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Buffer Time Optimisation in the Function of Timetable Stability

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ABSTRACT

Timetable stability depends on the regularity of trains. Any deviation from the planned timetable leads to its instability. Railway network characteristics determine the capacities of the transport service. Depending on the capacity calculation method, time components are added to the minimum headway to ensure timetable stability. The UIC 405 method is simple and can be used on all railways. The disadvantage is that the calculations are based on average data. According to the method, the minimum headway consists of the time of the average headway interval, additional time and the buffer time. The additional time is precisely defined by the number of APB sections, while the buffer time is in the average value. When creating the timetable, the goal is optimal utilisation of the infrastructure. If the headway is too long, the capacity is not used, and if it is too short, timetable instability will ensue. Instead of averaging, this work calculates a buffer time that depends on the ratio of the travel time of the previous and the following trains. In this way, the headway is optimised and the calculation of the UIC 405 method is improved.

KEYWORDS

simulation modelling; Petri net; buffer time; headway; traffic optimisation; traffic segmentation.

1. INTRODUCTION

Technological calculations in railway transport are used to ensure the stability of the timetable during its execution. In addition to ensuring timetable stability, the calculations determine the maximum railway permeability or capacity. The line capacity is defined as the maximum number of trains that can run on a line section expressed in terms of transport and capacity. The calculation can be performed using the following methods [1]:

– chart periods and relevant train headway intervals,
– calculation based on the free interval between trains,
– exponential distributions of free time,
– correlation factors,
– UIC 405 and UIC 406 methods.

These methods are divided into two groups, those dependent on the timetable and those independent of the timetable. The buffer times of the UIC 405 method are optimised by exponential distribution and correlation of travel times of previous and following trains. The study is based on the average delay consequences of suburban trains caused by the instability of the timetable of regional and long-distance trains. Regional and long-distance trains are affected by delays due to the length of their routes and, as they enter the area of suburban trains, they have a greater negative impact on the timetable stability of suburban trains. Since the main characteristic of suburban trains is punctuality and regularity, the negative impact on the service quality of suburban trains is very large. Previous research has addressed the above problems in a segmented manner. The positive results presented have been successful, but when implemented in a real system, the other segments that make up the organisation of traffic show inadequacies or inconsistencies. This environment includes a new segmentation of passenger trains, cycle timetables and minimal changes to organisational arrangements for suburban traffic.

The second chapter describes previous research of buffer time as part of headway in the function of infrastructure optimisation used in rail systems where calculations for the headway were sum calculations of the minimum headway with additional and average buffer time. The research is not only related to railway transport but the solution to the problem can be adapted by considering proposed solutions from other dynamic systems.

In the third chapter, the traffic quality indicators of the case study and the proposed model with coloured Petri nets are determined. In the proposed model, buffer time optimisation was performed using the exponential expression studied by the Monte Carlo method in calculating the capacity of the railway section. The simulation results show a reduction in delay and an increase in timetable stability of suburban trains as important indicators of traffic quality compared to the case study.

The conclusion summarises the improved business processes and timetable optimisation results that increased rail capacity.

2. LITERATURE REVIEW

In Croatian railway transport, the average interval of the minimum headway is calculated by the UIC 405 method. The average minimum headway interval (tsm) is the mean of all minimum headway intervals calculated for all train following cases at the observed limiting station distance. In such calculations, the average buffer time is the same for all trains.

The quality of rail transport depends on timetable stability. The optimal use of infrastructure depends on the robustness of the timetable. Matching the buffer time with the minimum headway is a key factor in both cases. Most infrastructure managers use a fixed buffer time in the technical definition of the minimum headway.

To increase robustness, most infrastructure managers in Europe add a fixed buffer time and minimum headway interval to their calculations to reduce or prevent the propagation of delays when a train is late. According to the research of Jovanović et al. [2], the specified method of technical calculations of the minimum headway interval leads to an increase in capacity consumption, which becomes a problem for heavily used lines. Through their research, they modelled the resource allocation problem as a Knapsack problem, where each buffer time is treated as an object whose value is determined according to commercial and operational criteria, and whose size is equal to its duration.

Zieger et al. [3] used correlation integrals with predictive delay analysis in their study to determine the additional time and prove the correlation by using the Monte Carlo method to simulate delay accumulation. This type of additional time calculation is used in the analytical traffic management application "STRELE" at Deutsche Bahn.

