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Operational Reliability of a Periodic Railway Line

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Abstract

The paper is focused on operational reliability of a railway line operated by periodic timetable, specifically of shuttle supplementary line creating connection to backbone line or lines. Relation between basic operational indicators (of all connected lines and interchange station) are researched by using of developed stochastic mesoscopic simulation model. Assessed relations will be helpful for evaluation of an interaction between transport operation and infrastructure within railway line capacity assessment.

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Keywords: delay; interchange; passenger transport; periodic timetable; railway; reliability; shuttle line; simulation model

Nomenclature

δ_u	time efficiency of sources [-]
ω_u	efficiency of sources by periodic timetable [-]
I	headway time (interval) between two trains on a line [min]
MT_R^s	minimal reversing time of a train set operated on the supplementary line at the final station of $s \in \mathbf{S}$ [min]
MT_T^j	minimal interchange time between train of backbone line of $j \in \mathbf{J}$ and the train of supplementary line [min]
MT_W^j	limit for maximal waiting time of the train of supplementary line on the train of backbone line of $j \in \mathbf{J}$ [min]
ST_R^s	scheduled reversing time of a train set operated on the supplementary line at the final station of $s \in \mathbf{S}$ [min]
T_D^j	time difference between departure on supplementary line and arrival on backbone line of $j \in \mathbf{J}$ [min]
T_P; T_u	length of timetable period [min]; effectively utilized time by a train set within this period of T_P [min]
T_S	shuttle time – minimal time needed between 2 departures of trains served by the same train set [min]
$\mathbf{S}$	set of final stations of the supplementary railway line $\mathbf{S}=\{A, B\}$
$\mathbf{J}$	set of backbone lines incoming to the station of A for interchange to the supplementary line

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1. Introduction

Periodic timetable is characteristic and standard feature of public passenger transport nowadays (after more than 40 years of utilization). In simple words, trains of one line are operated regularly with the same headway time of I. The same scheme of operation is creating period of timetable with the length of T_P. This period is repeated. Individual lines are connected in nodes of timetable at defined time position called as time of symmetry (usually at X:00 or X:30). System travel time allows this. For illustration, trains can meet e.g. at X:00 every hour. Edge time (travel time between nodes) must be shorter than 60 min. In general, it must be a little less than an integer multiple of needed system travel time.

The common issue of periodic timetable concept is that sources are utilized almost without (time) reserve or with a very small reserve. For example, reaching of system travel time on an edge (of network) is a complicated task. It is often related to application of new vehicles or to high volume of construction works on a line etc.

The second feature is economic point of view as well. Transport operators are trying to use rolling stock and train staff as effective as possible so that possible time reserves improving operational reliability are also limited.

It is necessary to study related qualitative aspects now. Operational reliability is a key factor for quality in transport. Public passenger transport (long-distance as well as regional) is still more or less considered as an integral part of sustainable development as it is mentioned e.g. by Kapetanovic et al. (2019) or Lakatos and Mándoki (2020).

Presented research is focused on (supplementary) shuttle railway lines creating connection to other (backbone) railway lines operated also in periodic regime. Marking of lines as supplementary or backbone is only for the purpose of this paper, not in general as a line category.

Research is conducted as generalized. Modelled supplementary line connecting stations of A and B is operated according to systematic (periodic) timetable. It means that the same traffic and the same operational situations are repeated within all the day.

Possible negative effects on operational reliability of supplementary line can be related to possible waiting on delayed trains of backbone lines at origin station of A. There are any other lines connected in the station of B in this model environment creating base for experiments. Possible delay of incoming trains of backbone lines can be propagated to focused supplementary line. This is operated every 120 min with departures shortly after X:00 from both final stations. Considered extent of operation consists of 8 reverse train rides per day. On ride (pair of trains) is named as iteration in the model. Three additional iterations are added before as a warming-up phase of simulation (these rides are applied for configuration of operational situation on the line). These warming-up iterations are not taken into assessment. If needed, some of bus lines (connected to A) can be incorporated in the model as well.

