RAILWAY CAPACITY ANALYSIS: METHODOLOGICAL FRAMEWORK AND HARMONIZATION PERSPECTIVES

EVANGELIA KONTAXI, PHD STUDENT – "SAPIENZA" UNIVERSITY OF ROME – DITS – TRANSPORT AREA, E-MAIL: *evangeliakontaxi75@gmail.com*

STEFANO RICCI, ASSOCIATE PROFESSOR – "SAPIENZA" UNIVERSITY OF ROME – DITS – TRANSPORT AREA, E-MAIL: *stefano.ricci@uniroma1.it*

ABSTRACT

The paper deals with capacity analysis techniques and methodologies for railway systems management and provides an accurate description of the methods classified by sector of interest, with a particular attention to point out all factors having a direct relation to the obtained results (input / output comparison analysis). The results are summarised in a comparison framework including quantitative elements useful for the planning of railway capacity analysis. Railway capacity has always been an attractive issue due to its relevance. In this paper all types of capacity will be defined: Theoretical Capacity (TC), Practical Capacity (PC), Used Capacity (UC), and Available Capacity (AC). The global aim of the research is to offer a technical manual including of overview and descriptions of the first branch of all Italian methods elaborated from 1950 till today. Synthetic and analytical methods, methods of optimization, simulation methods and their environments are compared and developed.
Keywords: Capacity, Techniques, Tools, Perspectives

INTRODUCTION

In an age where particular attention is focused on the best use, the maintenance and the technological adaptation of available resources, an important emphasis is played on the calculation of capacity in rail traffic. The growth of the rail transport demand leads to an increasing use of rail infrastructure, which often has a limited availability related to the topological configuration. Especially in the recent years the importance of quantifying the performance of the network in order to define the margins of railway capacity has become an important theme.

Motivation

The approach of the problem, very complex because of several factors, has been analyzed in several ways. The existing methodologies have been developed since 1950 and have been progressively updated to current times. Several factors have given inspiration to this

analysis offering a spectrum of choices and integration of different methods. Primary motivation for this research occurs as a result of the additional demands that are to be placed upon railways in Europe to provide third party usage of infrastructure.
The complete separation of railway infrastructure ownership and operation is also a potential reality in the near future, which would result in even greater competition for railway infrastructure. To ensure fair and impartial access under these new regimes, railway actors must be able to refer themselves to free (available) and used capacity recognised concepts.

Objectives

Rail capacity, however, is a difficult concept to define and compute. The difficulties are measured in a whole number of factors related to the complex structure of the rail system and the existing conceptual and terminological variety. In the present study all types of railway capacity are considered: Theoretical Capacity (TC), Practical Capacity (PC), Used Capacity (UC) and Available Capacity (AC).
In the above context, the ultimate goal of the present research, of which the first consolidated results are presented, is to provide a technical manual based on methods developed from the beginning of the 50's till today.

Paper Organization

The first part of the paper provides a description of the methods classified by sector of interest, with a particular attention to point out all factors having a direct relation to the obtained results (Input / output comparison analysis).

In the second part of the paper results of applications on a typical line (test network) and a typical node are explained, in order to identify and emphasize the practical operational problems. Railway capacity is not a formulaic science but rather a coordinated effort in the management of all aspects of the railways operation/assets, infrastructure and resources.
A first comparison will allow estimating the ability of the methods to deal with the typical operational situations and standards. The results of this preliminary analysis are summarised in a comparison framework including quantitative elements useful for the planning of railway capacity analysis.

STUDY START-UP

The themes proposed in this article are continuously evolving as the subject is wide and meets many developments and applications around the world. The part of this research inherent to the methodologies developed in Italy on calculating railway capacity has been completed and therefore it was considered that present a spectrum of this analysis could contribute to the technical knowledge in this field. This analysis will have its natural continuation with the deepening of the methods used abroad. The totality of the methods