The survey of the level of service (LoS) of a public transport system is an important aspect of determining service quality. According to Wang et al. [4], two classification methods have been established: a method that uses the mean and coefficient of variation to model the distribution and a method that only considers the mean. The methods are used to gather more detailed information about the system in time and space. This approach can be used to monitor the overall level of public transportation performance and correct for situations where system weaknesses occur, and LoS is a proven component to consider in timetable planning. Shang et al. [5] compared methods of determining an additional time of space segments and traffic density incorporating real delay effects. Based on this, they built a model of the distribution of deviation times and compared the models based on the standard error of each parameter in the model and created an objective function in which delay weight coefficients are determined and created a model using the method of mathematical analysis.

Landex et al. [6] demonstrated in a case study of commuter traffic in Copenhagen that speed reductions can increase timetable punctuality and stability. Speed reduction only applies to suburban traffic.

For the construction of a robust timetable in the area of high-frequency traffic, Bešinović et al. [7] investigated the use of train travel time models that reliably describe real speed profiles provided the model parameters are calibrated against measurements in a real system. In the course of their study, they developed a method for estimating train length and calibrating the estimation of real train motion. The computational efficiency of this approach allows it to be used in real-time applications.

In their research, Kroon et al. [8] developed a model optimised with the stochastic method to provide resilience to stochastic traffic disturbances, timetable robustness and stability. The study on the impact of delays on timetable stability shows that relatively small changes in the model can reduce the average network delays such as optimizing the average minimum headway interval.

A study on a timetable model to minimise the waiting times of passengers at public transport terminals by Hassannayebi et al. [9] is based on the introduction of frequency variables into nonlinear calculations using heuristic rules. The results of research on demand-responsive scheduling optimise passengers' train waiting times and train dwell times at the terminals.

The research of Li et al. [10] on the demand-responsive schedule problem for the busiest urban railway line considers uneven spatial and temporal capacity demand. To solve the problem, they propose the use of a two-stage genetic algorithm based on the relationship between user and operator costs, which leads to a better matching of transport capacity and demand.

Studies of the required capacities according to Duvnjak et al. [11] are the result of an analysis of passengers carried in public transport and a forecast of the required capacity for the introduction of integrated transport with a share of subsidies that can be achieved by a particular type of transport. The capacity needs are determined according to the number of tickets sold, but according to components which are important for the analysis of the number of passengers carried, route and capacity utilisation.

In their work, Restel et al. [12] describe robustness as a function of time reserves that help avoid unplanned interruptions due to traffic disruptions. They presented a simulation-based method that takes into account the probabilities of the occurrence of disruptions and their consequences to achieve an acceptable level of robustness, which can be quantified by the probability of delay-free propagation. The method of adding an iterative buffer time is based on operational data to achieve timetable stability.

The research work of Young and Du [13] is related to the determination of the ridership coefficient in favour of defining suburban areas according to passenger characteristics. They use the genetic algorithm to determine the integer programming model with the lowest total cost. The research results show that the zonal operation method is suitable for suburban railways.

The research of Shang et al. [14] which incorporates the train stop pattern into the timetable optimisation process aims to reduce the total travel time of passengers using the binary variable determination (BVD) method. For this purpose, they use a genetic algorithm (GA) based on the BVD method to solve the proposed model. The conducted study can reveal the improvement points in the operational services of the urban rail transportation lines.

Duvnjak et al. [15] performed an analysis of the current state of railroad operations on the railway line from Zagreb Main Station (Zagreb GK) to Dugo Selo and developed a new model of the railway system which included change in the existing topology of the railway infrastructure and signalling system. The simulation analysis of rail operations on the proposed model of the railway system has shown that the proposed changes can enable the application of the proposed cyclic timetable of suburban trains while separating regional trains from the suburban system, with the quality of infrastructure determining the division points for each area of the new proposed categorisation of passenger traffic.

In their study of general buffer times Weik et al. [16] focused on the effects of broken-down trains and the propagation of delays to other trains. Using an analytical approach to the stochastic model of the railway system, they use the "STRELE formula" to estimate additional delays based on the convolution of the delay distribution function.

A study by Mlinarić et al. [17] investigates the connection between power consumption and the efficiency of regional passenger transport. They conclude that the fundamental determinants of regional transport development are reflected in the satisfaction of transport needs on intercity routes, with an emphasis on daily passenger migrations. The research proved that optimal management of energy and fuel consumption affects the efficient implementation of the timetable and the economy of the transport system, while the increase in the efficiency of the regional transport system significantly affects the improvement of passenger traffic.