2. Research Aim and Hypothesis

The aim of the research is to find relation between some operational features, analytic indicators and operational reliability of supplementary line. The motivation is to create a possibility of simple assessment (anticipation) of operational reliability in a relative quickly way.

Research hypothesis can be stated as follows. It is possible to assess operational reliability by information about delay of other (backbone) lines incoming to the station of A and by some basic operational indicators (like: planned time positions of arrivals and departures; minimal time needed for interchange MT_T^j; limit for waiting on delayed trains MT_W^j; reversing times MT_R^s, ST_R^s etc.). Reliability is assessed by value of train delay (reached by in the model) and by ratio of finally ensured interchanges.

Mesoscopic stochastic simulation model designed for this case is applied. The model is developed in Microsoft Excel by using of the Visual Basic for Applications programming language. This way is seen as flexible for research. Final results of this research will be applied as a part of theoretical base for capacity assessment of railway lines.

3. State-of-art Knowledge

Railway is important transport mode for the future as it follows from the paper Popović and Luka (2013). Operational reliability of railway transport system is mentioned by Vromans et al. (2006). The main focus of that paper is put on timetable heterogeneity and on prediction of operational reliability. New indicators of heterogeneity (sum of shortest headway reciprocals; sum of arrival headway reciprocals) are presented. Rolling stock and staff circulations are considered as crucial factor for design of timetable. Circulations are accented also by Kaspi and Raviv (2013) as well as the fact that periodic timetable is more attractive for passengers (able to be easily remembered) and more easy to be designed by transport planners. Issue of rolling stock circulations in long-distance railway traffic is taking a part in the paper Vojtek et al. (2019) as well. Operational, technological as well as economic factors are mentioned as crucial, but transport irregularities and possible delay propagation are not mentioned. Schöbel and Ljevo (2017) are focused on application of periodic timetable in Bosnia and Herzegovina. They considered time headway of 120 min as suitable for that railway network. The authors of that paper present also one additional idea that possibility to reach time reserves can be based on improvement of transport infrastructure. Some economic aspects of railway capacity allocation are mentioned also by Široký (2017) and Šrámek et al. (2018). This brief analysis can be an illustration that these issues are important and operation parameters applied in the simulation model are adequate.

4. Analytic Indicators

Two simple analytic indicators were proposed as a support of assessment of reliability (and also efficiency) of (supplementary) railway line operation. The first is time efficiency of sources (rolling stock and train staff) marked as δ_u. This is a simple ratio of total time in utilization T_u (related to 1 timetable period) and the length of this timetable period of T_P as it is illustrated by formula (1).

$$\delta_u = 100 \cdot \frac{T_u}{T_P} \tag{1}$$

The second indicator called efficiency of sources by periodic timetable and marked as ω_u is defined by the formula (2). The indicator is based on shuttle time T_S expressing minimal possible time between 2 departures of two trains (served by the same train set) from the origin station of A. The indicator of ω_u is ratio of the remainder after dividing of T_S by headway time of I to this headway time of I.

$$\omega_u = 100 \cdot \frac{T_S - \left\{\left\lfloor \frac{T_S}{I} \right\rfloor \cdot I\right\}}{I} = 100 \cdot \frac{T_S \, mod \, I}{I} \tag{2}$$

5. State-of-art Situation in Practice in the Czech Republic

Theoretical background must be compared with practice as well. Basic headway time (interval) of I is set on 60 min with possibility to be shorten (30 min) or extended (120 min) according to transport demand and other operational conditions. The most of the railway network is operated by periodic timetable in long-distance as well as regional transport. Similar operational conditions like on the modelled supplementary line can be found on ca. 30 railway lines in the Czech Republic. There is also a number of cases where regular headway time of I is not applied for all the operation time in a day next to it, but the timetable of these lines is partially periodic as well.

