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STUDY OF PARAMETERS THAT DETERMINE RAILWAY LINE CAPACITY

ABSTRACT

In this work the study focuses on:

- *determining the elements required to determine the location for the installation of the main signals,*
- *calculated block lengths, and*
- *calculations of optimal headways, that have not been studied in detail although they deserve special attention due to their impact.*

Generally speaking, the signals are installed in compliance with the local circumstances, i. e. according to the technical and technological characteristics and conditions determined by the traffic places of work they protect.

The distribution and length of the blocks depend on: the railway line and its exploitation characteristics, structure and type of trains that run on the railway line, traffic organisation and signalisation system, as well as technical and exploitation characteristics of the traction vehicles and the rolling stock. What has to be considered is that the minimum section length cannot be shorter than the length of the braking distance, i. e. the length of the longest train which runs on the respective railway line.

The study of these parameters is supplemented by the calculation of the reduction in throughput capacity depending on the lack of uniformity in the operation of trains, which, in order to maintain the design quality of the transportation service, and in the activities of establishing and implementing the business policy shouldn't be left out nor bypassed.

KEY WORDS

railway line, throughput capacity, study of parameters

1. INTRODUCTION

The railway line capacity is the measuring instrument which defines the number of trains that a railway line of a certain level of technical equipment can accommodate per unit of time. It depends on a number of factors such as: number of tracks, material and technical equipment, type and technical-exploitation characteristics of transport means, set traffic organisation, and the selected and applied organisation of traffic management.

Depending on the number of tracks, i. e. whether the railway line is a single-, double- or multi-track line, the throughput capacities differ as well.

The maximum speed on the railway line which depends on the track plan and profile, locomotive traction force, train mass and drag, as well as the running speeds along turnouts straight and turning, determine the travelling times, including thus also the throughput capacities. The material and technical equipment (type of tracks and station protection, telecommunication systems, ETCS and GSM-R technologies) are significant guidelines and have significant influence on its values.

The applied scheme of train traffic organisation with the limiting separation (commercial, parallel, tact or other diagram models), as well as the modernisation level of the traffic control devices, have significant impact and reflect differently on the value of the throughput capacity.

Therefore, this work studies the parameters such as:

- determining of the signal location,
- length of blocks, and
- calculation of headway,

which determine the throughput capacity of the railway line, and have not been fully defined, although regarding the level of impact they do deserve special attention.

By installing permanent signals, the railway line has been divided into sections of tracks - blocks, and the traffic organisation uses the distance-interval system, which can be: station, announcing or block separation, provided one section can accommodate only one train at a time. For the railway lines that require very high throughput capacity, the block signals are distributed over the length of the braking distance.

In case of railway lines that accommodate high-speed trains, the lengths of distance separation conceived in this way are not sufficient, and additional railway line system of information transmission on the condition of signal aspects, as an upgrade of the permanent signals system is introduced, providing the engine driver with the information on the track conditions ahead of the train, thus allowing the train to travel behind the preceding train at a distance equal to the braking distance, known as traffic at «electrical visibility».

At Hrvatske željeznice (Croatian Railways) the train traffic operates in distance intervals. In case of railway lines equipped with automatic block system (ABS) the traffic is organised by using block sections. In such conditions it is possible to apply the double-, triple- or quadruple-signalling system.

3. DETERMINING THE LOCATION FOR INSTALLING THE MAIN SIGNALS

The main signals that are installed on the railway lines include: home, starting, block and mechanical signals, and these may be station or trackside signals depending on the place of installation.

The place of installing the home signals is predetermined by the local circumstances and cannot be less than 100 metres before the entry turnout, i. e. the point that needs to be protected. At traffic places of work where the entry tracks are used for shunting, the home and mechanical signals have to be installed at least at the length of the overlap safety way ahead of the shunting limit signal, but not less than 50 metres. The maximum distance of the home or mechanical signal from the point protected is 500 metres on the main railway lines and the 1st order lines, i. e. 300 metres on other railway lines.

On the railway lines with a descent of 10‰ and more before the home i. e. mechanical signal, the place of installation doubles.

The German Railways install home signals:

a) 100 metres ahead of the front of the first turnout over which the entry run passes along the turnout point,
b) 200 metres ahead of:
   - boundary of the first turnout over which the train passes down the turnout point,
   - shunting boundaries,
   - places of regular train stopping, i.e. end of the train at the railway station or other traffic place of work.

The presented data refer to the railway lines that are level. However, it there is a gradient on the line, the mentioned value for each per-mille of descent increases by 10%, and at ascent decreases by 5%, with maximum separation amounting to 300 metres, and minimum 50 metres on non-electrified railway lines, and 100 metres on the electrified ones.

The starting signals are installed at railway stations and crossing points where there is dependence between the travelling routes and the signals ahead of the protected point. If it signalises the starting from one track then it is called the track starting signal, and if it signalises the starting from a group of tracks or from all the tracks then it is called group starting signal.

The group starting signals are installed next to or behind the last starting turnouts of the respective tracks.

On the Russian railway lines the starting signals are installed ahead of the point marked as the stopping point of the running locomotive. For the tracks at which the trains start into a turn, or from which the trains that had first stopped at the railway station start, the group starting signals may be installed.

German railways have two regulations regarding the installation of the starting signals:

- if the overlap safety way has been insured, then the starting signals are installed at the length of the overlap safety way from the boundary on the starting side,
- if the overlap safety way has not been insured then the starting signals are installed for the drive through the first turnout down the turnout point at 1 metre ahead of the end of the insulated section, which is at 6 – 10 metres from the boundary. If the start is over the first turnout along the turnout point, then the starting signals are installed at 1 metre ahead of the beginning of the turnout insulated section.