The analysed domains on which the authors rely are related to the avoidance of average delays that affect timetable stability. Considering the conditions under which delays occur, the solutions are partially applicable to other systems. All the mentioned research is related to the reduction of delays calculated in a predictive way to increase timetable stability. The different research segments can be considered optimisation segments in creating a robust and high-quality timetable. For the aforementioned reasons, this work developed a mathematical model for buffer time and minimum headway calculation to optimise the utilisation of the infrastructure capacity, especially in areas with high traffic frequency.

The focus is on the optimisation of the average buffer time in terms of the correlation between the travel times of two trains on the considered route section. Due to different states of infrastructure quality, level of service (LoS) should also be taken into account when calculating the minimum follow-up time. When LoS is included in the calculation, it is about the execution of the planned timetable. When planning the timetable, it is not necessary to include LoS in the calculation of frequency.

3. MODEL ANALYSIS

The Yasper program uses coloured non-autonomous time Petri nets to represent the state of a time-dependent dynamical system. The railroad transportation system is a dynamic system determined by the travel time of trains and their timetable stability. A simulated case study model created with coloured Petri nets shows the dynamic state of the system depending on the calculated time parameters of the timetable for each train with the average deviation obtained from the analysis of the quarterly execution of the 2020/21 and 2021/22 timetables. A simulation model was created to demonstrate the optimisation. Case study models using the UIC 405 method and a simulation model in which the buffer time of the same method was optimised were compared. The reference case study was analysed on the Dugo Selo – Zagreb Main Station line. This route is the most frequently used in the Croatian railroad network, especially in the peak hours that occur during the daily migrations in the time intervals from 06:00 to 09:00 and from 14:30 to 17:30. In the case study, the morning peak hours were analysed and the headway was optimised in the simulation model for all trains operating in this time interval. The studied section is divided into block sections (APB) with main/distant signalling. The occupancy of each section is controlled by the section main/distant signals located at the beginning of each section (*Figure 1*).

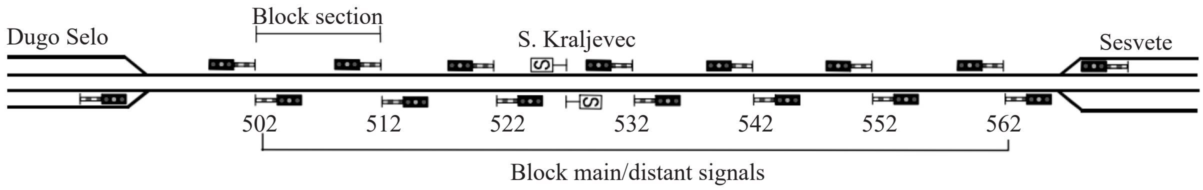

Figure 1 – Block section on Dugo Selo – Sesvete line

The safety elements of traffic management do not allow two trains to be on the same section, and main/distant signals inform the driver of the situation on the next two block sections.

The colour Petri net model of the case study shows the dynamic process of running suburban trains (places p6–p12), regional trains (places p6r–p12r) and long-distance trains (places p6'–p12'), while control occupancies of resources are modelled by control places kp1–kp7. Control places do not allow trains to catch up on the section to avoid delays [18–20], (*Figure 2*).