There is put an accent of efficiency of utilization of vehicles as well. It can be evaluated by the indicator of time efficiency of δ_u. The lines with highest values (and application of periodic timetable) are: line 198 Strakonice – Volary (δ_u = 95.4%); connected line 303+305 Hulín – Zborovice (δ_u = 90.0%) and line 176 Plzeň – Radnice (δ_u = 88.3%). Another line with high efficiency of δ_u = 82.5% is the line 225+227 Havlíčkův Brod – Slavonice, but by some regional expresses only.

The examples of periodic lines located in Eastern Bohemia are: line 236 Čáslav – Třemošnice with δ_u = 56.7% and line 047 Trutnov – Teplice nad Metují (δ_u = 51.5%). These values are valid also for weekend-operation.

One example from the area of the agglomeration Hradec Králové – Pardubice is line 016 in section Chrudim – Moravany with δ_u = 40.0%. There are two limitations – one pair of trains is not periodic and this line continues from Moravany to Holice with different operational concept. Focused trains on all mentioned lines are operated especially with a headway time of I = 120 min. Relation between time utilization of trains δ_u and operational reliability (expressed by average delay) is a scope of this research (see Table 5 in chapter 8).

6. Stochastic Simulation as Applied Research Method

Application of simulation for assessment of railway operation is relatively common. This application is usually connected to specific conditions of operation (e.g. on selected railway line). This corresponds with a descriptive nature of simulation models. Our research is based on general principles of railway operation. Model is developed on mesoscopic level due to this and parameters of modelled supplementary line can be changed. Specific cases can be assessed in more detail way on microscopic level if needed.

Important fact in our research is that it is not based on specific delay distribution values as it is common in microsimulation, but on repeated simulation by changing of input parameters related to delay (see Fig. 1 for illustration).

6.1. Model Structure

Elementary part of the model is one iteration. As it was mentioned it is one shuttle ride of train set on supplementary line from origin of A to destination of B and vice versa. Iterations are coupled into sets called replications. One replication can represent e.g. one day.

One replication in the model is usually consisted of 11 iterations including 3 iterations of warming-up phase. This can represent a common case of supplementary line with time headway (I) of 120 min between train services. Maximal capacity of model is 30 iterations. Number of replications is set on 365 due to technological reasons (365 days in one version of timetable). Maximal capacity of designed model is 1,200 replications.

The top level in structure of the model is a level of simulation scenarios. Our model assessment is divided into 15 simulation scenarios differing in values of input parameters according to the assessed operational conditions.

6.2. Ratio of Delayed Trains and Mean Value of Delay on Backbone Lines

One of specific aspects of developed mesoscopic simulation model is that the model works parallel with 220 combinations of values of these parameters in each replication. The assessment is more general in comparison with using of given values. It is an advantage for providing of extended information suitable for research.

Ratio of delayed trains (trains with delay > 0 min) of a backbone line coming to the origin station A of the supplementary line is modelled as changeable from 0 to 1 and the step of 0.1 is applied. The second input is mean value of delay (by exponential distribution), it is modelled from 1 to 20 minutes by step of 1 min.

There are 220 combinations of these input parameters. Each of them is assessed by 8 iterations and by 365 replications. Finally, each combination is assessed by 2,920 shuttle train rides (from origin to destination and back) on the supplementary line. In total 642,400 train rides are assessed within individual simulation scenario (e.g. one variant of reversing time ST_R^s). All assessments are realized by the same simulation seed so that the results are comparable. Warming-up phase of simulation is not incorporated in these numbers.