amounts to 40 and similarly the simulation tools treated are over 60.Also the techniques of calculation based on previous works which, however, provided innovative contents, have been studied. The literature provides with much information, particularly data input and output of individual methodologies. Therefore, relying on them, a database has been created which is clearly not exhaustive, but has allowed "comparing" all the aspects that are covered by the term "railway capacity». Where possible, the authors were also contacted to deepen the knowledge or request more clarification. The technical benchmark is completed by the application of the methods to a sample portion of the rail network. In particular, synthetic and analytical methods, methods of optimization and simulation methods, including Simulation Tools (automated systems) have been considered. Analytical methods model the railway infrastructure by means of mathematical expressions in a simple way that provides results of a first approximation, the optimization methods are based on research and best saturated schedules while simulation methods provide models capable of representing the reality in order to validate the timetable data. Referring to these, multiple products, which normally generate timetables by simulation using the laws of motion of trains are developed and then marketed.
The analytical computation is usually performed to obtain a first indication on the railway capacity in a preliminary state. It is applied through mathematical formulas and / or algebraic expressions. The Simulation Tools are tools available on the market, which dialogue with the user interface and simulate rail traffic. Usually they generate timetable graphs dynamically defined through equations in which the time is a fixed variable in defined intervals. They can identify delays and analyze the interference in a given time. A detailed analysis was carried out on a total of twenty Simulation Tools so far. Further step of research will take place with the formulation and development of an integrated instrument characterized by different degrees of detail, therefore, useful for academic, technical-scientific and operational scopes.

CARRYING CAPACITY AS CAPABILITY TO LET TRAINS RUNNING

Relevance and definition

In the rail traffic technique, the capacity of lines and nodes is a key issue, since it summarizes in numerical values, the set of functional characteristics of lines and stations themselves, combined with those of vehicles running on them. Due to the heterogeneous multitude of factors affecting it, it is not possible a unique definition.

Line Capacity

The capacity of a line is defined as the number of scheduled trains that can run on the line in the reference time.
Key elements that have a direct influence on the value of the capacity are:

- geometrical configuration of the track;
- line and stations and lay-out;
- features of signalling systems;

- movement rules and corresponding minimum distance between trains;
- operation and maintenance planning .

Capacity of Nodes

The capacity of a node must be considered as the capability of the node itself to receive trains on the tracks in the reference time without delays at traffic signals. It depends on the structure of the timetable or rather on the frequency of arrivals, which regulate the minimum lines headway, the topology of the system which determines the incompatibility and the interlocking system features. In this first stage the analysis has considered only the rail stations meanwhile the authors are working also on rail yards and freight terminals.

Typologies of capacity

The Theoretical Capacity (Figure 1) is defined as the number of trains that could run on a certain line section in a defined reference time in case of unperturbed operation, corresponding to the headway for all classes of trains and operational planning. The Commercial Capacity represents the portion of the actual capacity calculated taking into account the actual operation of the railway and its interaction with the network. The Used Capacity is the actual capacity committed by a particular rail system under certain operating conditions that is absorbed by a timetable. The Residual Capacity is the portion of the capacity still available to meet new demands in a timetable and/or under perturbed operation.