The block signal allows or prohibits the train entering a block. The lengths of the block sections, i. e. boundaries for their definition, are determined by various parameters such as: traffic volume, speed, train acceleration or deceleration, etc. In case of ABS-equipped railway lines the railway area is defined by home and starting signals, whereas the first block section is limited by the starting and first block signal.

3. BLOCK LENGTHS

Estimating generally, the block lengths should be such that with an adequate signalisation system they allow continuous run at maximal allowed speed according to the signal sign "clear passage, expect clear passage or caution", since the speed does not have to be reduced until the next main signal.

Continuous travelling is realised by making the travelling times through blocks uniform in such a way that the train travelling time through all the blocks is as equal as possible.

The calculated separation between two successive trains (L_p) on double-track lines can be calculated by using the following expression:

$$L_p = \frac{10^3 v_{sr}}{n}\alpha_{ps} \quad [\mathrm{m}] \qquad (1)$$

where:

- v_{sr} – mean travelling speed of the preceding train, taking objective acceleration, deceleration and possible stopping (km/h);
- n – planned throughput capacity of the railway line in the number of trains;
- α_{ps} – reliability coefficient of the operation of technical means;

or according to the previously used UIC method:

$$L_p = \left(\frac{60}{n} - r\right)\frac{v_{sr}}{0,06} \qquad (2)$$

where:

- r – reserve time which insures designed quality of service and amounts to $r = 0,67\, I + t_d$,
- I – headway,
- t_d – time addition stipulated by the number of inter-spaces.

In organising the traffic according to the signal sign "clear passage, expect clear or caution" the calculated separation between successive trains amounts to:

$$L_p = l_{dv} + 2l_{bl} + l_{pz} + l_v \quad [\mathrm{m}] \qquad (3)$$

where:

- l_{dv} – distance of signal visibility [m]
- l_{bl} – block length [m]
- l_{pz} – overlap safety way [m]
- l_v – train length [m]

which yields the length of the block section:

$$l_{bl} = 0,5\left[\frac{10^3 v_{sr}}{n}\alpha_{ps} - (l_{dv} + l_{pz} + l_v)\right] \quad [\mathrm{m}] \qquad (4)$$

$$l_{bl} = 0,5\left[\left(\frac{60}{n} - r\right)\frac{v_{sr}}{0,06} - (l_{dv} + l_{pz} + l_v)\right] \quad [\mathrm{m}] \qquad (5)$$

In applying the signalisation model presented in Figure 1b, which is the case on the Russian Railways, then the calculated separation between the trains that run in succession amounts to:

$$L_p = 3l_{bl} + l_v + l_{pz} \quad [\mathrm{m}] \qquad (6)$$

In this insurance system l_{pz} tends to zero resulting in:

$$L_p = 3l_{bl} + l_v \quad [\mathrm{m}]$$

In that case the block length amounts to:

$$l_{bl} = \frac{1}{3}\left(\frac{10^3 v_{sr}}{n}\alpha_{ps}\, l_v\right) \quad [\mathrm{m}] \qquad (7)$$

or

$$l_{bl} = \frac{1}{3}\left[\left(\frac{60}{n} - r\right)\frac{v_{sr}}{0,06} - l_v\right] \quad [\mathrm{m}] \qquad (8)$$

The train travelling speeds per single blocks are different since they differ in: railway line plan and profile, train types, and whether on the considered block the trains accelerate or decelerate, i. e. travel at maximum speed. There are two approaches to balance the travelling times per blocks, determining at the same

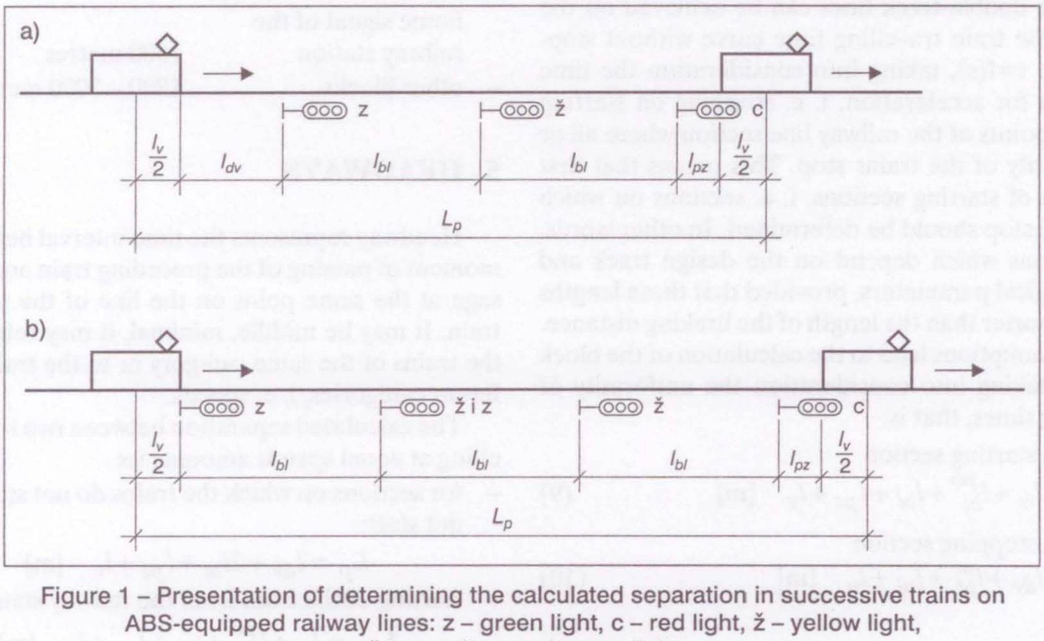

Figure 1 – Presentation of determining the calculated separation in successive trains on ABS-equipped railway lines: z – green light, c – red light, ž – yellow light, ž i z – yellow and green light

time their lengths. In the starting i. e. stopping blocks shorter separations are designed, whereas they are longer on the open railway line sections. Another approach uses the model of traffic organisation with two i. e. three sections of tracks cleared. Two cleared blocks are used on those railway line sections where trains accelerate or decelerate, and three clear blocks are used on the open line.

