MIRKO ČIČAK, D. Sc.
Institut prometa i veza
Kušlanova 2, 10000 Zagreb, Republika Hrvatska
TOMISLAV JOSIP MLINARIĆ, D. Sc.
Fakultet prometnih znanosti
Vukelićeva 4, 10000 Zagreb, Republika Hrvatska
BORNA ABRAMOVIĆ, B. Eng.
Institut prometa i veza
Kušlanova 2, 10000 Zagreb, Republika Hrvatska

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METHODS FOR DETERMINING THROUGHPUT CAPACITY OF RAILWAY LINES USING COEFFICIENTS OF ELIMINATION

ABSTRACT

This work presents the methodological procedure of determining the throughput capacity of the railway lines under the conditions of organising traffic with parallel and non-parallel graphs, i. e. travelling of trains at the same and different speeds. If the non-parallel graph traffic organisation is applied, i. e. trains of different speeds travel along the line, which is often the case, then the railway line capacity can be calculated by means of the so-called "coefficient of elimination". Therefore, the work defines the coefficient of elimination and presents the methodological approach to its determination for various traffic conditions, i. e. for single-track and double-track lines. Also, some empirical formulas are given which determine the coefficient of elimination.

KEY WORDS

railway lines, throughput capacity, coefficient of elimination

1. GENERAL CALCULATION PRINCIPLES

Methods for calculating the throughput capacity of railway lines in certain countries have experienced transformations over time. They have changed with the changes in technology, with taking into consideration the necessary time for maintenance, as well as by insuring time for achieving greater reliability of the operation of technical means.

The throughput capacity of a line section means the maximal number of trains or train pairs that can pass through in a time unit (day, hour) depending on the infrastructure (number of main tracks, signalling and safety devices, and telecommunication), type and power of the hauling means, mass and properties of the trains, as well as the organisation of traffic (graph type). The number of trains or pairs of trains that can pass along a railway line is usually determined for one day. For suburban sections with intensive passenger traffic, and due to great unbalance, the throughput capacity is determined not only for a day, but also for a period of the highest load on the section, which means the peak hour load.

The throughput capacity is usually determined for the line sections which are technically similarly equipped along the whole length, and which accommodate approximately the same volume of the freight and passenger traffic. The initial and final points of such sections are shunting and distributive stations, suburban section stations, and sometimes also the inter-stations as points of departure and arrival of the block trains.

Two principally different methods are used for the calculation of the throughput capacity of the technical means, and different train structures.

The first method determines first the maximum throughput capacity in the number of trains or train pairs, which prevail (are basic) on the observed railway line. Certain equivalents are use to transfer the trains of other types or categories to this basic (calculation) type of trains. Thus, for instance, the throughput capacity of the line sections is determined first for the parallel graph of traffic organisation (schedule) and expressed in trains of just one type, usually freight trains, and if the line is intended exclusively for passenger traffic, then in passenger trains of the respective category (suburban, i. e. distance). Then follows the evaluation of the influence on the throughput capacity of the trains which run at different speeds, i. e. the throughput capacity for non-parallel graph of traffic organisation is calculated.

Other methods determine the capacity without isolating the calculation category of trains, taking into consideration the probability of the influence of mutual relations of certain types of trains in the graphical presentation of the traffic organisation.

2. THROUGHPUT CAPACITY OF THE LINE IN PARALLEL GRAPH TRAFFIC ORGANISATION

The throughput capacity of the line section can be presented in the following manner:

$$N = \frac{1440 - T_{pr}}{T_{pg}} \alpha_{ps} \text{ (train pairs)} \qquad (1)$$

where:

T_{pr} – time of technological downtime, in min.;

T_{pg} – graph period, in min.;

α_{ps} – coefficient of operation reliability of technical means.

The duration of technological downtime encompasses the time during which travelling of trains is not possible, that is, the time intended for the current and investment maintenance of the tracks, catenary, signalling and automation. The duration of the technological downtime depends on the type of the installed means, i. e. devices, machines and mechanisms, but also on the applied technology of work. The duration of the technological downtime in calculating the capacity for double-track lines is taken as 120 min and on single-track lines 60 min.