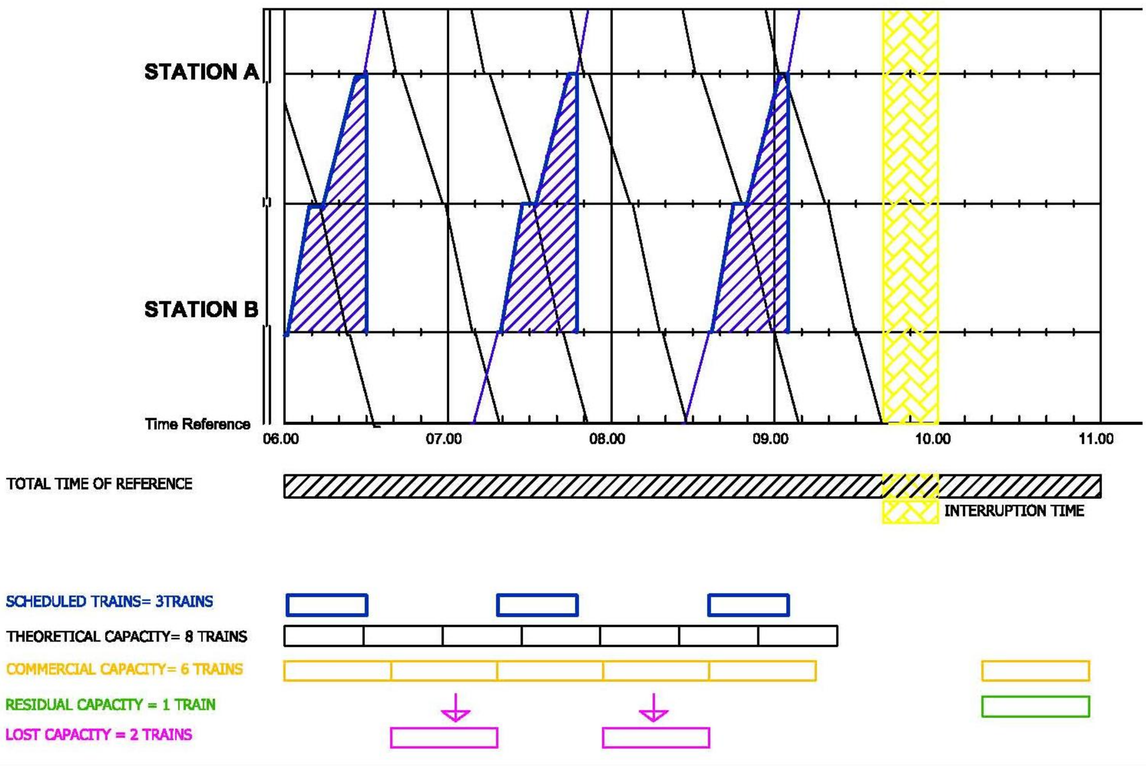


Figure 1: Typologies of lines capacity (one direction)

Parameters determining the carrying capacity

Variability and relevant parameters

Capacity is dynamic and closely linked to the elements that make up the rail system. They have an inherent variability, which is translated into a variation of the same capacity for different train typologies and performances and time allocated, the state of infrastructure and means of operation. In this analysis the main parameters affecting the determination of capacity have been considered: infrastructure parameters, operational parameters and traffic effects.

Infrastructure parameters

Number of Tracks
On single track lines, the section characterized by the highest travel time between two adjacent stations or intersections, is considered. On double-track lines a similar approach may be followed, with the caution to consider separately the trains of both direction of travel and related sections of highest travel time that may not be coincident. Therefore the first key distinction in the methodologies developed is due to single/double track. The calculation approach is nevertheless different because in the case of single-track lines the possible promiscuous movement of the two traffic directions requires higher safety margins. Many of the proposed methodologies only address the case of single track lines neglecting its extension on double-track lines and vice versa. The result is a discrepancy between the different methods and a lack of uniformity of these methods on two types of lines.
Distance between two crossing or passing stations
The distance between two stations with crossing or passing loops is a parameter of primary importance. In fact it characterizes the section block and consequently affects the whole line.
The theoretical number of trains that can move through a line is defined by the block section.
Total reference time
Methodologies and techniques normally refer to the whole day or peak periods. In the progressive evolution of these methods off-line time due to planned and unplanned maintenance was added. Therefore the capacity over 24 hours is normally overestimated.
Theoretical speed and project speed
Theoretical speed is the one prescribed by the infrastructure manager on the basis of traffic modules allowing accurate dynamic characteristics of rolling stock. The project speed is the speed with which a train can travel along a line section according to geometric features and state of the maintenance of the line.

Operational Parameters

Operational model

The operational model, intended as paths occupied by trains on the time-space frame, in addition to the technical specifications of temporal and spatial separations between trains required for crossing and overtaking operations, determines the travel time required by each train. Methodologies and techniques for the determination of capacity are distinguished, in this respect, into two main categories: those taking into account the number of scheduled trains and calculating the remaining capacity and those calculating an average travel time for trains and, therefore, getting an overestimation of the capacity itself.

Rolling stock features

The characteristics of both traction and braking curves and the composition of the trains determine the running time, the resulting required stopping distance and, therefore, headway and allowed speed according to the geometrical features of the line and the possible ability to partially compensate onboard the transversal acceleration.

Traffic typology

The traffic typology is defined as the distribution of different rolling stock assets running on a line. The different performances of trains reflect on the allowed speed, normally defined in speed classes. Many authors considered this fundamental aspect by expressing the variation of the capacity depending upon these classes. **Headway**

The spatial distance between two following trains and, therefore, the length of the block sections determines the maximum traffic intensity from which the capacity itself is depending. Many authors dealt with the relationship between headway and capacity with the adoption of a system rather than another [21] [18]. The number of trains increases as short as the intervals between them are and on the lines with block systems allowing more than one train between two stations.

Operational Effects

Generation and Propagation of delays

The delay produced by any conflict may depend upon the following factors:

- difference between the speeds of conflicting trains;
- minimum distance between two trains;
- distance between two following stations and number of tracks available for crossing and overtaking operations;
- priority rules for running;
- time for routes manoeuvring and releasing in the stations.

