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Comparative Application of Methods for Nodes Capacity Assessment

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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. Station areas represent the bottlenecks of railway operations, due to many incompatible train routes crossing each other that lead to many potential conflicts between trains. Goal of the research is to compare some literature methods to study nodes capacity, by application of if-then processes to analyze stability or variability of results obtained by various timetabling to occupy the minimum capacity and increase the number of trains. It is a typical critical circuit, which can be seen as the bottleneck of the timetable to prevent conflicts and delays. 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. The further development includes the comparative applications of the analytical methods, with respect to variation of input data, and of a simulation approach.

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

1. Introduction

The rail transport customers, both passengers and freight forwarders, want to arrive on time at their destinations. Reliable and predictable timetable performance is a major factor in the service provided by a transport operator. In this context, capacity bottleneck area in railway networks are especially prone to generate delays due to the high number of trains' interactions, reason why they require special attention (Lüthi, M., Medeossi, G., & Nash, A., 2007).

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Capacity at station is critical and the present paper highlights these aspects in a specific analysis on station capacity fluctuations. As noted, (Potthoff, G., 1970) evaluates the delay generated by the station as a consequence of the random presentation of the trains at the stations, without any consideration of the timetables and calculates a corresponding medium delay. In the real operation, once a train is delayed, this may cause delay propagation in the station and timetable should include buffer times for arrival and departure partial or total recovery of such delay. Recovery times (or buffer times) can compensate or even eliminate the delays (Koelemeijer, G. S., Goverde, R. M. P., & van Egmond, R. J., 2000), the buffer time intrinsic by timetabling in Muller method are going to be cross checked with the Potthoff method to get comparative values.

These differences may lead to different capacity consumptions for stations, due to the localization of bottlenecks, which may lead to incorrect allocation of resources as well as to a reduced level of service on the railway network. In this context, the analysis and the identification of these bottlenecks will help to increase the capacity, where necessary, and to improve the corresponding passengers and freight services. The present paper introduces an approach to investigate the relationships between the node capacity variation studies under disturbances and hints for the potential synchronization and generalization of this method for a complex network.

2. State of 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). A chronological scheme of line and node methodologies is in Fig. 1.