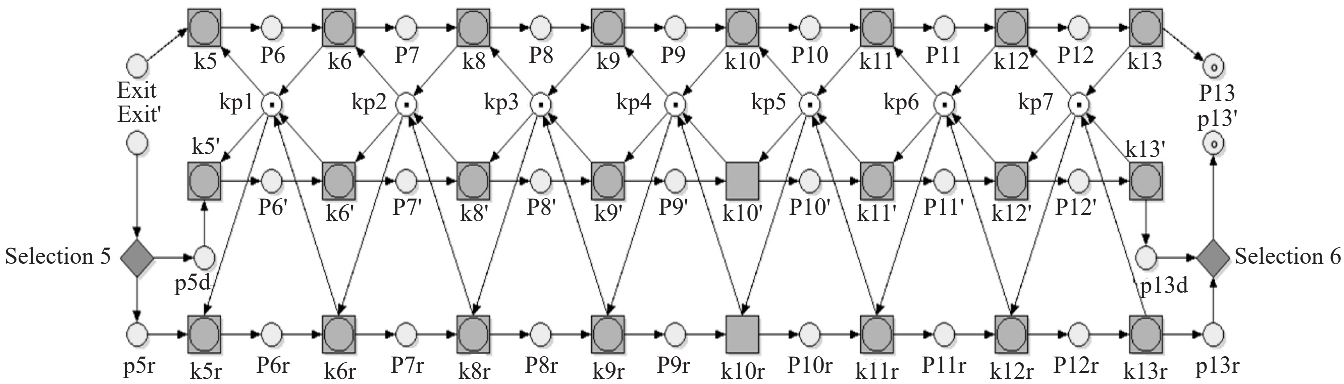

Figure 2 – Petri nets model of APB sections on Dugo Selo – Sesvete line

The simulation process of the train dispatch organisation in the case study is shown in *Figure 3*. Point "E" is an emitter that generates a certain number of trains according to the given roles.

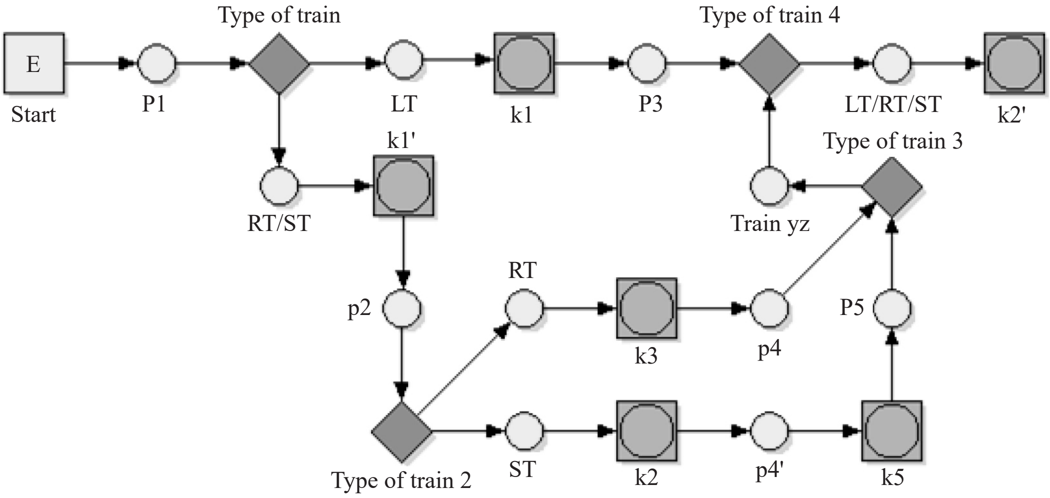

Figure 3 – Petri net model of the organisation of the train dispatch model

In the process of train departures from the station on the graphical representation created with Petri nets, the places "p" are processes that require a certain time interval. This time interval is contained by time triggers "k". What distinguishes Yasper from other applications of Petri nets is the graphical form of a rhombus which allows selection at the moment when a process detects a conflict situation, the solution of which is precisely defined by valid rules and conditioned by the results of previous actions. In the presented figure, the chosen train with a higher rank in the place LT/RT/ST depends on which train can depart first, and every chosen train has an equal time of departure presented in transition place k2'.

The research model developed with coloured Petri nets shows the dynamic state of the system as a function of the calculated schedule time parameters for each train with the average deviation also determined by the quarterly timetable execution analysis. The differences between the case study and the studied model are in the buffer calculation method. In the studied model the calculation of the buffer time depends on the travel times of the previous and following train and in the segmentation of passenger traffic, whereby if a regional train delay is disturbing dispatch of the suburban train, suburban trains have priority dispatching from the station. In the studied model, the buffer time is calculated according to the proposed calculation expression which means reduced buffer time and headway optimisation.

The segmentation of passenger trains is precisely defined by their characteristics and traffic segmentation areas. For suburban traffic, only suburban trains run and use the cycle timetable (*Figure 4*).