The value of the operating reliability coefficient of the technical means (α_{ps}) ranges within 0.86÷0.98 for double-track lines, and 0.87÷0.98 for single-track lines. In the calculation of the hourly throughput capacity of the line sections the technological downtimes are not taken into consideration, but the maximum value of the operation reliability coefficient of the technical means is considered, i. e.: $T_{pr} = 0$, and $\alpha_{ps} = 1$.

The graph period of the single-track lines means the occupancy time of the inter-station distance by a group of trains, which are characteristic for the given type of graph. The graph period on the double-track line sections equipped with automatic track block, represents the headway interval between the trains.

The throughput capacity for a parallel graph is calculated for every physical distance separately. The physical distance with the minimal throughput capacity is called *limiting*, and it determines the capacity of the section as a whole.

The throughput capacity may be calculated by expression 1 only if one type of the graph period of train traffic (i. e. one scheme) is applied. Under real conditions in case of parallel graph of train traffic during the day the scheme, i. e. the type of train traffic period changes. The necessity for changes results from the odd number of trains per directions, need to dispatch at certain times trains in banks and for other reasons. This practically means that the graph period schemes change during the day. Therefore, it is better to determine the throughput capacity on the basis of the following formula:

$$(1440 - T_{pr})\alpha_{ps} = \sum_{i=1}^{n} N_i T_i \qquad (2)$$

where:

N_i – the number of trains i. e. train pairs according to the "i"-th graph period scheme on the limiting space distance; $i = 1,2, \ldots, n$;

T_i – time during the day occupied by trains of the "i"-th traffic organisation scheme;

n – total number of graph period schemes of train traffic.

On single-track lines with constant oddity of traffic volume, when the number of freight trains in one direction amounts to less than 90% of the number of trains in the opposite direction, the throughput capacity is determined for the conditions of odd and non-bank (unbundled) graph. It is calculated for every direction separately, at a given relation of the oddity level (γ_{np}), i. e. the number of trains in the opposite direction (N_{ss}), according to the number of the direction of higher intensity (i. e. with priority N_{sp}).

The total daily time of occupancy of the limiting physical distance consists of the sum of times that reoccur, and which consists of the period of the even graph (T_{pg}) and the interval of train headway time in the direction which has priority ($t_v + \tau_{sl}$) (Fig. 1a).

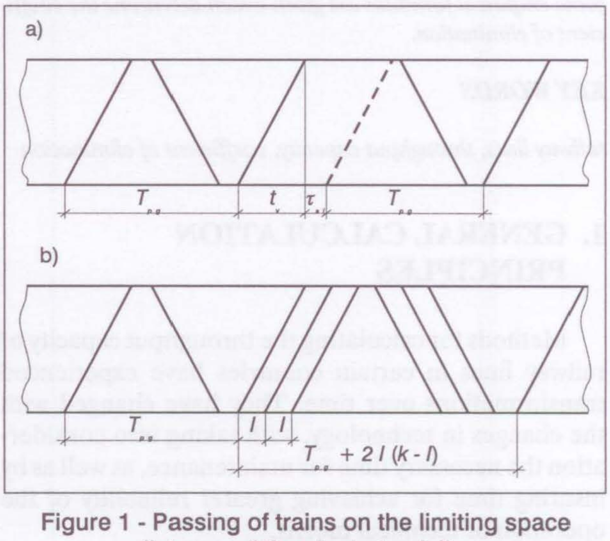

Figure 1 - Passing of trains on the limiting space distance of the single-track line

Considering that the number of repeated graph periods during the day equals the number of trains in the opposite direction, and the number of train headway intervals equals the difference between the number of trains per directions, i. e.:

$$(1440 - T_{pr})\alpha_{ps} = T_{pg} N_{ss} + (N_{sp} - N_{ss})(t_v + \tau_{sl}).$$

This formula yields:

$$N_{sp} = \frac{(1440 - T_{pr})\alpha_{ps}}{T_{pg}\gamma_{np} + (t_v + \tau_{sl})(1 - \gamma_{np})}.$$

The throughput capacity in the opposite direction is:

$$N_{ss} = N_{sp}\gamma_{np}.$$

For *an even and partly bundled traffic graph* the time during the day on the limiting space distance is occupied by trains which are dispatched individually or in banks (Fig. 1. b). The balance of time is expressed in the following condition:

$$(1440 - T_{pr})\alpha_{ps} = T_{pg}(N - N_{pk}) + \\ +[T_{pg} + 2I(k-1)]\frac{N_{pk}}{k} \quad (3)$$

where:

- N – the required throughput capacity expressed in train pairs;
- N_{pk} – number of train pairs that travel in banks on the limiting spacing,
- T_{pg} – common period of the graph, in min.;
- I – headway interval in bank, in min.;
- k – number of trains in bank.