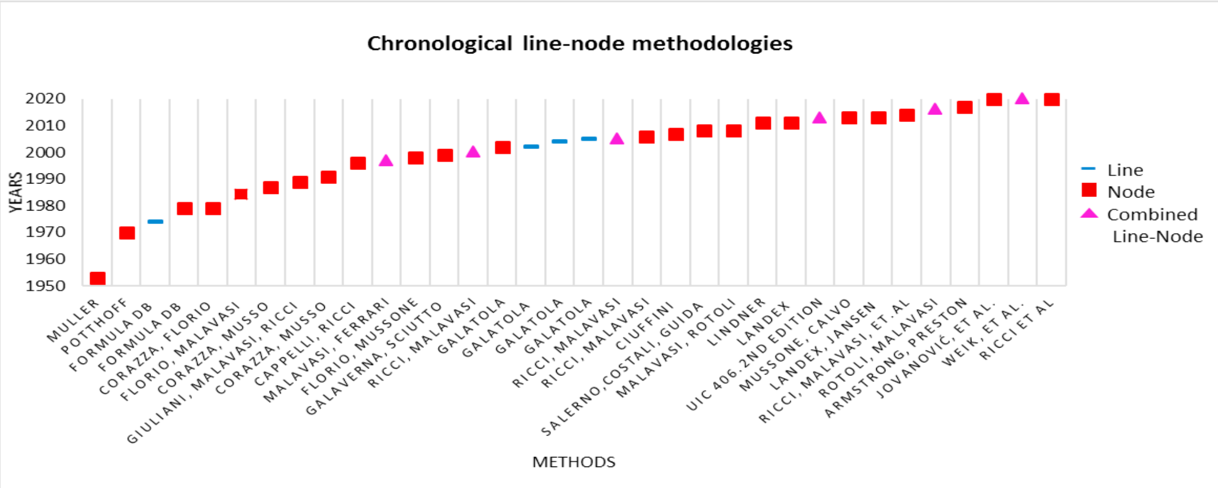

Fig. 1. Chronological line-node methodologies

2.1. Node capacity

Some methods are focused on capacity analysis for railway stations, node in railway network commonly tending to act as bottlenecks limiting the capacity of the entire network. In particular (Malavasi G., Rotoli F., 2008) (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. Similar topics regarding the relationships between capacity utilization and performances in railway stations and junctions was analysed by (Mussone L., Calvo R.W., 2013) (Armstrong J., Preston J., 2017). Meanwhile, (Landex A., Jensen L.W., 2013) developed five methods to describe and analyse the capacity of stations by the use of measures for track complexity and robustness of operation at stations. Moreover, 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 (Florio L., Mussone L., 1998) (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. (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. (Landex A., 2011) (Lindner, T., 2011) described how the (UIC Code 406, 2004) capacity method can be expounded for stations and the UIC itself provided in the 2nd version of (UIC Code 406, 2013) with a guideline for capacity calculations applicable for stations. However, the method is only partly applicable, as it requires the schedule of all movements, making it hardly applicable to large stations, characterized by a high number of train routes and shunting movements. (Rotoli F., Malavasi G., Ricci S., 2016) proposes a synthetic methodology for capacity and utilisation analysis of complex interconnected rail networks starting from (Potthoff, G., 1970) and (UIC 405 OR, 405) methods. Lastly (Weik N., Warg J., Johansson I., Bohlin M., Nießen N., 2020) developed a methodology for capacity assessment of railway stations and line segments in a case study along the Swedish Southern Main Line corridor and (Kianinejadoshah A., Ricci S., 2020) compared some literature methods for the assessment of nodes and lines capacity to identify their reciprocal effects.

3. Methodologies application to case study

The value of capacity over a railway network is variable according to the effects of various parameters. The ongoing research deals with the investigation of this variability with a special focus on the station's features.

In view of the setup of a synthetic method, it is necessary to quantify the effects of the parameters above on the capacity, here tested on a reference network layout, including three stations, two single track and two double track line sections in Fig. 2.

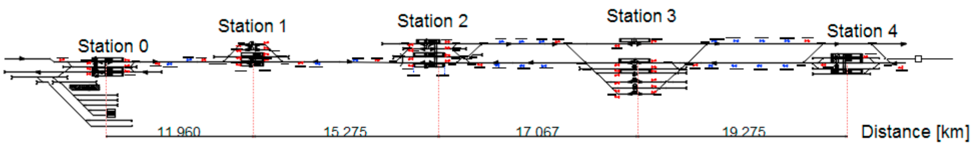

Fig. 2. Case study network layout

3.1. Operation by Potthoff method

Despite the normally larger number of tracks, stations and larger nodes may represent capacity bottlenecks of the networks (Armstrong J., Preston J., 2017) when their morphology reduces the compatibility of the movements. Moreover, this effect is depending on the frequency of use of the station routes, which share sections with the nearby lines. The Potthoff method (Potthoff G., 1970) includes combinatorial procedures able to quantify the utilisation rate of single routes, station areas and the station as a whole Fig. 3. shows the architecture of the automatic calculation procedure setup for it.

This method assumes that trains could arrive at any instant with the same probability within the reference time T; therefore, it does not require an assigned timetable, which simplifies its application (Rotoli F., Malavasi G., Ricci S., 2016) and (Malavasi G., Rotoli F., 2008). Moreover, the application considered the following hypotheses:

1. The single-track line has one block and one warning signal per direction;
2. All trains are in transit, except those finish their ride in the intermediate stations;
3. All stations tracks are bidirectional;
4. First in, first out (FIFO) service discipline for the station;
5. Constant probability density for the arrival of trains during the reference period *T*.