The braking section where the trains usually stop is located in the railway station area and is defined by home and starting signals. Its length depends on the technical and technological elements of the railway station. The same is true also for the section where the trains accelerate, and which stretches from the starting to the first block signal.

In determining the block lengths on a railway line and at railway stations it is necessary to consider the following conditions:

- minimum block length should not be shorter than the length of the braking distance,
- minimum block length should not be shorter than the maximum length of the train running on the line.

The length of the braking distance is pre-determined by the travelling speed of the trains and ranges from 700 to 1500 metres. In German Railways a maximum travelling speed of 160 km/h is allowed on a 1000-metre braking distance. The conditions of thus set exploitation require high percentage braking insurance which allows deceleration at $1 m/s^2$, but also means great discomfort for the passengers. A far more acceptable solution is with a 1500-metre braking distance which at a speed of 160 km/h allows stopping at deceleration of $0.66 m/s^2$.

Approximately equal travelling times on certain blocks on double-track lines can be achieved on the basis of the train travelling time curve without stopping, i. e. t=f(s), taking into consideration the time necessary for acceleration, i. e. stopping on starting and end points of the railway line section where all or the majority of the trains stop. This means that first the value of starting sections, i. e. sections on which the trains stop should be determined. In other words, the sections which depend on the design track and technological parameters, provided that these lengths are not shorter than the length of the braking distance. These assumptions lead to the calculation of the block lengths, taking into consideration the uniformity of travelling times, that is:

- for the starting section

$$L_{pp} = l_{is} + l_{bl}^{po} + l_{bl} + l_{pz} + l_v \quad [m] \qquad (9)$$

- for the stopping section

$$L_{pz} = l_{dv} + l_{bl}^{us} + l_{ul} + l_v \quad [m] \qquad (10)$$

- for other blocks

$$L_p = l_{dv} + 2l_{bl} + l_{pz} + l_v \quad [m] \qquad (11)$$

where:

l_{is} – distance between the starting signal and the front of the stopped train,

l_{ul} – distance between the home signal and the turnout insulated section,

l_{bl}^{us} – distance between the pre-signal and home signal.

On railway lines where high throughput capacity should be insured, the lengths of the block sections can be dimensioned by using the travelling time curves of the representative trains, balancing the travelling times per single blocks, setting the traffic organisation which provides the calculated separation between successive trains on:

- starting section;

$$L_{pp} = l_{is} + l_{bl}^{po} + l_{pz} + l_v \quad [m] \qquad (12)$$

- stopping section;

$$L_{pz} = l_{dv} + l_{bl}^{us} + l_{pz} + l_v \quad [m] \qquad (13)$$

- other blocks

$$L_p = l_{dv} + 2l_{bl} + l_{pz} + l_v \quad [m] \qquad (14)$$

For determining the curve of the train travelling time, the category of the most represented train, i. e. its superior model is taken as the reference.

As example, for a double-track line which requires ABS installation, where heavy traffic is expected for the estimated values one can take the following block lengths:

– starting section	1000 metres, exceptionally 1200 metres
– stopping section	1000 – 1500 metres
– last block ahead of the home signal of the railway station	1500 metres
– other blocks	1800 – 2000 metres.

5. HEADWAYS

Headway represents the time interval between the moment of passing of the preceding train and the passage at the same point on the line of the successive train. It may be middle, minimal, it may refer only to the trains of the same category or to the trains of different categories, i. e. speeds.

The calculated separation between two trains travelling at equal speeds amounts to:

- for sections on which the trains do not stop and do not start:

$$L_p = l_{dv} + 2l_{bl} + l_{pz} + l_v \quad [m]$$

- starting of the train from the railway station:

$$L_{pp} = l_{is} + l_{bl}^{po} + l_{bl} + l_{pz} + l_v \quad [m]$$

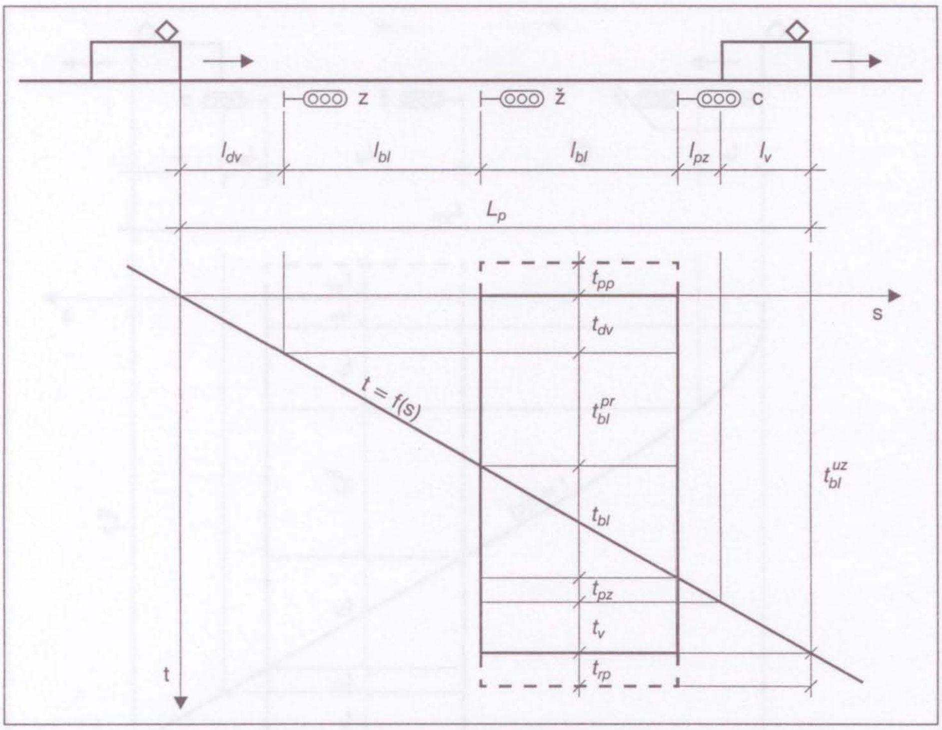

Figure 2 – Scheme for determining the calculated train separation

– for the train that stops at the railway station:

$$L_{pz} = l_{dv} + l_{bl}^{us} + l_{ul} + l_v \quad [\mathrm{m}]$$

The time of the overall occupancy of a block (t_{bl}^{uz}), which at the same time represents the minimum time separation between the successive trains travelling one after another, amounts to:

– for sections on which trains do not stop and do not start,

$$t_{bl}^{uz} = t_{pp} + t_{dv} + t_{bl}^{pr} + t_{bl} + t_{pz} + t_v + t_{rp} \quad (15)$$

– in starting a train,

$$t_{bl}^{uz} = t_{pp} + t_{rm} + t_{is} + t_{bl}^{po} + t_{bl} + t_{pz} + t_v + t_{rp} \quad (16)$$

– in stopping of a train,

$$t_{bl}^{uz} = t_{pp} + t_{dv} + t_{bl}^{po} + t_{ul} + t_v + t_{rp} \quad (17)$$

where:

t_{pp} – time necessary to set the route,

t_{dv} – time necessary for the train to travel the distance of the signal visibility length,

t_{bl} – time necessary for the train to pass the preceding block.

in which the presented symbols have the following meanings:

t_{bl} – travelling time of the train through a block,

t_z – travelling time from the block signal to the end of the insulated section,

t_v – time necessary for the train to pass the distance of its length,

t_{rp} – time necessary for setting the train routes in the regular position,

t_{rm} – time of perceiving the change in the signal aspect,

t_{is} – travelling time from the stopping point to the starting signal,

t_{bl}^{po} – time necessary for the train to travel from the starting signal to the first block signal,

t_{bl}^{us} – time necessary for the train to travel between the fore-signal and the home signal,

t_{ul} – time necessary for the train to travel from the home signal to the end of the insulated section which allows route release and managing of the home turnouts.

Due to low values the following can be taken $t_{pp} = t_{rp} = 0$, then the minimal headway amounts to:

– for blocks of the railway line where the trains do not stop,

$$t_{bl}^{uz} = t_{dv} + t_{bl}^{pr} + t_{bl} + t_{pz} + t_v \quad [\mathrm{min}] \quad (18)$$

– for trains that start from the railway station,

$$t_{bl}^{uz} = t_{rm} + t_{is} + t_{bl}^{po} + t_{bl} + t_{pz} + t_v \quad [\mathrm{min}] \quad (19)$$

– for the successive train if the preceding one stops at the railway station,

$$t_{bl}^{uz} = t_{dv} + t_{bl}^{us} + t_{ul} + t_v \quad [\mathrm{min}] \quad (20)$$

Depending on the plan and profile of the railway line, the location of the signal, and the set organisation of traffic and the same train travelling speed, there are differences in the occupancy of single blocks, with the different headways as well (Fig. 5).

Headway for the railway line is determined by the maximum value obtained by comparing all the possi-