Substituting $N_{pk} = N\alpha_{pk}$ in the equation (3) the throughput capacity is obtained:

$$N = \frac{(1440 - T_{pr})\alpha_{ps}k}{T_{pg}[k + (1-k)\alpha_{pk}] + 2I(k-1)\alpha_{pk}} \quad (4)$$

where:

α_{pk} – coefficient of train banks ($\alpha_{pk} = \frac{N_{pk}}{N}$).

Due to long stays of trains that travel in banks, on intersections as well as in overtaking by passenger trains, the number of trains in bank is usually limited to two. In that case the throughput capacity is:

$$N = \frac{2(1440 - T_{pr})\alpha_{ps}}{(2 - \alpha_{pk})T_{pg} + 2I\alpha_{pk}} \quad (5)$$

On *double-track sections of lines equipped by automatic track block* bundled traffic graph is applied. The time of occupancy of the limiting spacing from the train in this case equals the headway interval in bank, and the throughput capacity in each direction equals:

$$N = \frac{1440 - T_{pr}}{I}\alpha \quad (6)$$

where:

- I – headway interval between trains of the observed direction, taking into consideration the maximum stipulated by physical sections and station, in min.

Formula (6) is applicable only if the headway interval is big. In shorter intervals the lack of uniformity of train travelling is more emphasised. The spacing between the trains changes almost constantly, that is, the distance between them is shortened or lengthened. Therefore, in the formula (6) for the calculation of the throughput capacity, the value of headway interval "I" is increased by the added value ΔI, i. e.:

$$N = \frac{1440 - T_{pr}}{I + \Delta I}\alpha_{ps} \quad (7)$$

Value ΔI is greater the lower the calculated headway interval.

3. RAILWAY LINE CAPACITY IN NON-PARALLEL TRAFFIC GRAPH

The calculation of the throughput capacity in case of non-parallel traffic organisation involves distribution of the resulting throughput capacity of the section, determined for the parallel traffic graph, between the trains of different categories, i. e. between the passenger trains, which include also the suburban trains, as well as freight trains, which include all categories of freight trains.

In non-parallel traffic graph, the throughput capacity of the railway line for freight trains is expressed by the number of freight trains of the set mass and speed, that can pass the section or railway line for the traffic of a given number of passenger, accelerated freight and feeder trains. A part of the day which cannot be used for the passage of freight trains, because trains of all other categories travel at that time is called the time of elimination.

The throughput capacity for the basic freight traffic, represented as a rule by direct and section trains of approximately equal masses and speeds amounts to:

$$N_t = \frac{(1440 - T_{pr})\alpha_{ps}}{T_{pg}} - \frac{[t_{sk}^{p}N_p + (t_{sk}^{ub} - T_{pg})N_{ub} + (t_{sk}^{sb} - T_{pg})N_{sb}]}{T_{pg}} \quad (8)$$

where:

- N_p, N_{sb}, N_{ub} – number of pairs of passenger, feeder and accelerated freight trains;
- $t_{sk}^{p}, t_{sk}^{sb}, t_{sk}^{ub}$ – time of elimination of the freight trains by one pair of passenger, feeder and accelerated freight trains.

This dependence can be represented also in the changed form in the following way:

$$N_t = N - E_pN_p - (E_{ub} - 1)N_{ub} - (E_{sb} - 1)N_{sb} \quad (9)$$

where:

- N - throughput capacity of the line section for freight traffic under the conditions of a parallel graph:

$$N = \frac{1440 - T_{pr}}{T_{pg}} \alpha_{ps};$$

$E_p, E_{ub}, E_{sb},$ – coefficient of elimination of the common freight trains by passenger, accelerated freight and feeder trains, that is:

$$E_p = \frac{t_{sk}^{p}}{T_{pg}};\ E_{ub} = \frac{t_{sk}^{ub}}{T_{pg}};\ E_{sb} = \frac{t_{sk}^{sb}}{T_{pg}}$$

The time i. e. coefficient 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.