Required and expected quality of service

The quality of service normally depends upon the traffic typology and the requirements fixed in the agreements between infrastructure managers and train operators (e.g. in Italy these requirements reflect on priority rules for rail traffic management issued by the infrastructure manager).

CALCULATION TECHNIQUES AND METHODS

Classification

The different techniques and methodologies for calculating the capacity can be divided into three main categories according to the used methodology, the compiled data and the level of detail.
They are:

- Synthetic: deterministic expressions; the variables contained in these cannot change its state and assume fixed values during the reference time; from the mathematical point of view they are equations were the unknown quantities are mutually independent, they are also called static;
- Analytical: probabilistic expressions; from the mathematical point of view they are equations were the unknown quantities are mutually dependent, they are also called dynamic;
- Analogical: further divided into asynchronous methods (providing the optimization of one or more variables) and synchronous methods (traffic simulation), for instance the optimization methods are based on procedures looking for delays minimization in the mixed speed traffic, as well as the simulation methods represent the evolution of advanced research and are often used to validate the results of other methods.

Line Capacity

Methodological framework

One of the first formulation adopted by the Italian State Railways (1986) [14] considers travel times and stopping times for only two categories of trains. It has been updated by a new expression (2004) adopted by Italian Rail Infrastructure Manager (RFI), which is based on UIC 405.1 and allows to calculate both theoretical and practical capacity of a line. The method used by the German Railways [14], which uses the so-called DB formula is based on computing probabilistic functions of the average interval distance between trains, taking into account two speed classes only. Later Petersen (1974) [5] presented an analytical method for single-track lines, assuming a uniform distribution of departures of trains and three different speed classes. Cascetta and Nuzzolo (1980) [8] have implemented a method to determine the practical capacity of a line by introducing the calculation of delays and actual availability of tracks for crossing operations. The method proposed by UIC (1983) [11] determines the capacity by referring to the most critical section; through the introduction of an additional time, depending on the number of block sections and an increased margin (calculated from queuing theory), the method considers the actual level of service. A new UIC formulation (1996) allows relating capacity and quality of service. Corriere (1984)[13] introduced the variable “behaviour of trains” on the programmed speed, propagation of delays and various speeds, providing a vital contribution to the calculation of practical capacity. Canciani (1991) [19] treats capacity of double track lines with alternating circulation, considering the delays of overhauling and thus made possible the assessment of the maximum capacity allowed by the stations. The same model, taking into account the delays due to conflicts, is reapplied to determine the capacity in the case of a reduction of service onto a double track line. Malaspina and Reitani (1995) [22] treat the double-track lines by introducing parameters such as the composition of traffic, the priority degree and the extent and impact of delays. This method can be considered both synthetic and analytical, and introduces the likelihood that a conflict occurs. Galaverna and Sciutto (1999) [27] introduced, in a double track line, the additional delay of overtaking manoeuvre and its probability. The method takes inspiration from [13] however reaching a new formulation for the capacity. Delfino and Galaverna (2003) [33], proposed a comparative analysis on the impact of fixed block and moving block on the capacity of a railway line. Finally Genovese and Ronzino (2006) [47], starting from Corriere's results, introduce the delays due to planned stops and the coefficient of stability, by calculating the theoretical capacity.

Capacity of Nodes

Methodological framework

In the field of nodes capacity the methodological framework is more restricted. In general any method which treats the complex problem of calculating the capacity of railway nodes is based on the topological analysis in order to verify the compatibility between planned movements (number and type of trains) and the given infrastructure characteristics along with the technology of the node itself. For railway node it is intended a delimited zone in a plant or system in which one train running along any route prevents the circulation of one or more trains moving on one or more incompatible routes. In other words, the railway node works as a bottleneck in the railway flow as it allows an average number of movements (sometimes just once a time) that is always lower than that that allowed by a system working in parallel. To overcome these deficiencies various analytical techniques for railway nodes have been developed which today can be conventionally considered in two main categories: the synthetic and the analytical methods. In the context of synthetic methods, the prominent position is held by Potthoff of the University of Dresden who intended the node uprooted from the railway system as being interested by an average number of movements to seek time by time using the "compatible routes matrix". The Potthoff method (1965) [2] became a reference method for many others and allows to the determine a regular occupation time of the node and an extra occupation time due to the conflicts faced during the reference time. Given the structure of the node and assuming a random distribution of arrivals in the time period under exam, Potthoff defines a set of indicators to assess the saturation degree of the node, its possible capacity margins and allows, therefore, the comparison between different structural solutions. This method does not require an assigned timetable since is based on a comprehensive quantitative analysis of traffic in the time period under examination. It is characterised for its immediate identification of results along with the simplicity and agility of application, while it is set against a lack of transparency of the analysis or a lack of information regarding the true movement of trains within the node, but especially a poor match to the actual operation, since it is based on the hypothesis that the probability of arrival within the time period under examination is constant. These features make the method mentioned above particularly effective for very short time periods of observation, such as rush hour, in which the compensation between soft-hours and rush-hours cannot occur. Moreover it must be added that the assessment of the delays generated inside the nodes suffers of certain empiricism. During the current research an automatic procedure to apply this method has been developed following the scheme in figure 2.

