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Transportation Research Procedia 55 (2021) 103–109

Transportation Research Procedia

www.elsevier.com/locate/procedia

14th International scientific conference on sustainable, modern and safe transport

Comparative Application of Analytical and Simulation Methods for the Combined Railway Nodes-Lines Capacity Assessment

Atieh Kianinejadoshah[a], *Stefano Ricci[a]

[a]*Department of Civil, Building and Environmental Engineering, Sapienza University of Rome, Italy*

Abstract

Nowadays a considerable percentage of trains mature delays due to nodes and stations congestion. They are normally a combination of effects of routes conflicts in stations on lines and propagation in stations of delays suffered along the lines. In order to prevent the conflicts and minimize delays, desirable timetables should be robust; accordingly, an accurate estimation during timetable design and implementation is necessary. Goal of the research is to compare analytical and simulation methods for the assessment of railway lines and nodes capacity to pinpoint their mutual effects, analyze stability or variability of the obtained results achieved by traditional and innovative approaches. The work is included in a research framework with the final goal of optimizing the use of railway network capacity.
In order to tackle the purpose, the paper introduces synthetically the methods and applies them systematically to a complex network, including single and double track lines and various typologies of stations.

Peer-review under responsibility of the scientific committee of the TRANSCOM 2021: 14th International scientific conference on sustainable, modern and safe transport

Keywords: Capacity; stations; lines; traffic conflicts; delays minimization; timetabling

1. Introduction

The train timetable is a plan of all train movements that are supposed to occur in a railway system over a given period of time (Li Z., Zhang Q., Ren Y., Sun Y., Miao C., Duan J., 2020). Unfortunately, with increasing traffic volume delay

* Corresponding author. Tel.: +39644585142
E-mail address: Atieh.Kianinejadoshah@uniroma1.it; stefano.ricci@uniroma1.it

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Peer-review under responsibility of the scientific committee of the TRANSCOM 2021: 14th International scientific conference on sustainable, modern and safe transport
10.1016/j.trpro.2021.06.011

propagation is increasing, too. That is the case because the intervals between consecutive trains are smaller for a higher traffic volumes, which makes it more likely that one train's delay impacts others trains' punctuality as well (Haehn R., Ábrahám E., Nießen N., 2020). In order to employ effectively the railway capacity, the timetable structure must contain the intelligence providing the required robustness and neutrality across service market segments and operators (Gestrelius S., Peterson A., & Aronsson M., 2020).
A consolidated method to compute the robustness of a timetable is to simulate it with predefined delays propagating in the concerned network (Huang Z., Fan W. D., Xu R., Lee D. H., Zhu W., 2020).
The present paper introduces an approach to investigate the relationships between the analytical model proposed by Muller and largely applied (Muller G., 1960) (Giuliani L., Malavasi G., Ricci S., 1989) and the simulation by a largely recognized software, such as OPENTRACK® (Nash A., Huerlimann D., 2004), to calculate the capacity, identify bottlenecks and conflicts in a complex network.

2. State of the art

The evolution of research and the continuous increase of interest in railway capacity offer an extraordinarily rich bibliography of existing methodologies developed since 1950s (Kontaxi E., Ricci S., 2011) until current times (Kianinejadoshah A., Ricci S., 2020).

2.1. Node capacity

Some methods are focused on capacity analysis for railway stations based on Muller method (Corazza G.R., 1979) (Florio L., Malavasi G., 1984) (Corazza G. R., Florio, L., 1987) node in railway network commonly tending to act as bottlenecks limiting the capacity of the entire network. In particular (Malavasi G., Molková T., Ricci S., Rotoli F., 2014) provide a review of some capacity methods for complex railway nodes and a detailed description of some synthetic approaches starting from (Potthoff, G., 1970). The optimisation model described in (Jovanović P., Pavlović N., Belošević I., Milinković S., 2020) provides theoretical capacity for railway nodes and stations, without details regarding train sequences and timetables.

2.2. Combined line-node capacity

Regarding the rail system as a whole, several papers focused on the issue of capacity at network level (Malavasi G., Ricci S., 2000) with approaches based on synthetic, probabilistic and combinatory models for links and nodes, interacting each other, sensible to the performances of the signalling systems and not depending upon the timetable structure. Some studies (Crenca D., Malavasi G., Ricci S., 2005) (Crenca D., Malavasi G., Mancini R., 2006) analysed the relationship between carrying capacity and various parameters to evaluate the effects of infrastructure and operational improvements to fully use the capacity. The last version of UIC Code 406 (UIC, 2013) described the extension of capacity method to stations. However, the method is hardly applicable to large stations, characterized by a high number of train and shunting movements. Last studies deal with synthetic methodology for:

- Capacity utilisation analysis of complex interconnected rail networks (Rotoli F., Malavasi G., Ricci S., 2016);
- Capacity assessment of railway stations and line segments along the Swedish Southern Main Line corridor (Weik N., Warg J., Johansson I., Bohlin M., Nießen N., 2020):
- Comparison of some methods for the assessment of nodes and lines capacity and their reciprocal effects (Kianinejadoshah A., Ricci S., 2020).