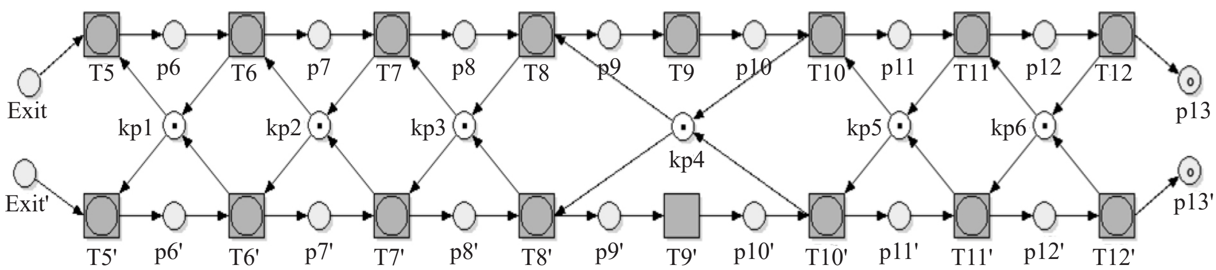

Figure 4 – Petri net model with passenger traffic segmentation

According to the proposed segmentation, the characteristics of regional and long-distance trains in the area of suburban traffic are identical in terms of speeds and stops at stations and train stops. Therefore in the graphic representation of the simulation model, they move in the range p6'–p7', while the suburban trains move in the range of p6–p7.

The markers "p" in both models represent Petri nets and denote places where certain actions can be performed, and on the section, Dugo Selo – Sesvete, these are the markers p6–p9, p11, p12 of the section signals (in *Figure 1* markers 502–562) and the train stop Sesvetski Kraljevec (p10 and p10').

In the studied model, suburban trains have priority when leaving the station, followed by other trains. Such dispatching procedures ensure the stability of suburban train timetables. To determine the maximum transport capacity, it is necessary to calculate the maximum railway capacity, which depends on the minimum headway. To calculate the minimum headway interval using the UIC 405 method, the following formula is used (*Equation 1*):

$$t_{sm} = \frac{\sum_{i=1}^{n_p} n_i \cdot t_{si} + \sum_{j=1}^{n_u} n_j \cdot t_{sj}}{\Sigma n_{ij}} \tag{1}$$

where:
t_{sm} – average interval of minimum headway [min/train]
n_i – number of following trains by category *i*
n_j – number of following trains by category *j*
t_{si} – intervals of minimum times between two categories of travel times
t_{sj} – intervals of minimum following trains between two categories of travel times
n_u – number of previous trains
n_p – number of following trains

The calculation of the average buffer time depends on the time interval in which the calculation is made, so for the hour's timetable, the constant used in the calculation is 0.33 (*Equation 2*).

$$t_b = t_{sm} \cdot 0.33 \tag{2}$$

For the daily timetable, the constant in the calculation of the additional time is 0.67 (*Equation 3*).

$$t_b = t_{sm} \cdot 0.67 \tag{3}$$

For the organisation proposal to be feasible, the calculation of rail capacity must be optimised. The study of optimisation models and the verification of calculations with the Monte Carlo method resulted in an exponential expression. The average buffer time according to the UIC 405 method is optimised with the exponential *Equation 4*.

$$t_b = \frac{t_{pi} \cdot \left(t_{pi} + 1 - e^{-\frac{t_{pi}}{t_{sm}}} \right)}{t_{pj} \cdot \left(1 + e^{-\frac{t_{pj}}{t_{sm}}} \right)} - t_{pi} \tag{4}$$

where:
t_b – buffer time [min]
t_{pi} – travel time of following train [min]
t_{pj} – previous train travel time [min]
t_{sm} – average minimum headway time [min]

Inclusion in the minimum headway model created with Petri nets with optimised buffer time, together with the proposed segmentation of passenger trains, resulted in an 8% increase in the capacity of the section under consideration. *Table 1* shows the results of the minimum headway with buffer time calculation for all passenger train categories. However, the calculation is valid for all categories and types of running trains in the study section.

Table 1 is composed of average headway, additional time and buffer time. *Figure 5* shows the different travel times that depend on the proposed calculations.

The research conducted as part of a case study on the RFC corridor lines of Croatian railroads shows a very low percentage level of service (LoS). The research data show that railway maintenance is not adequate on a large part of corridor lines (*Table 2*).