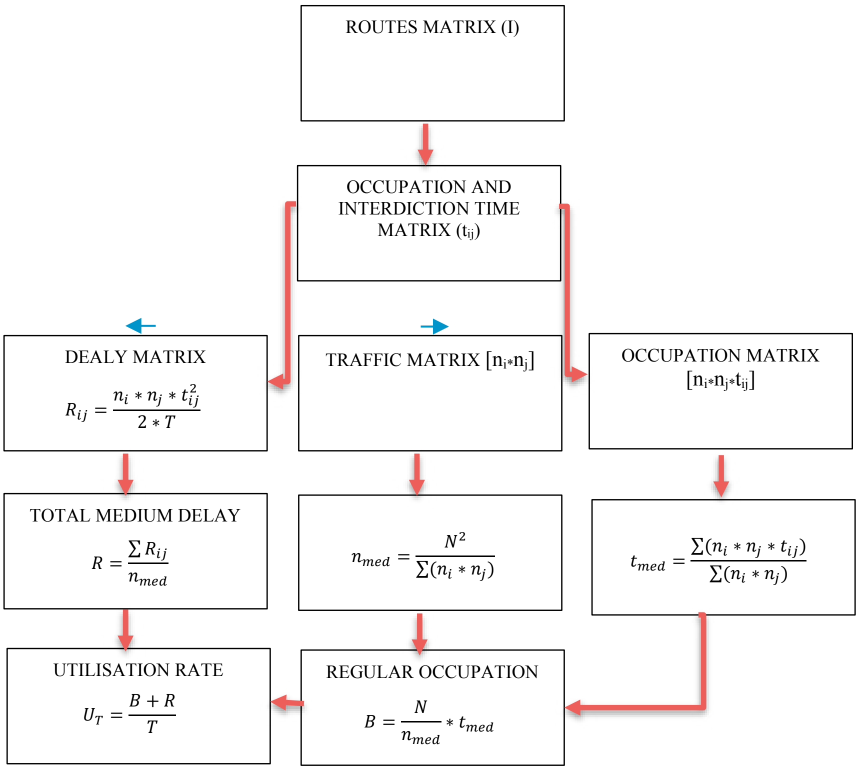

Fig. 3. Potthoff method procedure

The following parameters are also considered:

- $N = \Sigma n_i = \Sigma n_j$ = total number of movements;
- n_{med} = average number of simultaneous movements allowed by the layout;
- t_{med} = average occupation time of routes.

The described approach bases on a combination of train paths. Therefore, the method allows calculating the total delay (ΣR_{ij}) generated in the node as the sum of the delays generated by each incompatibility between two routes *i* and *j*. The ratio between ΣR_{ij} and n_{med} represents the total delay obtained considering movements of n_{med} trains simultaneously as well as the medium delay/train is the following:

$$R_{med} = \frac{\sum R_{ij}}{N} \tag{1}$$

As an example, with reference to the stations included in the case study network, the diagram in Fig. 3 shows the medium delay/train generated by a variable amount of running trains.

Moreover, the global utilization rate U_t is determined by:

$$U_t = \frac{\left(\frac{N}{n_{med}} * t_{med}\right) + \left(\frac{\sum R_{ij}}{n_{med}}\right)}{T} = \frac{B+R}{T} \tag{2}$$

The results of the calculation of the global utilisation rates and the corresponding medium delay/train according to the increase of traffic are in the diagrams reported in Fig. 4.