2.3. Simulation

Simulation techniques largely support analysis and optimization of railway systems operation. A number of synchronous micro-simulation models are appearing in the last years. After an extended and comprehensive investigation carried out some years ago (Kontaxi E., Ricci S., 2010), innovative approaches are anyway frequent in such very productive sector (Table 1). OPENTRACK® is one of the most accurate and widely applicable simulator to determine the performances of a railway network, analyze the capacity of lines and stations as well as the robustness of timetables. Relevant for the integrated modeling of stations and lines are also VILLON® (Adamko N., Klima V., 2008), RAILSIM X® (De Fabris S., Medeossi G., Montanaro G. 2018).

Table 1. Selection of synchronous micro-simulators applicable for railway operation

Software	Main performances	Country
CAPRES	Planning-aid system for analysis of rail network capacity	Switzerland
DEMIURGE	Network capacity optimisation and measurement	France
FALKO	Design and validation of timetables	Germany
FASTA	Stability analysis of rail network capacity)	Switzerland
IRSIM	Investment in railway capacity increase model	Slovenia
OPENTRACK	Railway planning to model, simulate and analyze various rail systems	Switzerland
PETER	Performance evaluation of timed events in railways	Netherland
RAILCAP	A computer tool for studying capacity problems of railway networks	Belgium
RAILSYS	Technical and operational planning of railway transport	Germany
SIMONE	Simulate and analysis large scale train network	Netherlands
VILLON	Simulation of transportation processes within logistic terminals	Slovakia
RAILSIM X	Modelling and simulating rail system’s operations and performance	Canada

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3. Case study applications

The value of a railway network capacity is variable according to the effects of various parameters. The ongoing research deals with the investigation of these variabilities (Kianinejadoshah A., Ricci S., 2020), here tested on a reference network layout, including stations, single-track and double track line sections (Fig. 1).

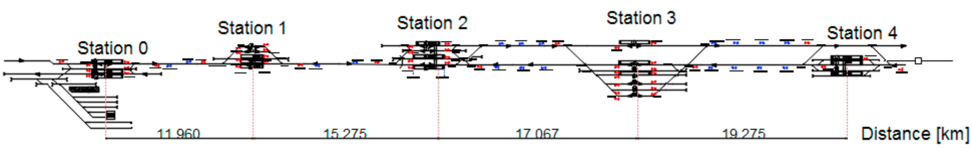

Fig. 1. Case study network layout

3.1. Analytical method

According to the Muller method (Giuliani L., Malavasi G., Ricci S., 1989), the occupation and interdiction times are variable according to the extension and location of the common sections of incompatible routes and the temporal succession of arrivals and departures depending on the station timetabling. In the present application, the following assumptions are valid:

- Daily capacity reference time: 18 hours;
- Train stops time at all stations: 1 minute;
- Trains considered arriving on time (potential generation of delays due to overlapping of incompatible routes only).

The timetable includes arrival/departure time and used routes, represented in the occupation/interdiction diagram (**Chyba! Nenašiel sa žiaden zdroj odkazov.**), where the black rectangles are occupation times in entrance, the hatched area stop times.

OPENTRACK® is a microscopic model that simulates the behaviour of all railway elements (infrastructure network, rolling stock and timetable) during the operation, by an iterative process capable to evaluate changes in each of these elements with system optimization purposes.

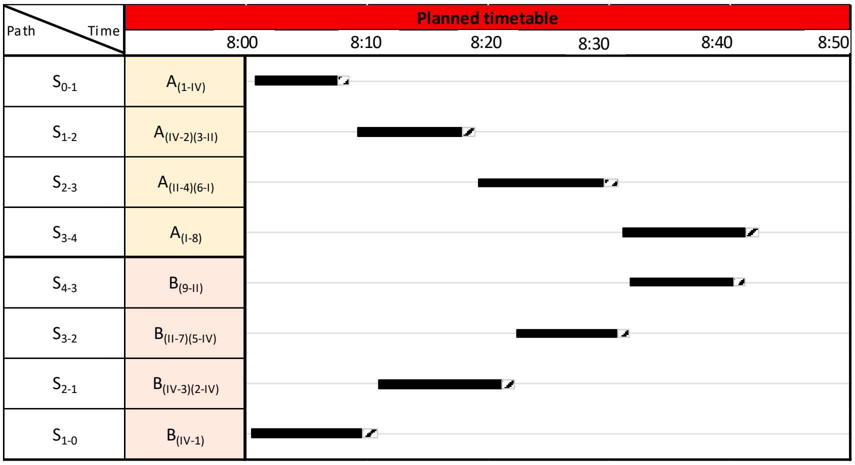

Fig. 2. Occupation diagram of line sections and stations: planned timetable for trains A and B