Time of elimination of freight trains by a pair of passenger trains consists of the occupancy time of the space distance (inter-station distance) by the pair of passenger trains "$t'_{pv} + t''_{pv}$" and the additional time of elimination "t_d" which has resulted from the difference of intervals between the passenger trains or freight and passenger trains, and which is not the same as with freight trains, i. e.

$$t_{sk}^{p} = t'_{pv} + t''_{pv} + t_d.$$

Depending on the factors which define it, the coefficient of elimination, as well as the time of elimination are composed of two parts, and these are:

$$E_{sk} = \frac{t_{sk}}{T_{pg}} = \frac{t'_{pv} + t''_{pv}}{T_{pg}} + \frac{t_d}{T_{pg}} = E_o + E_d.$$

The value E_o is called the coefficient of basic elimination, and E_d is the coefficient of additional elimination, that is:

$$E_o = \frac{t'_{pv} + t''_{pv}}{T_{pg}};\quad E_d = \frac{t_d}{T_{pg}}. \tag{10}$$

The coefficient of additional elimination can be practically determined only by the construction of the train scheduling graph, i. e. by developing special simulation models, and by experimenting with them. For orientation calculations, statistical processing of the realised or experimental traffic graphs is used.

4. COEFFICIENT OF ELIMINATION ON SINGLE-TRACK LINES

The coefficient of basic elimination of freight trains by passenger trains in the common traffic graph (Fig. 2) amounts to:

$$E_o = \frac{T_{pg}^{pv}}{T_{pg}} = \frac{t'_{pv} + t''_{pv} + 2\tau}{t'_{tv} + t''_{tv} + 2\tau + t_{uk}}, \tag{11}$$

where:

T_{pg}^{pv} – passenger trains graph period;

t'_{pv}, t''_{pv} – pure travelling time of passenger trains excluding acceleration and deceleration times in one and the other direction;

t'_{tv}, t''_{tv} – pure travelling time of freight trains excluding acceleration and braking times in one and the other direction;

τ – station interval;

t_{uk} – time necessary for acceleration and braking in freight trains.

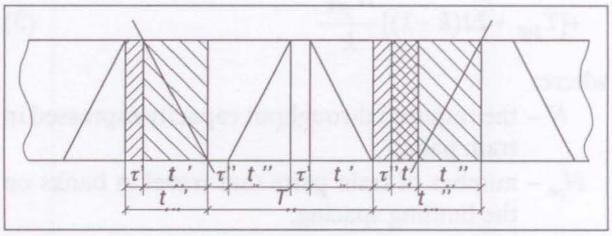

Figure 2 - Elimination of freight trains by passenger trains on single-track lines

On single-track lines equipped with automatic track block the passenger and freight trains at a limiting distance can pass in two different ways, and these are:

- the same as in case of the common odd graph (Fig. 2), i. e. the occupancy time of the space distance by a pair of passenger trains is expressed by their graph period T_{pg}^{pv};
- with the dispatch interval of the freight train following the passenger train "I_{ot} "and with the interval of freight train arrival before the passenger train I_{dl} (Fig. 3). In this case, the occupancy time of the space distance with the pair of passenger trains is determined only on the basis of intervals I_{dl} and I_{ot}: $t'_{pvz} + t''_{pvz} = I_{dl} + I_{ot}$

Considering the above-mentioned, the coefficient of elimination by a passenger train can on these lines be determined in the following manner:

$$E_o^{ab} = \frac{(1-\sigma) T_{pg}^{pv} + \sigma (I_{dl} + I_{ot})}{T_{pg}} \tag{12}$$

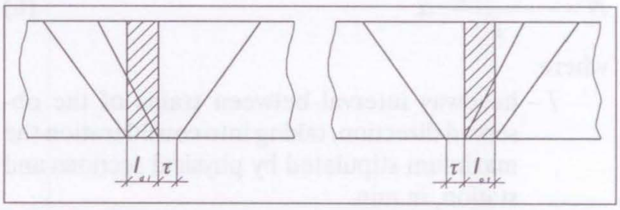

Figure 3 - Position of freight and passenger trains on the limiting space distance of the section equipped with APB

where:

σ – part of passenger trains which pass the limiting space distance according to the scheme presented in Figure 3.

The coefficient of additional elimination depends on many factors, the basic of which are: the number of passenger trains, randomness of space distances, relation of velocities of different categories of passenger trains to freight trains, and qualification and experience of scheduling designers. Since it is not possible to include all these factors in the analytical expression of dependence, additional elimination has to be determined based on the statistical processing of a great number of actual graphs.