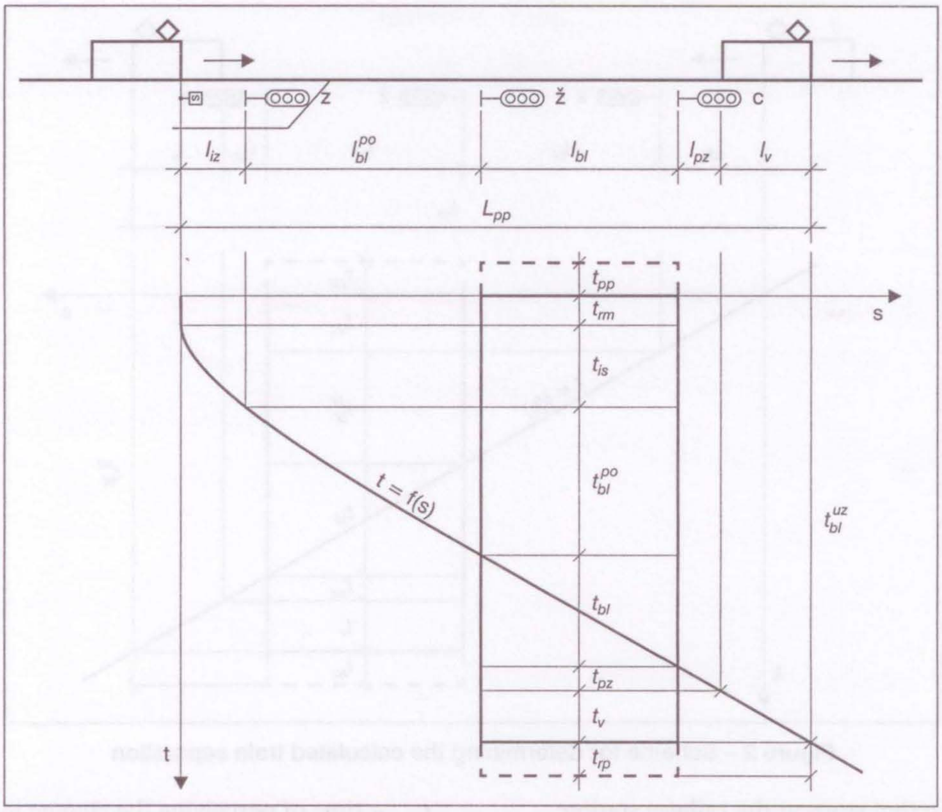

Figure 3 – Model of calculating the earliest start of the stopped train from the railway station when the block is occupied by the preceding train

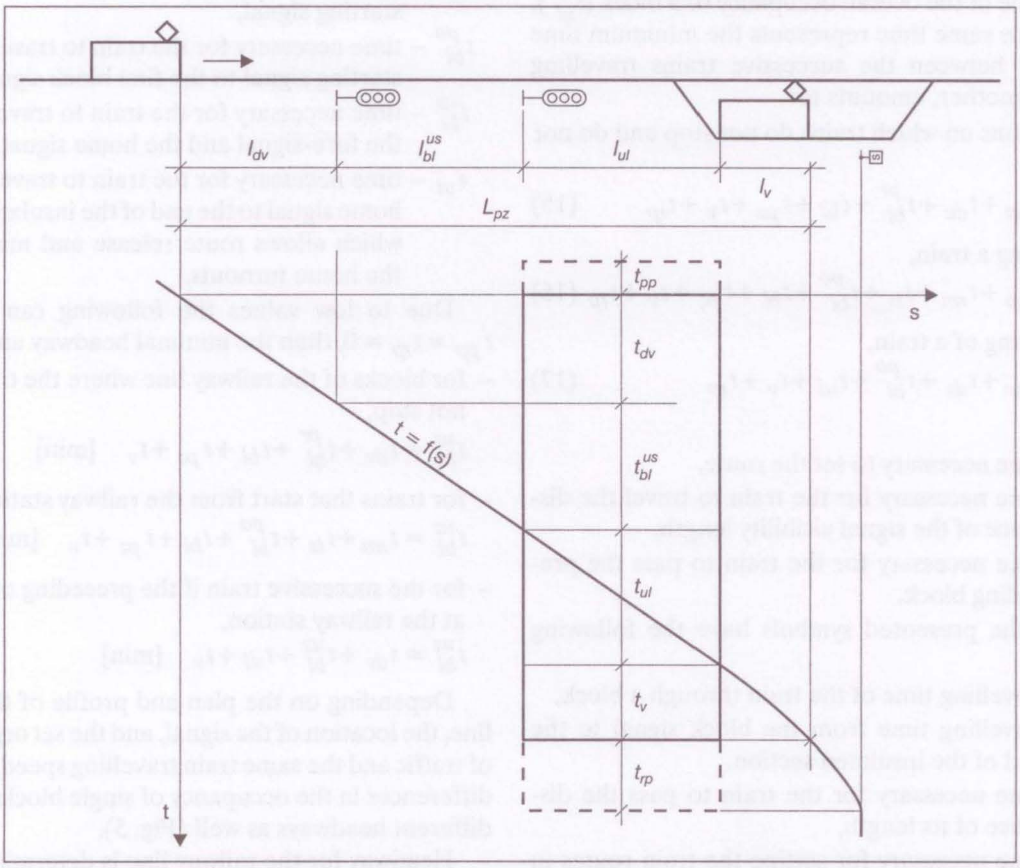

Figure 4 – Model of calculating the headway between trains when the preceding train stops at the railway station