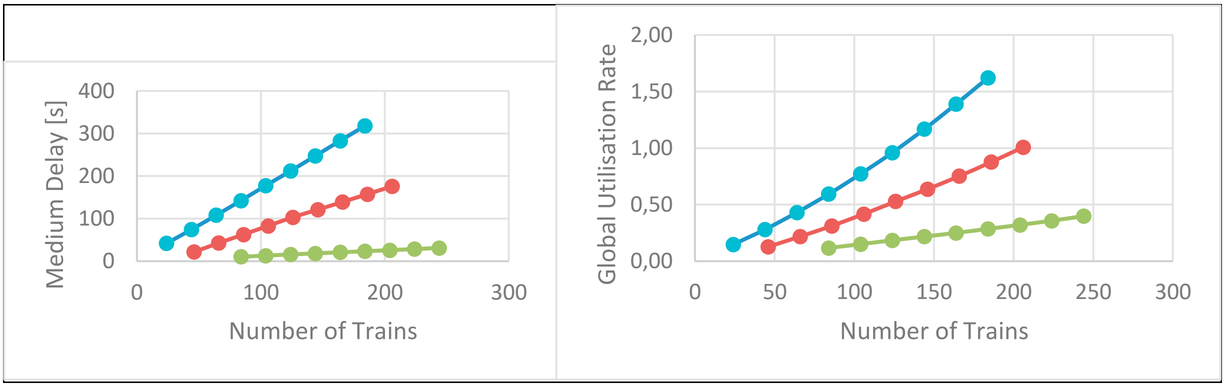

Figure 4: Medium delay/train and global utilisation rates calculated for stations 1 (blue), 2 (red) and 3 (green)

The calculation of the corresponding capacity needs to fix a reference value of punctuality, e.g. in terms of maximum allowed delay, and to derive from it the corresponding maximum amount of trains compatible with such value.

In respect of the specific purpose, with the same input data, the Muller method allows a further step forward by timetabling.

3.2. Operation by Muller method

The proposed method is based on the logic diagram in Fig. 5, which shows the architecture of the automatic procedure developed to apply Muller method (Giuliani L., Malavasi G., Ricci S., 1989) with synthesis aimed at basically obtaining the following three objectives:

- Give a graphical and analytical representation of the potential of a station system in an exhaustive manner;
- Provide an evaluation tool, simple as an application and immediate as a reading of the results;
- Consider the presentation of trains to the station according to their real distribution, of which arrival on time is only one of the possible cases.

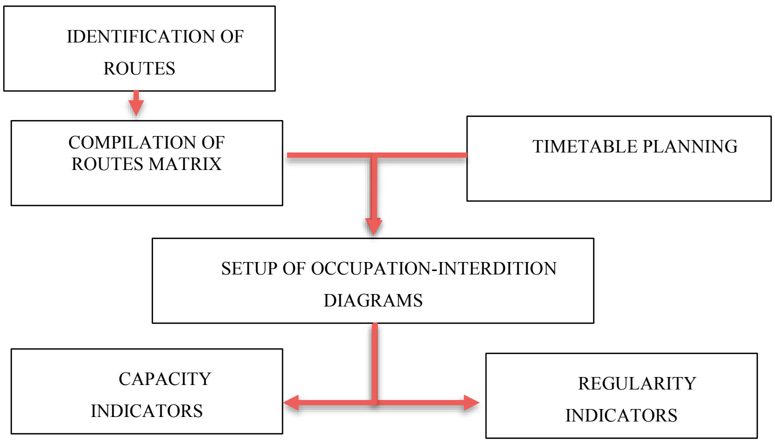

Fig. 5. Muller method procedure

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:

- Occupation time calculated in Potthoff is an input for timetabling in Muller;
- Daily capacity is for a 18 hours period, as well as hourly capacity is from 8.00 to 9.00 in the morning;
- The train stops time at all stations is 1 minute;
- All the trains are initially considered arriving on-time, therefore the station is the only potential generator of delays due to overlapping of incompatible routes used by trains;
- The timetabling is basing in the criteria of the lowest occupation time, in order to consume the capacity as less as possible.

The timetabling gives the information about arrival/departure time and the occupied/interdicted routes. To avoid the conflicts and overlapping of train, the occupation-interdiction diagrams for stations are represented in 6, where the black rectangles are occupation times in entrance, the hatched area stop time and white rectangle interdiction times.