6.3. Other Model Inputs

Reversing times of trains on the line A – B are entered into the model in 2 ways as minimal – as technically needed time for reversing (MT_R^A, MT_R^B) and scheduled (ST_R^A, ST_R^B). Specific travel time on the line A – B is not crucial on this theoretical research basis. It is limited by headway time (interval) on the (supplementary) line of I. Arrivals of trains of backbone lines to the station of A are next important input. These arrivals are specified by a time difference between scheduled departure of train on supplementary line and scheduled arrival of train on backbone line (T_D^j). Minimal time needed for interchange (walking) between trains at the station of A (MT_T^j) and maximal waiting time of train of supplementary line on possibly delayed trains of backbone lines (MT_W^j) are next crucial inputs.

6.4. Model Outputs

Assessment of operational stability is based on 2 important outputs of the simulation model. The first is delay of trains (operated on focused supplementary line A – B). Second is a ratio of practically connected interchanges between trains of backbone and supplementary lines within stochastic simulation. Evaluation is based on average values.

7. Results – Factors Influencing Stability of Operation

The aim of this chapter is to define selected factors influencing stability of operation on focused railway line (A – B) and to assess this influence. Stability is influenced by a number of factors. Selected factors will be assessed by developed simulation model individually and then together on some selected study cases inspired by reality. This can illustrate principles, what can be followed by analytical assessment of proposed timetable within anticipation of future operational stability. Simulation is a descriptive model. It means that the results correspond with finished experiments. Generalization is allowed due to the fact that a study railway line with changeable parameters is taken into account. On the other hand, these results can be classified as recommendation. Accuracy of assessment can be possibly improved by microsimulation model for specific conditions of a specific railway line if needed.

7.1. Ratio of Delayed Trains and Mean Value of Delay on Backbone Lines and Reference Scenario

These factors are important feature in model structure as it is characterized in the chapter of 6.2, but both factors are crucial for the operational reliability itself as well. Influences of both of these factors can be illustrated on the simulation scenario for 1 backbone line at the station of A and MT_R^A = 3 min; MT_R^B = 3 min; ST_R^A = 11 min; ST_R^B = 11 min; MT_T^1 = 3 min; T_D^1 = 8 min; MT_W^1 = 100 min (almost “unlimited”). Scenario with these parameters is considered as reference scenario in the research, because of values able to be considered as “common” with exception of MT_W^j. Both factors are increasing resulting values of average delay, see Fig. 1.

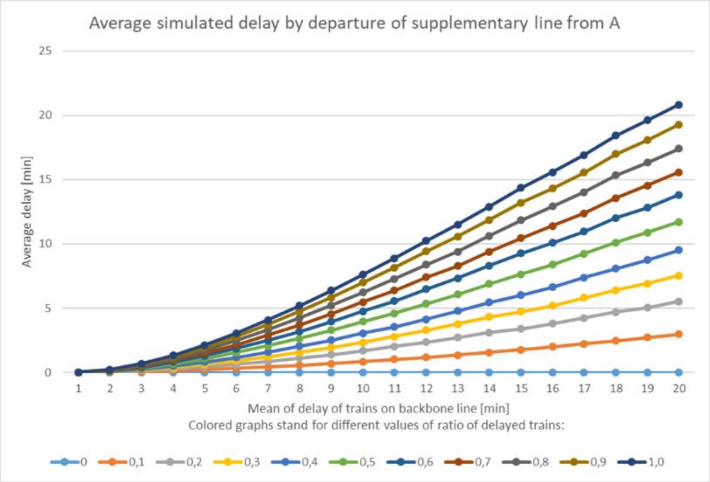

Fig. 1. Simulated delay by different mean value of delay and different ratio of delayed trains. Source: Authors.

7.2. Number of Backbone Lines Connected to the Station of A for Interchange

Influence of number of backbone lines coming to the station of *A* for interchange is also an important factor. It is simulated for a reference scenario (see chapter 7.1) by 1, 3, 5 and 7 incoming lines to the station of A. Presented values are reached by mean of delay of 10 min, see Table 1 (all values in minutes). Delays on departure of supplementary line from the origin station of A are displayed.