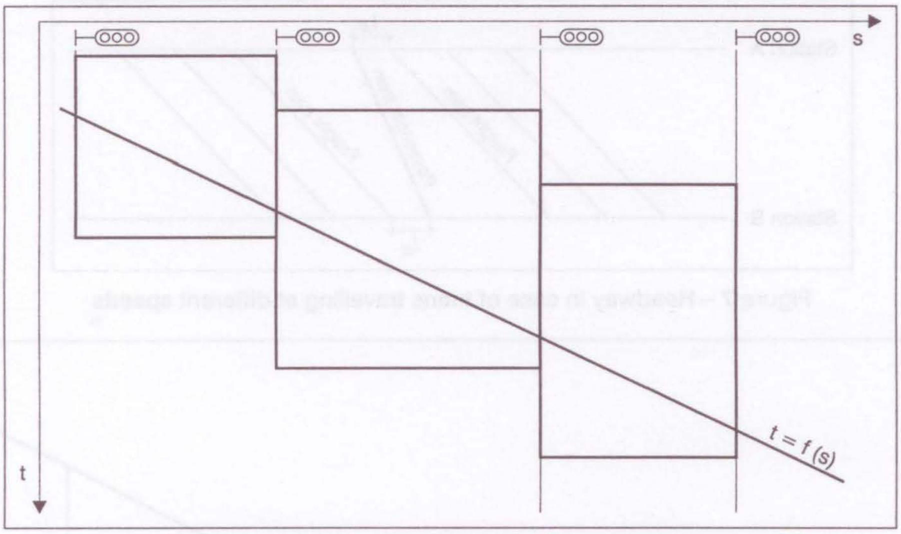

Figure 5 – Occupancy of blocks due to train starting

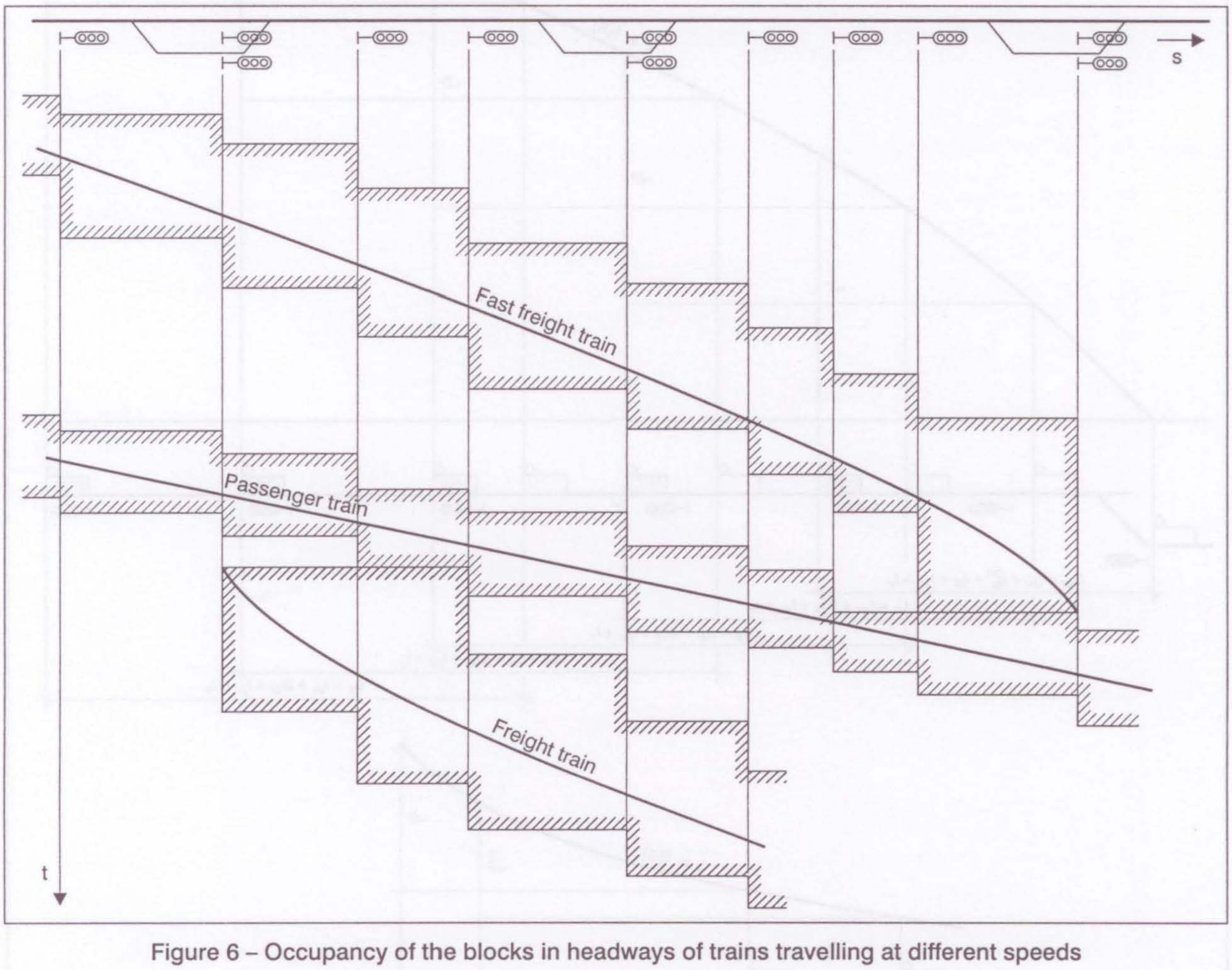

Figure 6 – Occupancy of the blocks in headways of trains travelling at different speeds

ble calculated positions of trains on the railway line and the methodology is as follows:

- for the considered railway line section the travelling time is calculated depending on the travelled path, t = f(s), Fig. 8,
- headway is calculated for every block section depending on the set traffic organisation,
- calculated interval is increased by 15 to 25% if the travelling speed on this section is 60 km and more,