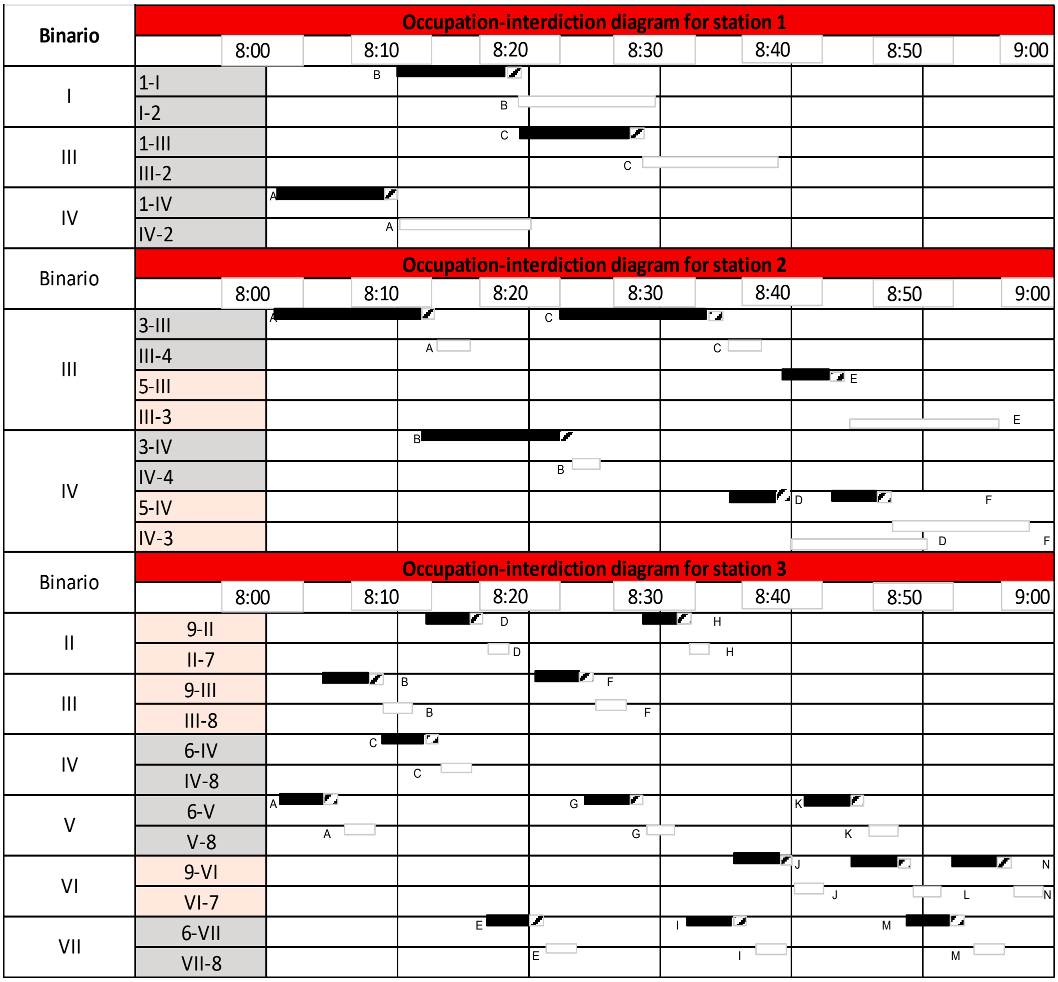

Fig. 6. Occupation-interdiction diagrams for stations 1, 2 and 3

The final step is the calculation of the residual buffer times, as free times resulting from the diagrams between occupation of trains sequence, according to the timetable, in the same direction or in opposite directions.

4. Capacity results

The value of capacity over a railway network is depending on various parameters. The focus is here on the punctuality ensured by the buffer times in the timetables, usable to recover arrival delays matured out of the concerned station (lines and/or previous stations).

The results of timetable planning in the present application for stations 1, 2 and 3 is summarised in Fig. 7, where are reported the calculations of:

- Medium delay (due to conflicts in the station) and corresponding hourly capacity calculated by Potthoff method (Kianinejadoshah A., Ricci S., 2020);
- Medium buffer times available according to the planned timetable and corresponding hourly virtual capacity calculated by Muller method;
- Medium delay matured out of the station recoverable by the residual buffer (difference between medium available buffer and medium delay matured in the station) and corresponding hourly capacity.