Table 1– Calculation of minimum headway time by Equation 4

		Time of previous train							
		t_r	7	8	9	10	11	12	t_{amh}
Time of following train	7	1.5	5.17	6.01	7.27	8.77	10.52	12.52	3.67
	8	1.5	5.17	5.18	6.19	7.45	8.93	10.64	3.67
	9	1.5	5.17	5.17	5.30	6.36	7.62	9.08	3.67
	10	1.5	5.17	5.17	5.17	5.43	6.51	7.77	3.67
	11	1.5	5.17	5.17	5.17	5.17	5.55	6.64	3.67
	12	1.5	5.17	5.17	5.17	5.17	5.17	5.66	3.67

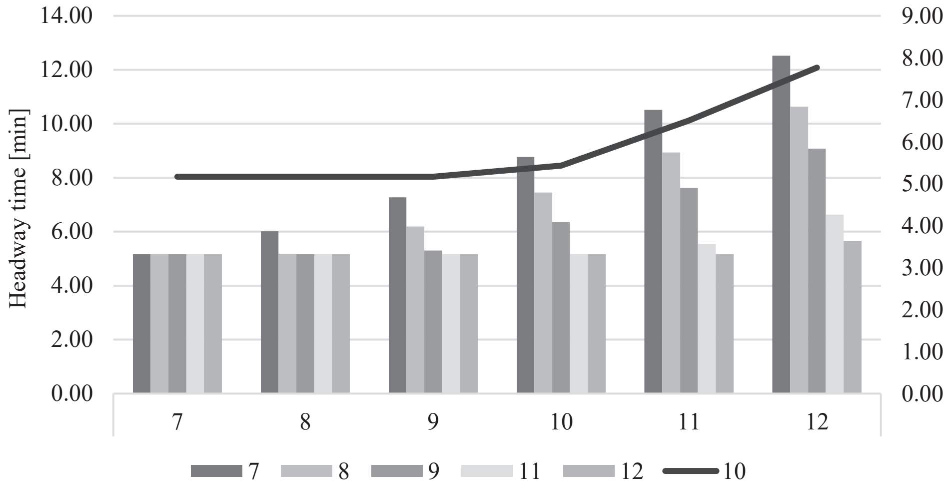

Figure 5 – Chart of headway times with dynamic buffer times

Table 2 – A percentage of maximum speeds on the corridor lines

RH-1			RH-2			RH-3		
km/h	l	%	km/h	l	%	km/h	l	%
≤60	78.086	25	≤60	67.473	21.91	≤60	17.459	17.05
60	28	9	60	35.055	11.38	60	4.821	4.71
70	34.2	11	70	36.405	11.82	75	1.52	1.48
75	0	0	75	51.48	16.72	80	4.288	4.19
80	4.4	1	80	7.091	2.30	100	79.119	77.28
95	1.2	0	90	22.268	7.23			
100	76.5	25	95	4.017	1.30			
120	61.2	20	100	45.301	14.71			
160	56.2	18	110	18.039	5.86			
≥100		62	120	30.867	10.02			
			140	25.019	8.12			
			≥100		38.71			

The calculations in *Table 2* target a schedule for traffic planning in a given period, but if during that period LoS decrease, the maintenance of stability of the timetable is disturbed. Because of that, the percentage of LoS lost in the research model was included in the calculation of a minimum headway. If the calculation is performed for lines where timetable stability is disturbed due to a decreased level of service, then the percentage of LoS must be taken into account for headway so that the difference of the percentage of complete quality and the deviation is added so that the headway interval is multiplied by this difference in *Equation 5*.

These calculations optimise the timetable and improve robustness. The calculations can be applied in suburban traffic areas with high frequency traffic.

$$t_h = \left[\frac{t_{pi} \cdot \left(t_{pi} + 1 - e^{-\frac{t_{pi}}{t_{sm}}} \right)}{t_{pj} \cdot \left(1 + e^{-\frac{t_{pj}}{t_{sm}}} \right)} - t_{pi} \right] + t_{sm} + t_a + \left\{ \left[\frac{t_{pi} \cdot \left(t_{pi} + 1 - e^{-\frac{t_{pi}}{t_{sm}}} \right)}{t_{pj} \cdot \left(1 + e^{-\frac{t_{pj}}{t_{sm}}} \right)} - t_{pi} \right] \cdot \left[1 - 0.257 \cdot exp\left(-1{,}3 \cdot p_{pt} \right) \cdot t_{sched} \right] \right\} \quad (5)$$

where:
t_h – headway time [min]
t_a – additional time
p_{pt} – share of passenger trains
t_{sched} – length of schedule period

The time between the departures of the previous and the following trains when including their travel times according to the valid timetable in the extended formula for determining the minimum headway ensures timetable stability.

The calculation data with *Equation 5* differ by the added lost fraction of LoS (*Table 3*).