For practical purposes, with sufficient accuracy, the mean value of additional coefficient of elimination can be used $E_d = 0.3$ for $j \leq 0.8$ and $E_d = 0.4$ for $j > 0.8$, (j – coefficient of randomness of the space distances of the section).

5. COEFFICIENT OF ELIMINATION ON DOUBLE-TRACK RAILWAY LINES

The coefficient of elimination of freight trains by passenger trains consists of two parts: the first part which does not depend on the number of tracks in inter-stations (E_n) and the second part which depends on the number of tracks (E_z), i. e. the coefficient of elimination on double-track lines is:

$$E_{dp} = E_n + E_z.$$

If there is a sufficient number of tracks per inter--stations then $E_z = 0$. The part of the coefficient of elimination that does not depend on the number of tracks per inter-stations (E_n) consists of the basic (E_o) and additional (E_d).

On tracks equipped with automatic track block, the basic part of the coefficient of elimination depends on the travelling times of the freight (T_{tv}) and passenger train (T_{pv}) on the section and the limiting space distance (t_{tv} and t_{pv}), and also on the mutual position of the passenger trains on the graph.

The travelling time of trains of different categories shows the greatest influence on their mutual position on the graph, and thus also on the coefficient of elimination. Four versions are possible here:

***Version* I**: $T_{tv} - T_{pv} \leq I_{tv}$ (Fig. 4). This is the section with almost parallel travelling graph, i. e. overtaking in such conditions is useless. The elimination time is:

$$t_{pvz} = T_0 - I_{tv}$$

where:

$$T_0 = I_{dl} + I_{ot} + T_{tv} - T_{pv} + t_{uk};$$

I_{dl}, I_{ot} – arrival interval of the passenger train following the freight train, that is, the time of dispatching the freight train after the passenger train.

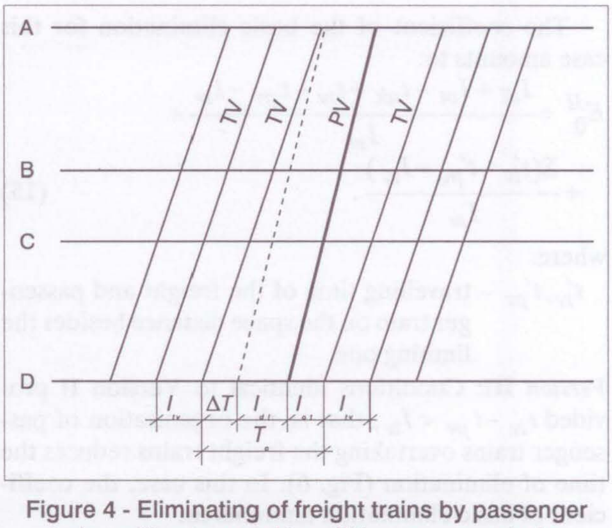

Figure 4 - Eliminating of freight trains by passenger trains without overtaking; PV - passenger train, TV - freight train

where:

$$E_0 = \frac{t_{pvz}}{I_{tv}} = \frac{T_{tv} - T_{pv} + I_{dl} + I_{ot} + t_{uk} - I_{tv}}{I_{tv}} \tag{13}$$

If $\Delta = \dfrac{T_{pv}}{T_{tv}}$ is substituted, then the expression gets the following form:

$$E_0^I = \frac{(1-\Delta)T_{tv} + I_{dl} + I_{ot} + t_{uk}}{I_{tv}} - 1 \tag{14}$$

***Version* II**: $T_{tv} - T_{pv} > I_{tv}$. The case when the section accommodates higher speeds of passenger trains. The value of the time of elimination on such sections is not just influenced by the travelling time of the freight and passenger trains on the track section, but also on the limiting and adjacent space distance with $t_{tv} - t_{pv} > I_{tv}$ (Fig. 5).