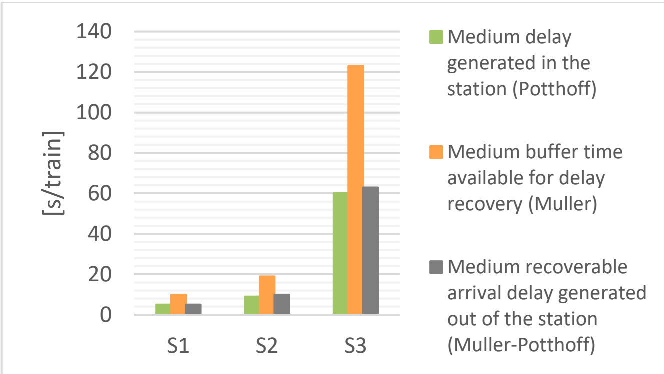

Fig. 7. Delay, buffer times and corresponding capacity for stations 1, 2 and 3

This last value could be considered as a medium extent of the distribution of arrival: e.g., in case of triangular delay distribution, the half of the base length of the triangle.

Finally, Fig. 8 is representing, in a global overview, the hourly capacity calculated by the combined application of Potthoff and Muller methods with reference to a common level of punctuality, in comparison with the capacity value obtained by the Potthoff method only.

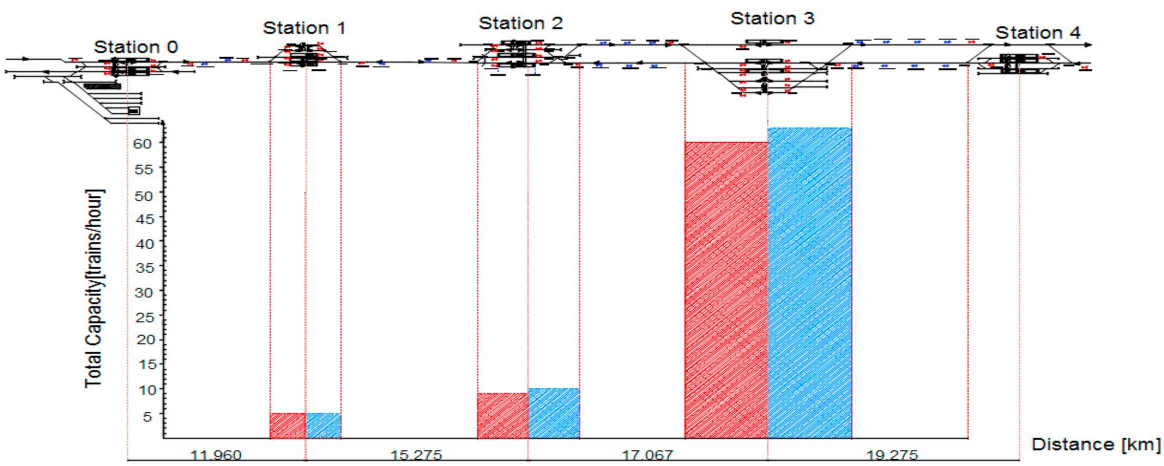

Fig. 8. Hourly capacity by Potthoff method (random arrivals, in red) and its combination with Muller method (planned timetable, in blue)

5. Closing remarks

The obtained results shows that the timetable planning activity (Muller method hypothesis) is able to get a moderate increase of the capacity in stations 2 and 3 in comparison with values obtained in a totally random structure of arrivals and departures (Potthoff method hypothesis), thanks to the buffer time saved by the *intelligent* timetable planning useful to recover delays matured out of the station.

The combined effects of line and station operation is demonstrated by the negligible capacity increases achievable for stations linking single track line sections, in which the bottleneck role of these sections is self-evident.

These are very preliminary results, which provide with interesting hints and exemplifications of combined line-station effects. The further validation and generalization of the conclusions on methodological approaches performances will include: i) analysis of the signalling systems effects on capacity and punctuality; ii) further tests based on traffic simulation on the concerned railway networks; iii) crosscheck of achieved results with collected real operation data.

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