modified methodology KŽD, all blocking sections are analyzed every time it can be concluded what is the actual capacity of all of them. To compare the results, an average value of these blocking sections was found to get the final result of the whole line section capacity consumption. This means 81 train paths which give an average capacity consumption of 34.4%.

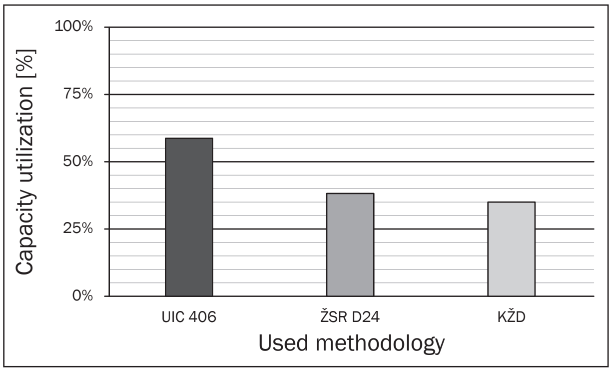

Figure 4 – The result comparison of methodologies used in the research

This graphically shown result does not tell what methodology is better to use; it just clearly describes what kind of different values you can get by using these methodologies. Significant advantages of the methodology core must be used as selection criteria.

7. CONCLUSION

The proposed methodology offers new possibilities for the perception of transport processes with regard to railway infrastructure and makes it easier to address detection, publishing and granting issues followed by re-evaluation of railway infrastructure capacity.

The modified methodology KŽD can express capacity consumption in accurate absolute terms covering the diversity of traffic operation, calculation periods (frames) and track line sections. It is based on the detection of consumed capacity in each blocking section. Importantly, it has been proven that the mixture of train paths in a timetable diagram depends enormously on the degree of capacity utilization. This methodology provides a very simple tool for unambiguous capacity determination. It can be confirmed that it is always about business transactions with time under the core processes of any infrastructure manager.

This proposed methodology does not replace simulation methods, which offer a better result of capacity values, as these processes consider the precise sequence of trains and also delays may be considered. It is easy to adapt to the conditions of another timetable design that is used in Western Europe as well as in other software for timetable construction (Germany, Austria, etc.). The authors examined the adaptation under the conditions of the Railways of the Slovak Republic. This methodology can be integrated into the leaflet UIC 406 and constitutes a uniform methodology for capacity determination for all infrastructure managers.

Our method can be used in market liberalization of railway services. All calculation was made according to traffic law in the railway sector. As we have the real position of all train paths, we can use this methodology for all interlocking systems ever. Every time the way of interlocking (ETCS or national systems) system needs to be respected in terms of train diagram construction. This article should kick-start a broad discussion about the new method proposed by the authors among the scientific community.

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ABSTRAKT

NOVÝ GRAFICKÝ PRÍSTUP K ZISŤOVANIU KAPACITY ŽELEZNIČNEJ INFRAŠTRUKTÚRY

Vo svete je dnes používaných mnoho metodických postupov pre zisťovanie kapacity železničnej infraštruktúry. Tento príspevok uvádza základné princípy vybraných použitých metodík – analytickej metódy (napr. Železnice Slovenskej republiky, metodika ŽSR), metodiky UIC a vyvinutej grafickej metodiky Katedry železničnej dopravy Žilinskej univerzity v Žiline (KŽD). Na základe týchto nových prístupov je skúmaný čas obsadenia. Nová metodika je založená na grafickom prístupe, ktorý využíva prevádzkové intervaly ako súčasť času obsadenia v súlade s metodikou ŽSR. Táto metodika vychádza z grafického spôsobu určenia kapacity a jeho koncepčného rámca vyvinutého autormi pre jednoduchšie zisťovanie času obsadenia v grafikonoch vlakovej dopravy.

KĽÚČOVÉ SLOVÁ

zisťovanie kapacity; grafikon vlakovej dopravy; čas obsadenia; detekčná trasa; ukazovatele;

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