Table 3 – LoS for the line Dugo Selo – Zagreb Main Station

Type	Number of trains	p_{pt}	t_{sched}	LoS	1-LoS
Long distance trains (LT)	3	0.14	4	0.85	0.15
Regional trains (RT)	7	0.33	4	0.67	0.33
Suburban trains (ST)	11	0.52	4	0.52	0.48

Table 4 – Calculation of headway increase for lost LoS

			Headway time					
	t_{sp}	t_r	t_{bi}-7	t_{bi}-8	t_{bi}-9	t_{bi}-10	t_{bi}-11	t_{bi}-12
t_j-7	3.67	1.5	5.01	6.01	7.27	8.77	10.52	12.52
t_j-8	3.67	1.5	5.01	6.01	7.27	8.77	10.52	12.52
t_j-9	3.67	1.5	4.34	5.15	6.19	7.45	8.93	10.64
t_j-10	3.67	1.5	3.79	4.44	5.30	6.36	7.62	9.08
t_j-11	3.67	1.5	3.67	3.84	4.54	5.43	6.51	7.77
t_j-12	3.67	1.5	3.67	3.67	3.89	4.64	5.55	6.64

The computation of supplemented headway time consist of average headway interval, the additional time, percentage of lost LoS and buffer time. If the buffer time is smaller than the average minimum headway interval the reserved time is lower if the difference of the calculation is negative *Table 4*.

The time from the dispatching of the previous train and the departure of the following train when including their travel time according to the valid timetable in the extended formula for determining the minimum headway ensures the stability of the timetable *Figure 6* shows the different travel times that depend on the proposed calculations.

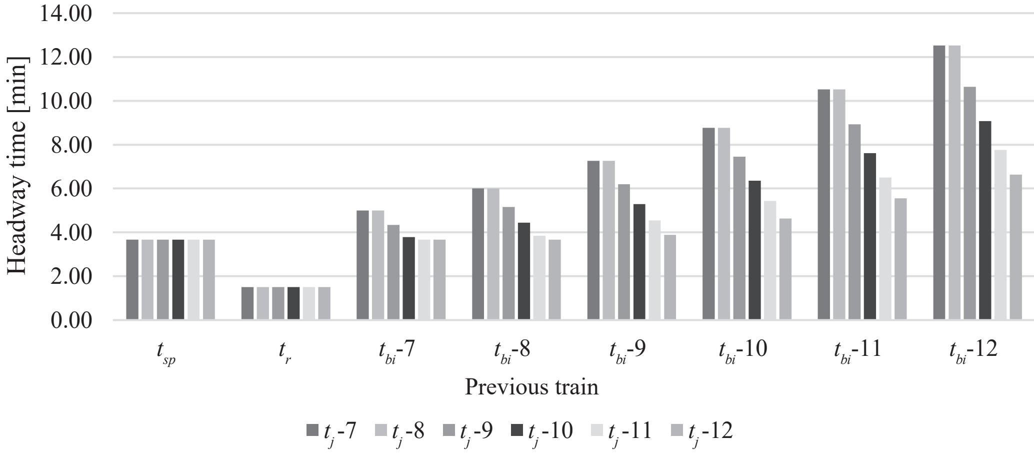

Figure 6 – Calculation with added lost percentage of LoS

The simulation of the proposed buffer time calculation model and the organisational proposal were incorporated into the case study model and verified by non-autonomous coloured Petri nets [21]. In the time interval of the morning peak hour, the maximum line capacity is required, so this time interval is simulated in the simulation model with the introduced timetable of suburban trains. The number of suburban trains has increased by nine, and the passenger trains from regional traffic are represented with an average deviation, but without participation in suburban traffic. In the simulation model, the difference is in the minimum headway time interval of following trains from the station.

The rank of the train is defined by the number with which its route is marked in the timetable. During execution, there may be deviations where trains of a higher rank have priority when continuing out of the station.

The simulation was run in the same time interval as the analysed case study model, but timetable stability was achieved with a higher number of suburban trains with cycling timetables, and the exclusion of regional passenger trains from suburban traffic.

Table 5 shows the number of trains running in the observed time interval in the column "Completed", while "Wait time" shows the average waiting time of suburban trains (regional passenger trains and long-distance trains from the case study are included in the research model).