Table 1. Impact of number of backbone lines connected at the station of A. Source: Authors.

Number of backbone lines	1	3	5	7
Average delay by 10% of delayed trains	0.84	2.28	3.58	4.77
Average delay by 30% of delayed trains	2.34	6.29	9.44	11.91
Average delay by 50% of delayed trains	3.95	9.64	13.64	16.55

7.3. Application of Maximal Limit for Waiting on Backbone Line Trains at the Station of A

Influence of this limit is studied by reference scenario (see chapter 7.1) for 3 variants of maximal limit of MTW^j equal to 5, 10 and 100 minutes, see Table 2. It is simulated by 5 incoming lines to the station of A. The results are presented for the case of 30% of delayed backbone trains and mean of delay of 10 minutes.

Table 2. Impact of limit for maximal waiting time at the station of A. Source: Authors.

Limit for waiting time MT_W^j [min]	5	10	100
Average delay by 30% of delayed trains [min]	0.94	2.29	3.58
Ratio of connected pairs of trains [-]	0.89	0.93	1.00

Complex point of view on this issue in context of changing ratio of delay trains and changing mean value of delay is provided by the Fig. 2. Ratio of ensured interchange connections (from planned) is displayed.

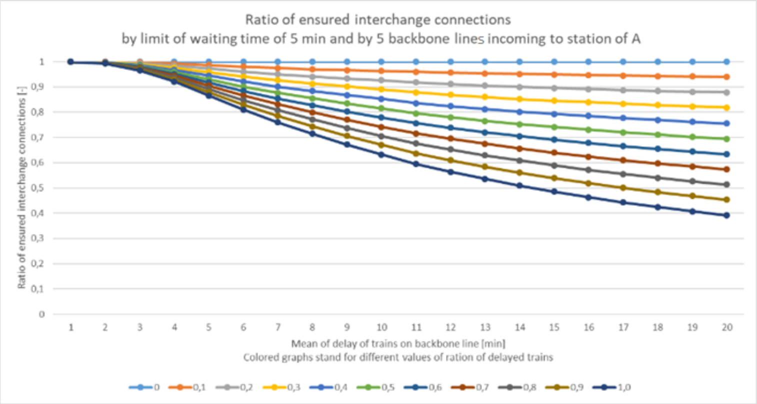

Fig. 2. Ratio of ensured interchanges in simulation. Source: Authors.

7.4. Location and Volume of Time Reserves on Supplementary Line

Another factor is volume and location of time reserves on the supplementary line. These reserves can be expressed as a sum of differences between scheduled ($ST_R{}^s$) and minimal reversing time ($MT_R{}^s$) at final stops of A and B. Various combinations of scheduled reversing times ($ST_R{}^s$) at stations of A and B are presented by 30% of delayed trains and mean value of 10 min, see Table 3.

Table 3. Impact of scheduled reverse times on the supplementary line. Source: Authors.

Reversing time $ST_R{}^A$+$ST_R{}^B$ [min]	8+3	8+14	11+11	14+8	15+15
Average delay by departure from A [min]	4.25	2.34	2.34	2.34	2.08
Average delay by departure from B [min]	4.25	0.76	1.04	1.41	0.60

Parametrical analysis of scheduled reversing time (ST_R^s) – the same for both final stops of A and B – has been simulated for 40% of delayed backbone trains and mean of delay of 10 min, see Fig. 3.

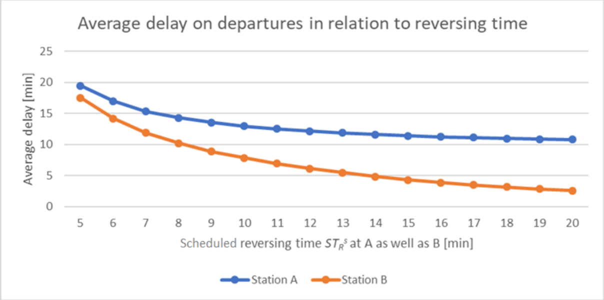

Fig. 3. Average values of simulated delay in relation to reversing time. Source: Authors.