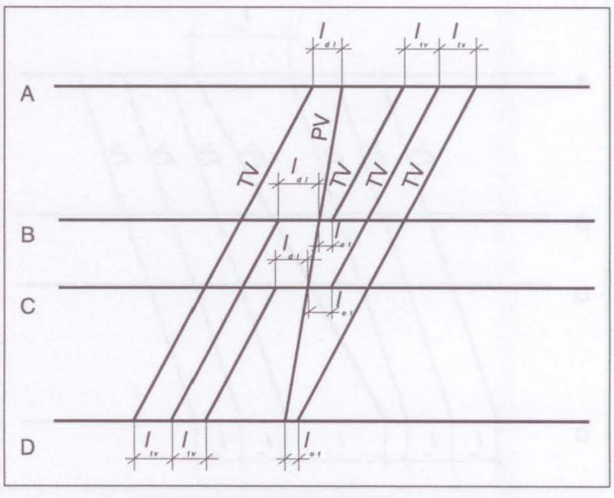

Figure 5 - Eliminating of freight trains by passenger trains under the conditions of overtaking, for: $t_{tv} - t_{pv} > I_{tv}$

The coefficient of the basic elimination for this case amounts to:

$$E_0^{II} = \frac{I_{dl} + I_{ot} + t_{uk} + t_{tv} - t_{pv} - I_{tv}}{I_{tv}} + \\ + \frac{\Sigma(t'_{tv} - t'_{pv} - I_{tv})}{I_{tv}}. \qquad (15)$$

where:

t'_{tv}, t'_{pv} – travelling time of the freight and passenger train on the space distance besides the limiting one.

Version III: Conditions identical to Version II provided $t_{tv} - t_{pv} < I_{tv}$, that is, the organisation of passenger trains overtaking the freight trains reduces the time of elimination (Fig. 6). In this case, the coefficient of basic elimination amounts to:

$$E_0^{III} = \frac{I_{dl} + I_{ot} + t_{uk}}{I_{tv}} - 1 \qquad (16)$$

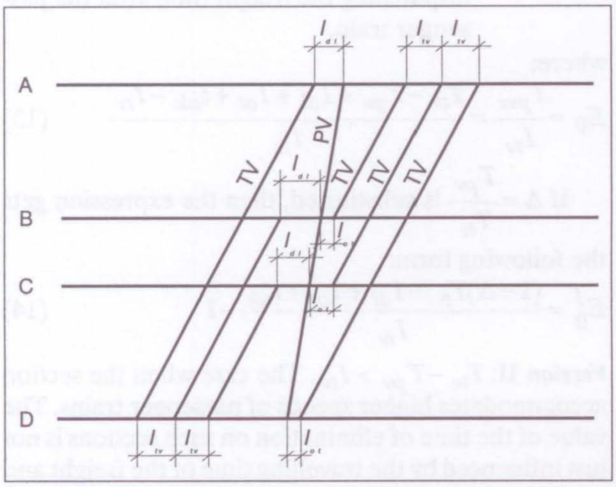

Figure 6 - Elimination of freight trains by passenger trains with overtaking, but for the case: $t_{tv} - t_{pv} < I_{tv}$

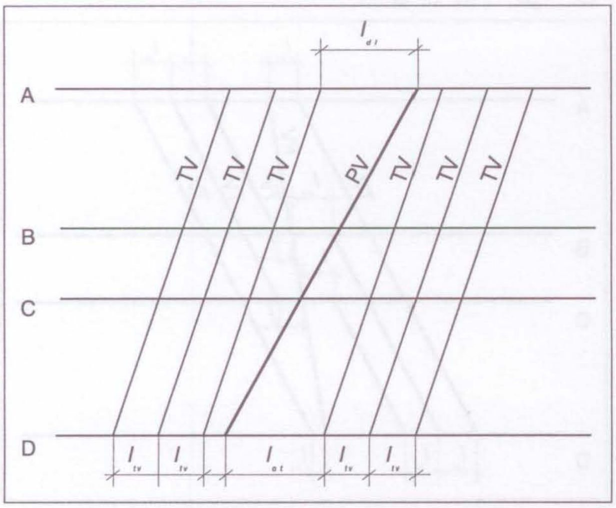

Figure 7 - Elimination of freight trains by passenger trains, provided commercial velocity of passenger trains is lower than the one of freight trains

Version IV: $T_{tv} - T_{pv} < 0$, i. e. when passenger trains with delays at the stops and inter-stations have lower commercial velocity than the freight trains, but still passenger trains are not overtaken by freight trains (Fig. 7). The coefficient of basic elimination in that case amounts to:

$$E_0^{IV} = \frac{T_{pv} - T_{tv} + I_{dl} + I_{ot}}{I_{tv}} - 1. \qquad (17)$$

The coefficient of additional elimination E_d, which occurs as result of the lack of uniformity of the periods between the elimination zones of adjacent passenger trains, i. e. their headways, which amounts to 0.3 on double-track lines.