Table 5 – Comparison of analysed case study model and results of simulated model data

	Completed	Wait time	Cycle time	Work time
Case study	26	55.35	80.89	80.89
Research model	35	0	26.19	25.07

4. DISCUSSION

The results of the analysis show that there are two significant weaknesses in the current system that can be addressed to improve timetable stability. The first weakness refers to the elements of the regional timetable of passenger trains used in suburban traffic. These trains have to stop at all stops, they are not adapted to a quick change of passengers and they have long travel distances, which has a great impact on the stability of their timetable. Because of that, the impacts make the timetable of suburban trains less stable and decreased the capacities of passenger transport because, upon arrival in the suburban transport area, their capacities are used more than 50%. To solve this problem, the proposed model excludes regional passenger trains from participating in suburban traffic. This results in reduced travel time and increased commercial speed for these trains in the suburban area.

The proposed model of segmented passenger traffic trains also introduces the concept of two zones in suburban traffic, with the possibility of adding a third zone in the future. The traffic organisation in the proposed way enables the participation of regional passenger trains in the formation of the third zone of suburban traffic with a driving time of 60 minutes from the urban centre, while on the rest of the route they operate in regional traffic. In this model, regional passenger trains with a travel time limit of 60 minutes are included in the area outside the second zone. This helps to increase timetable stability, improve train efficiency and reduce delays and disruptions.

Another weakness is related to the rank of suburban trains. In the current system, suburban trains are ranked lowest among passenger trains and have to wait for higher-ranking trains that come into collision with the suburban train timetable due to delays. This leads to delays and timetable instability. The analysis shows that 67% of delays in suburban traffic are the result of waiting for higher-class trains. To solve this problem, the proposed suburban train model ranks higher in the suburban area, which automatically reduces the primary and secondary delay by 67%.

5. CONCLUSION

The proposed changes to the existing system show promising results in terms of timetable stability. A detailed analysis and comparison of the simulation model and the existing case study model have demonstrated that the optimised model has a more stable timetable under the same conditions. The optimisation of the calculation of the minimum progression interval has had a positive impact on the capacity of the route, increasing it by 8%. This increase in capacity has made it possible to include more suburban trains in the suburban traffic with a cycle timetable, thereby reducing the average delay caused by regional passenger trains.

To maintain this stability, it is crucial to maintain a quality infrastructure that allows the stability of maximum speeds on the infrastructure. This can be achieved by including a buffer time in the calculation of the minimum headway interval, further optimising the timetable.

The proposed segmentation of passenger trains based on time parameters and the elements of the timetable of regional passenger trains offers a feasible solution to the instability of the existing system and should be implemented in a real system. The boundaries of suburban service are subject to change, depending on the quality of the infrastructure. As better infrastructure enables higher commercial speeds, the 60-minute time limit of suburban areas can be geographically expanded. Such an approach involves the active participation of the infrastructure manager in maintaining the infrastructure, along with railway carriers in the implementation of new trains and in improving the quality of transport for passengers. They together improve the level of service of passenger transport, particularly in suburban areas.

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Optimizacija rezervnog vremena u funkciji stabilnosti voznoga reda

Sažetak

Stabilnost voznoga reda ovisi o redovitosti vlakova, a svako odstupanje od planiranog voznog reda dovodi do njegove nestabilnosti. Karakteristike željezničke mreže određuju kapacitete prometne usluge. Ovisno o metodi izračuna kapaciteta, određene vremenske komponente dodaju se minimalnom intervalu slijeđenja kako bi se osigurala stabilnost voznog reda. Metoda UIC 405 je jednostavna i može se koristiti na svim željeznicama. Nedostatak je što se izračuni temelje na prosječnosti. Prema metodi, minimalni interval slijeđenja sastoji se od vremena prosječnog intervala slijeđenja, dodatnog vremena i rezervnog vremena. Dodatno vrijeme je precizno definirano brojem APB blokovnih odsjeka, dok je rezervno vrijeme izračunato kao prosječno. Pri izradi voznog reda cilj je optimalna iskorištenost infrastrukture, jer ako je izračunato vrijeme slijeđenja predugo, kapaciteti pruge nisu iskorišteni, a ako je prekratko, doći će do nestabilnosti u izvršenju voznog reda. Umjesto prosjeka, ovaj rad izračunava rezervno vrijeme ovisno o omjeru vremena putovanja prethodnog i uzastopnog vlaka. Na taj način optimizira se interval slijeđenja, a time i unaprjeđuje izračun metode UIC 405.

Ključne riječi

simulacijsko modeliranje; Petrijeve mreže; rezervno vrijeme; interval slijeđenja; optimizacija prometa; segmentacija prometa.