7.5. Relation to Scheduled Time Difference between Supplementary Line Departure and Backbone Line Arrival

Positive impact of rising value of time difference between departure of train of supplementary line and arrival of train of backbone line can be illustrated by the Table 4. The values are expressed for 30% of delayed backbone trains and delay mean value of 10 min.

Table 4. Impact of time difference between departure and arrival at the station of A. Source: Authors.

Time difference between departure and arrival T_D^j [min]	5	8	11	14
Average delay by departure from A [min]	3.15	2.34	1.74	1.28
Average delay by departure from B [min]	1.41	1.04	0.76	0.55

8. Simulation Inspired by Practical Cases

Developed stochastic simulation model was applied on 4 cases inspired by practice. Mentioned results are for simulation by 30% of delayed trains on backbone lines and by mean value of delay of 10 min, see Table 5.

Table 5. Simulation inspired by practice. Source: Authors.

Line	Backb. lines	T_D^j [min]	MT_W^j [min]	ST_R^A $/ST_R^B$	δ_u	ω_u	Avg. delay at A [min]	Avg. delay at B [min]	Ensured interchanges
176 Plzeň – Radnice	7	27-6-16-6-16-23-15	10-20-10-10-10-10-10	11/8	88.3%	93.3%	3.59	3.59	96%
225+227 Havlíčkův Brod – Slavonice	4	10-4-4-16	10-20-20-10	6/59	82.5%	50.8%	3.78	0.00	96%
236 Čáslav – Třemošnice	4	15-12-29-22	20-20-20-20	34/23	56.7%	57.8%	2.59	0.00	99%
016 Chrudim – Moravany	1	11	25	52/9	40.0%	54.2%	1.04	0.45	99%

Model is only inspired by reality, because not all practical features (especially MT_T^j and MT_W^j) were incorporated in an accurate way. The effort to create illustrative cases with more or less different operational conditions to be assessed is the reason. Relations between main indicators including newly mentioned indicators of δ_u and ω_u can be found in the Table 5. The results can be compared with theoretical cases modelled and mentioned before. The line No. 016 is located in the agglomeration Hradec Králové – Pardubice.

9. Discussion, Further Research and Conclusion

The result is that almost all mentioned factors have an influence on operational reliability of the shuttle supplementary line. Rising mean value of delay of trains on backbone lines will cause increase of average value of delay on supplementary line. The ratio of delayed trains on backbone line (delay > 0 min) will make the increase more important (see Fig. 1). Number of backbone lines coming to the origin station of A can have serious impact on rising values of average delay (see Table 1). Application of maximal limit for waiting on possibly delayed backbone trains can improve operational reliability of the supplementary line in the delay point of view, but it can also improve ratio of disconnected interchange relations (see Table 2 and Fig. 2). Location of time reserve on the supplementary line is more effective at the station of B, especially for accuracy of return ride (B – A) and subsequent interchanges to backbone line or lines. Relative long scheduled reversing times ST_R^B in practical cases of Slavonice and Třemošnice can ensure reliable operation of return rides (almost with no delay), see Table 5. Simulated negative relation between increasing reversing times and average delay is displayed by the Fig. 3. Serious impact of time difference between scheduled departure of train of supplementary line and scheduled arrival of train of backbone line on average delay on focused supplementary line (by ride from A to B) is illustrated by the Table 4.

The research aim has been fulfilled. Important factors influencing operational reliability were defined, assessed and their impact summarized. There are no information leading to rejecting of the hypothesis found.

This complex topic has high potential for future research as well. Increased number of simulation experiments and scenarios can be realized for higher accuracy of generalized results. Individual effects can be studied in more detail way, but this basic overview can provide a base for better relating of capacity assessment to current (or planned) way of operation.

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