3.3. Comparative analysis

The focus of the comparative analysis is to identify conflicts and delays as a difference between simulated and planned timetables, by identifying the potential bottlenecks, mitigating the conflicts and minimizing the delays. The stepwise structure proposed method is in Fig. .

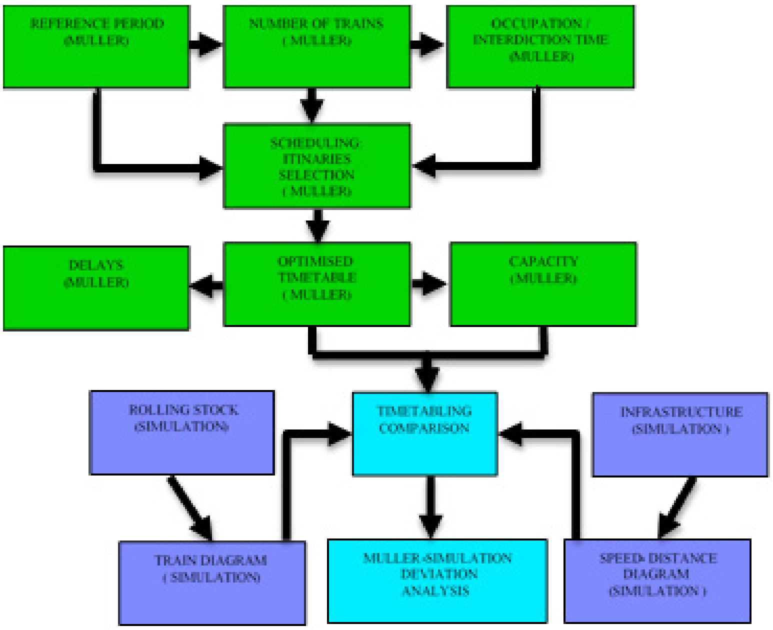

Fig. 3. Muller-simulation integrated procedure

4. Capacity results

The outputs of the simulation are the space-time diagrams comparing planned and simulated timetable (Fig.) for a bidirectional couple of trains (A) and B): the black line is the planned timetable based on the input inserted and the blue line is the simulated timetable by the software. The largest deviations are due to prolonged stay in stations for crossing maneuvers along the single-track sections. The maximum experienced deviations are between 336 s (train A) and 257 s (train B) over the 3 stations, meanwhile the average buffer time is variable between 282 s and 386 s for train A and between 285 s and 389 s for train B (Fig. 6). On this basis, the buffer time can recover the deviations partially for train A and completely for are partially for train B.

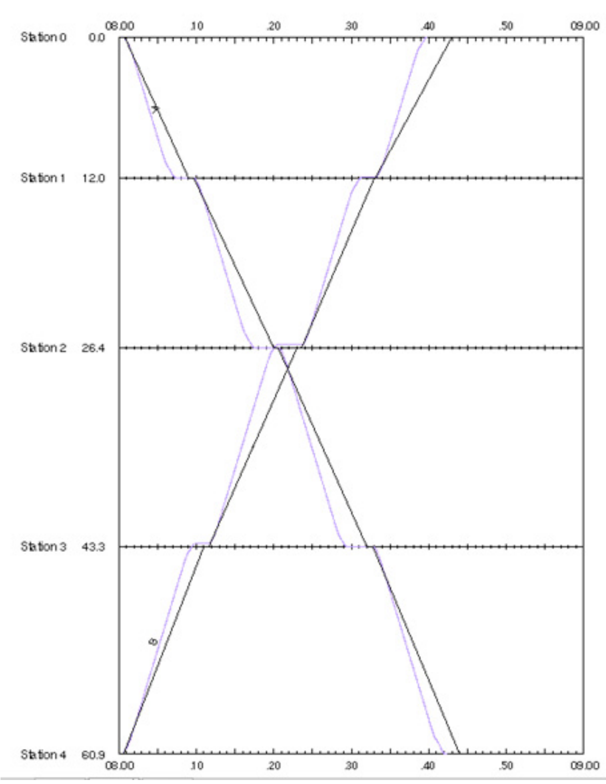

Fig. 4. Space-time diagram: planned and simulated paths

The next step was the progressive increase of traffic, which produces a corresponding more than linear increase of generated delays, though differentiated according to the utilized approach. By the analytical method, the trains' arrival is rigid (constant probability of arrivals) within the reference time and the generated delays are growing with an almost linear trend. Meanwhile, the simulation optimizes the timetable by looking for solution minimizing the delays. However, over a certain traffic threshold (4 trains/hour in this specific case study), the optimization is no longer possible and the delays are overwhelming (Fig. 7). This threshold is corresponding to a practical capacity value, obtained by the *intelligent* use of the buffer times introduced into the planned timetable as a valuable reserve of punctuality.