Apart from the common coefficient of elimination, in passing of passenger trains on the section, this may result in the elimination of trains due to the insufficient number of tracks (E_k). In case the number of overtaking tracks is not sufficient, the coefficient of elimination is:

$$E_k = \frac{T_{tv}(1-\Delta) + I_{dl} + I_{ot}}{I_{tv}} - (E_0 + \Sigma N_{pr}) - 1, \qquad (18)$$

where:

ΣN_{pr} – the number of freight trains that may be dispatched on the section in time T_k^{pr} when the passenger trains overtake it (this number may be taken to be equal to the number of overtaking tracks at inter-stations of the section for the observed direction).

6. COEFFICIENT OF ELIMINATION DEPENDING ON FAST FREIGHT AND FEEDING TRAINS

The throughput capacity of a line is influenced by the fast, i. e. express and accelerated freight trains with travelling speeds greater than the speeds of freight trains. The equivalent of these trains is determined as a rule in the same manner as for the passenger trains. The coefficient of additional elimination, due to the possibility of moving these trains on the traffic graph, has lower value than in case of passenger trains ($0.1 \div 0.2$).

Feeder trains, with purely technical speeds identical to speeds of common freight trains, also affect the throughput capacity. Unlike passenger trains, the feeder train routes on the traffic graph are not fixed in advance and their passage along the section can be organised in such a way that their influence on the throughput capacity is maximally reduced. After every stay of the feeder train at an inter-station, for the purposes of leaving or collecting waggons, there is a need for re-routing, which results in special time loss.

7. CONCLUSION

It may be concluded that the methods for calculating the railway line capacities are rather complicated. They are especially complicated under the conditions of mixed traffic and different structure of trains, and they are extremely sensitive to greater differences in train travelling speeds. This is especially reflected on the coefficient of elimination, the values of which cannot be obtained by exact analytical method.

Usually the coefficient of elimination is analysed for the concrete railway line conditions, i. e. conditions of traffic organisation. Many authors propose a series of empirical formulas for different conditions of traffic organisation, which were obtained by studying the numerous versions of traffic organisation for the planned railway line conditions, or by means of experiences, and recently more and more by means of simulations.

The principles of these methods for calculating of the railway line capacity can be used at the Croatian Railways, but special care should be taken in determining the coefficient of elimination. As a rule, it is correct to determine the coefficient of elimination on the basis of study carried out for each line separately, using the simulation models for the experiments of numerous versions of traffic organisation.

MIRKO ČIČAK, D. Sc.
Institut prometa i veza
Kušlanova 2, 10000 Zagreb, Republika Hrvatska
TOMISLAV JOSIP MLINARIĆ, D. Sc.
Fakultet prometnih znanosti
Vukelićeva 4, 10000 Zagreb, Republika Hrvatska
BORNA ABRAMOVIĆ, B. Eng.
Institut prometa i veza
Kušlanova 2, 10000 Zagreb, Republika Hrvatska

SAŽETAK

METODE ZA UTVRĐIVANJE PROPUSNE SPOSOBNOSTI ŽELJEZNIČKIH PRUGA KORIŠTENJEM KOEFICIJENATA SKIDANJA

U ovom radu izlaže se metodološki postupak utvrđivanja propusne sposobnosti željezničkih pruga u uvjetima organizacije prometa pri paralelnom i neparalelnom grafikonu, odnosno prometovanju vlakova istim i različitim brzinama. Ukoliko se primjenjuje organizacija prometa uvjetovana neparalelnim grafikonom odnosno na pruzi prometuju vlakovi različitih brzina, a što je veoma čest slučaj, onda je propusnu moć pruge moguće računati uz korištenje tzv. «koeficijenata skidanja». Stoga se u radu definira koeficijent skidanja i izlaže metodološki pristup njegovom utvrđivanju za različite uvjete prometa, odnosno za jednokolosječne pruge i dvokolosječne pruge. Također se daju i neke empirijske formule za utvrđivanje koeficijenta skidanja.

KLJUČNE RIJEČI

željezničke pruge, propusna sposobnost, koeficijent skidanja

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