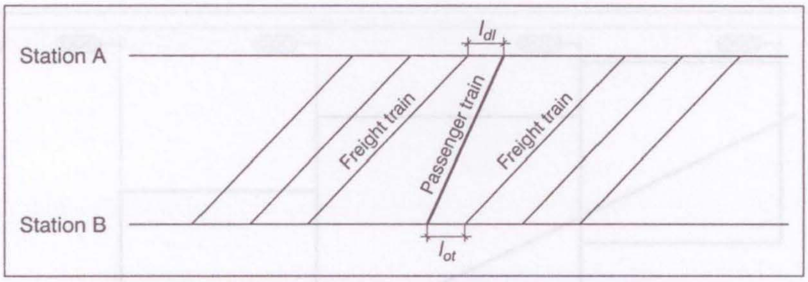

Figure 7 – Headway in case of trains travelling at different speeds

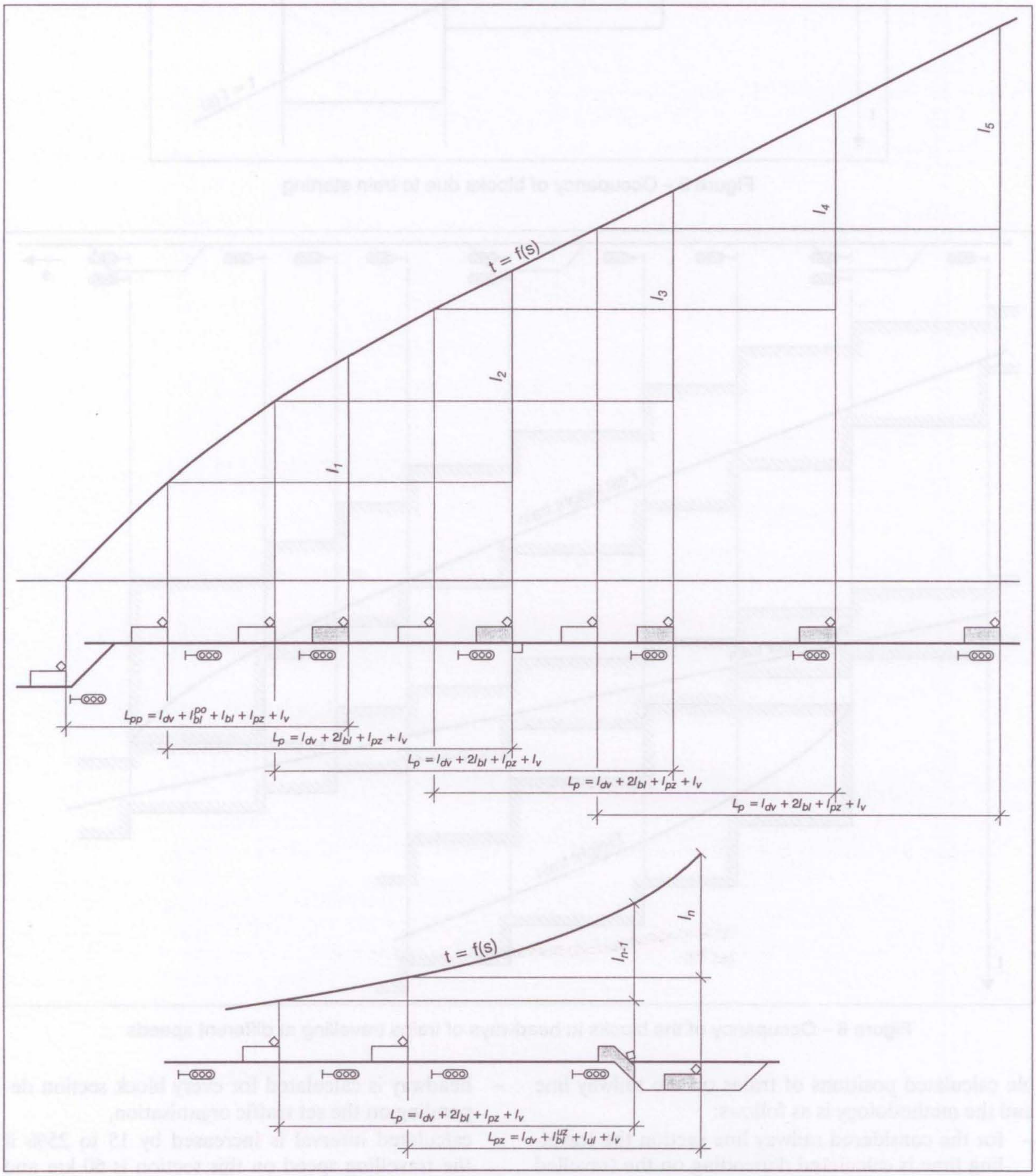

Figure 8 - Scheme of train separation for calculating the headway

– unique headway is the highest value obtained by the calculation.

Different trains travel the same section of the railway line in different travelling times, which means that the separation between the trains changes constantly. However, the time of calculated separation (t_x) changes constantly as well. This statement leads to the conclusion that the travelling time changes constantly at the calculated separation thus changing also the headway which is a random variable, whose mathematical expectation is greater than the calculated values.

The distribution density of the travelling times of the calculated separation shows clearly the areas in which the constant train travelling time is influenced, as well as the areas in which this influence does not exist.

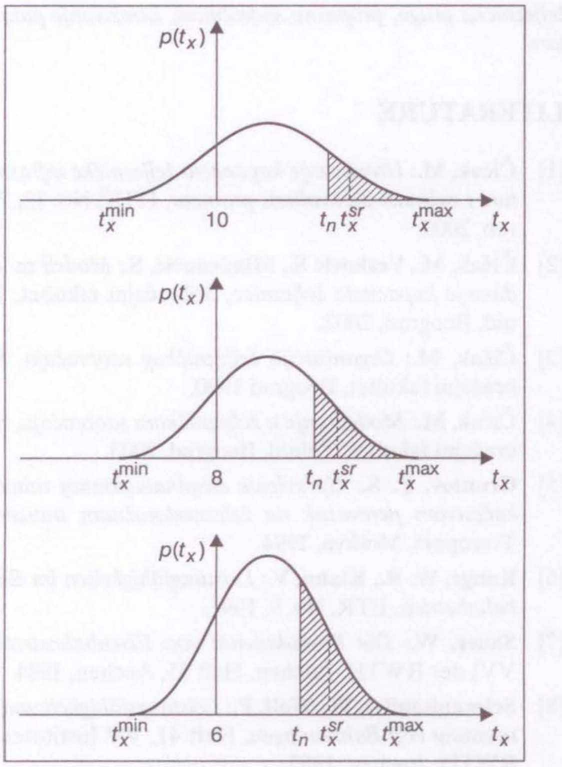

Figure 9 – Headway distribution density in intervals of 6, 8 and 10 minutes

The probability that the travelling time of the train at the calculated separation is within the interval $t_n - t_x^{\max}$ in normal distribution amounts to:

$$p(t_n < t_x \le t_x^{\max}) = \frac{1}{\sigma\sqrt{2\pi}} \int_{t_n}^{t_x^{\max}} e^{-\frac{(t_x-m)^2}{2\sigma^2}} dt_x \tag{21}$$

where:

m – mathematical expectation of the travelling time distribution at the calculated separation,

t_n – travelling time that does not reduce the throughput capacity of a railway line,