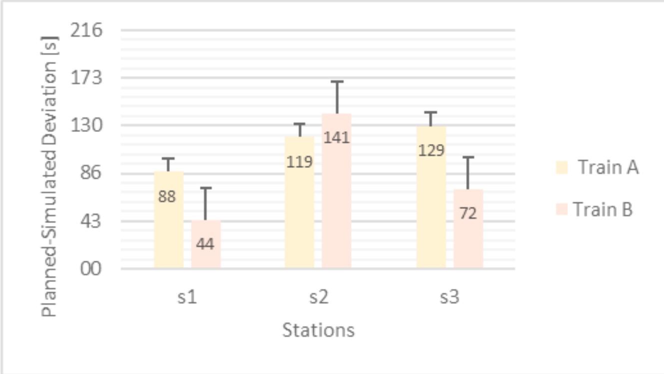

Fig. 5. Planned-simulated deviations for trains A and B in stations S1, S2 and S3

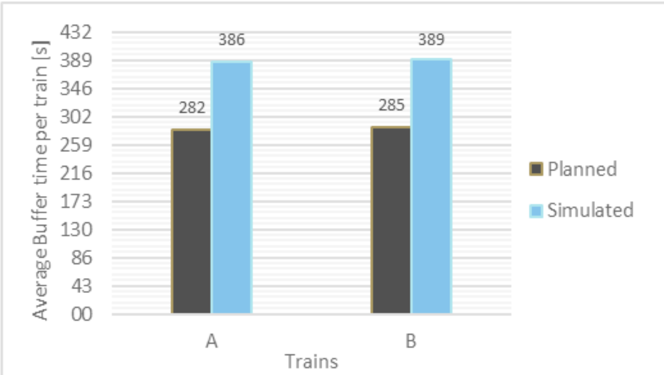

Fig. 6. Average buffer time per train calculated by Muller (planned in the timetable) and arising from the simulation

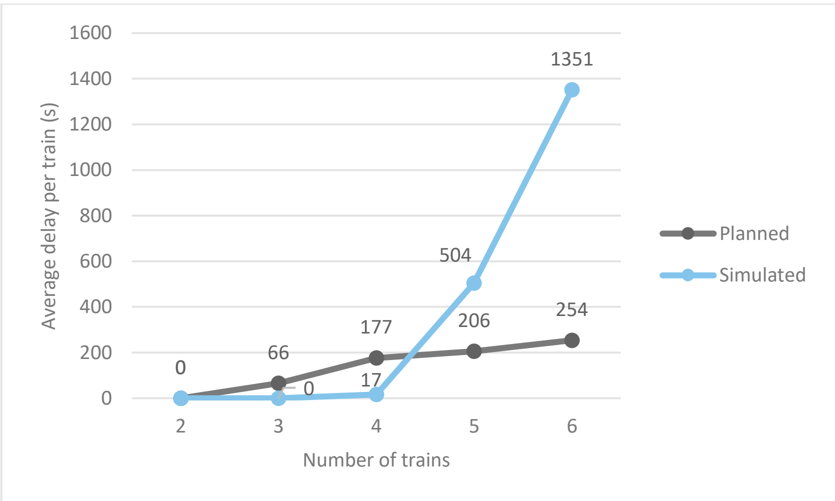

Fig. 7. Average delay per train calculated by the analytical method (planned) and the simulation

5. Closing remarks

The obtained results show that the deviations between planned and simulated timetables are significant and that the evaluation of the capacity obtained by the analytical (Muller) method is prudential and the intrinsic reserve of punctuality setup by this method is effectively usable for the increase of capacity by an optimized timetabling process. In this respect, we can presently conclude that:

- The use of analytical method appears in line with the scope of high-level analyses for the identification of the most appropriate infrastructure layouts and signalling systems to adopt in a long-term perspective, independently upon a specific timetable structure;
- The implementation of a simulation model is necessary for in-depth analyses aiming at the optimization of the use of capacity and the timetable structure itself.

Nevertheless, further developments of the research should include a larger testing phase to check systematically the sensibility of the results to various timetables structure and to different signalling systems, e.g. according to the various ERTMS levels.

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