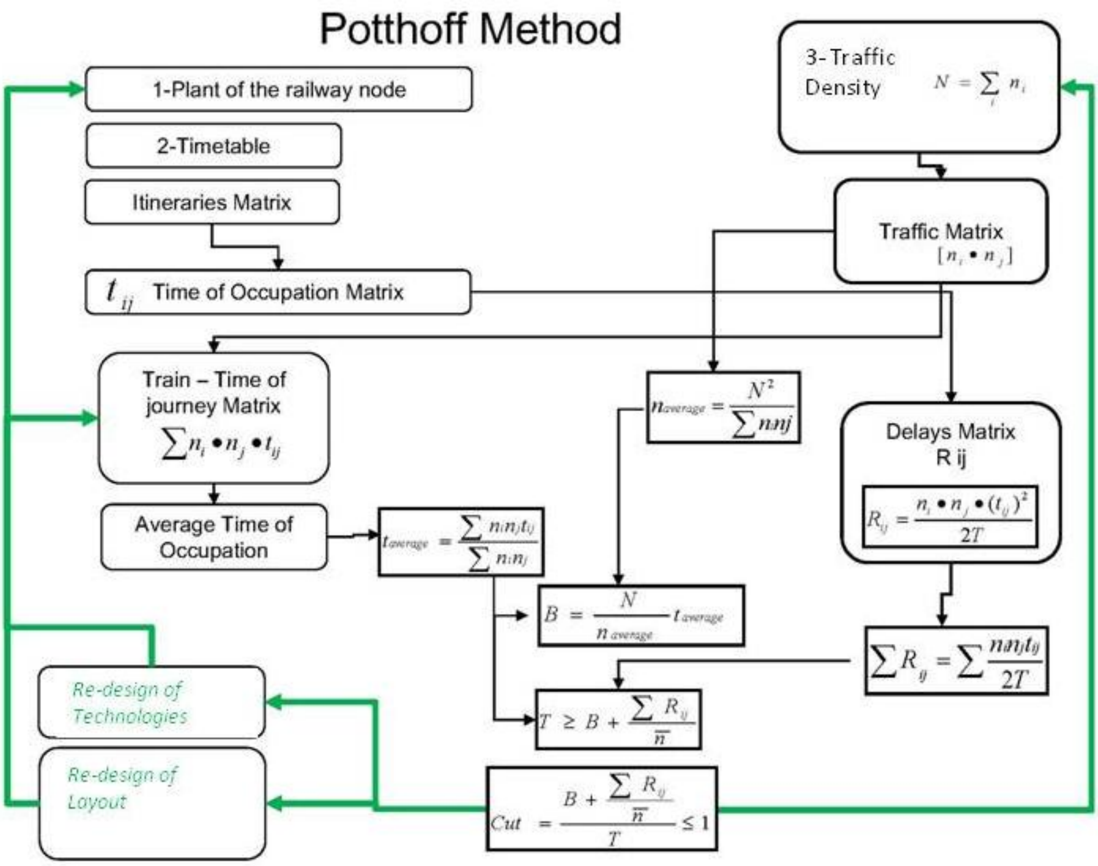


Figure 2: Potthoff method procedure flowchart

Regarding the analytical methods the birthright is held by the Muller method which was taken over in the technical guidelines of the German railways (DB). The analytical methods use as input data, the node's layout and the operational plan. They check the state of occupation or freedom of the entities covered by the movements of trains in the node and they produce a timeline situation of the two possible states described above. The degree of actual occupation and the margins of use can be traced back from this. The analytical methods are particularly effective when dealing with nodes of a certain size where the entities to be kept under observation are many. The examination of these two lines of thought brought Giuliani, Malavasi and Ricci (1989) [17] to develop an analytical method, based on Assigned Timetables, capable to provide at least with as good results as of the complete version of Muller method, though easier in comparison to it. This method aims to obtain basically the following three objectives:

1) To give an analytical and graphical representation of the node's capacity;
2) To provide with an assessment tool characterized by simplicity in its use and immediate implementation reading the results;
3) To take into account the arrival of trains to the node according to their actual distribution, this means that their planned arrival time is just one of the possible cases and often not even the most likely.