$t_x^{\max}$ – maximum travelling time at calculated separation,

σ – mean square deviation of the travelling time,

For normal distribution law at the calculated separation the mean value of the travelling time that exceeds the allowed value t_n amounts to:

$$t_x^{sr} = \frac{\int_{t_n}^{t_x^{\max}} t_x e^{-\frac{(t_x-m)^2}{2\sigma^2}} dt_x}{\int_{t_n}^{t_x^{\max}} e^{-\frac{(t_x-m)^2}{2\sigma^2}} dt_x} \tag{22}$$

Knowing the probability and the mean value of exceeding the critical travelling time it is possible to calculate the loss of throughput capacity due to the lack of uniformity of train operation, which yields:

$$\sum t_x^{sr} = \frac{1440}{I} p(t_n < t_x \le t_x^{\max})(t_x^{sr} - I) \tag{23}$$

i. e. after replacement,

$$\sum t_x^{sr} = \frac{1440}{I\sigma\sqrt{2\pi}} \int_{t_n}^{t_x^{\max}} e^{-\frac{(t_x-m)^2}{2\sigma^2}} dt_x \cdot \left(\frac{\int_{t_n}^{t_x^{\max}} t_x e^{-\frac{(t_x-m)^2}{2\sigma^2}} dt_x}{\int_{t_n}^{t_x^{\max}} e^{-\frac{(t_x-m)^2}{2\sigma^2}} dt_x} - I \right) \tag{24}$$

After reducing the previous equation it follows:

$$\sum t_x^{sr} = \frac{1440}{I\sqrt{2\pi}} \left\{ 2\sigma \left[e^{-\left(\frac{t_n-m}{\sigma\sqrt{2}}\right)^2} - e^{-\left(\frac{t_x^{\max}-m}{\sigma\sqrt{2}}\right)^2} \right] - \sqrt{2\pi}(m-1)\left[\Phi\left(\frac{t_x^{\max}-m}{\sigma}\right) - \Phi\left(\frac{t_n-m}{\sigma}\right) \right] \right\} \tag{25}$$

where Φ is the Laplas function.

The presented formula allows the loss of the throughput capacity of the railway line for different headways to be calculated, which depends on the lack of uniformity in the train movements regardless of the fact that they are identical per type and structure, and using the same parameters for designing the timetables.

6. CONCLUDING REMARKS

The aim of the entire elaboration of the influencing parameters that determine the capacity of a railway line was to explain certain issues that affect or may affect the letting through of a certain number of trains along a certain railway line, as well as estimating the influence of the throughput capacity on the quality of the transportation service.

In case of railway lines and railway stations with heavy traffic, there are delays in traffic and standstills, the travelling times are increased, and different than the designed ones. In such conditions the level of quality of the proclaimed service decreases, the dissatisfaction of transportation service users increases, with the eventual extremely unfavourable results reflected in reduced profits.

The slowdowns and standstills in traffic with great delays characterize the railway lines with high percentage capacity exploitation, at the same time resulting in the fall of service quality. Therefore, the analysis of every element that directly or indirectly affects the throughput capacity of a line is welcome, especially regarding the size of the spare time which assures the designed quality of the transportation service. The analysis has resulted in the knowledge that the mean value of the installed spare time per train is the measure of the railway line section quality, including the quality of the transportation service. Thus the designed traffic quality on the railway line section will be guaranteed by the set traffic organisation which can eliminate small individual disturbances of the timetable, not resulting in even greater delays i. e. conditioned delays of other trains.

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SAŽETAK

ISTRAŽIVANJE PARAMETARA KOJI DETERMINIRAJU PROPUSNU SPOSOBNOST PRUGE

U ovom radu izučavanje je usmjereno na:
- *utvrđivanje neophodnih elemenata za utvrđivanje lokacije za ugradnju glavnih signala,*
- *proračune duljine prostornih odsjeka*
- *i izračune optimalnih intervala slijeđenja, koji nisu do kraja istraženi, a po utjecaju zaslužuju posebnu pozornost.*

Generalno rečeno, signali se ugrađuju sukladno mjesnim prilikama, odnosno prema tehničko-tehnološkim karakteristikama i uvjetima koje determinira službeno mjesto kojeg štite.

Raspored i duljina prostornih odsjeka uvjetovana je: prugom i njenim eksploatacijskim osobinama, strukturom i vrstom vlakova koji prugom prometuju, organizacijom prometa i sustavom signalizacije, te tehničko-eksploatacijskim osobinama vučnih i voznih sredstava. Svakako valja voditi računa da najmanja duljina prostornog odsjeka ne može biti kraća od duljine zaustavnog puta, odnosno od duljine najdužeg vlaka koji dotičnom prugom prometuje.

Izučavanju ovih parametara dodaje se i proračun gubitka propusne sposobnosti uvjetovane nejednolikim kretanjem vlakova, koji u cilju očuvanja projektirane kvalitete prijevozne usluge, te u aktivnostima postavljanja i provođenja poslovne politike ne smije biti ispušten i zaobiđen

KLJUČNE RIJEČI

željeznička pruga, propusna sposobnost, istraživanje parametara

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