Corazza and Florio (1979) [6] proposed a method for calculating the capacity of a node based on the preliminary determination of delays and the Potthoff method itself, able to consider the organization and randomness of the timetable and the resulting conflicts between trains. Florio and Malavasi [14] (1984) studied the capacity of a complex railway node determined by entry and exit areas under the assumption of a stochastic distribution of arrivals and departures. One of the key results of this method is the demonstration that the regularity (deviation from theoretical schedule for each train) has an influence on the station occupation of the same order of magnitude than the amount of traffic. Florio and Malavasi (1989) formulated a method for complex nodes, assuming a perturbed operation by evaluating the variability of selected indicators and its effects on the capacity (totally and partially by track). Florio and Mussone (1998) [26] proposed an analytical method in which the overall number of trains running in a railway node in a reference time can be expressed as a super-vector that can assume all values of the hyper-surface composed by the number of trains potentially travelling in each component.

SIMULATION TOOLS

A number of analogical simulation methods (simulation tool) have found their natural application development in commercial tools. These instruments normally provide an interface for the dialogue with the user and simulate the rail traffic. Usually generate schedules graphs dynamically defined through equations in a defined timetable. They can identify delays and analyze the conflicts in a reference time. The detailed analysis carried out to date, as part of this research, has a total of thirty-seven environments of which a comparative analysis is provided in Figure 3.The next step followed was to compile a summary statement of analysis, so as to offer a spectrum of results obtained through comparative analysis performed. This analysis has been based in this first stage on the technical data available from e-sources and manuals of each simulation tool. In each simulation tool many details and elements are analyzed, mainly inputs and outputs, for the determination of rail capacity. The input parameters are classified into the infrastructure, network parameters and effects of the operation. The output data are different depending on whether the simulation environment allows the calculation of theoretical capacity, commercial capacity, used capacity or residual capacity. In addition, these simulation tools have been classified on the basis of the main functions performed:

- Simulation: processes the data input and offers a graphical interface with the user in order to simulate a railway system.
- Optimization of schedules: processes the trains running and provides with the timetable through defined scheduling optimization rules.
- Hours: allows creating a timetable.

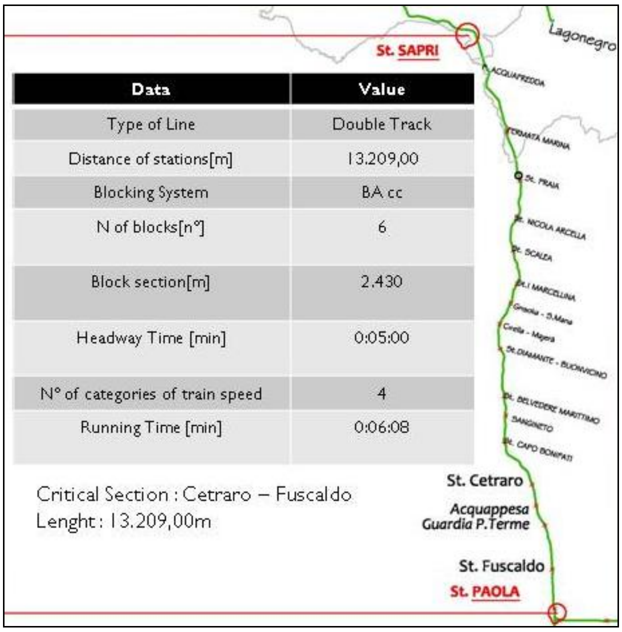
- Railway Capacity: calculates the capacity.
- Infrastructure: manages the infrastructure data of a railway system.
- Facilities Management: manages the infrastructure facilities data of a rail system.
- Turn: manages the rolling stock scheduling.
- Economic Evaluation: performs economic analysis on projects concerning infrastructure and network expansion.
- Sensitivity analysis: processes more than one scenario calculating indicators of performances in different conditions.

COMPARATIVE ANALYSIS			Simulation Enviroments - TOOLS																																				
			AFAIG	CAPRES	CASSANDRA	CMS	DEMIURGE	DONS	FALKO	FAST TRACK II	FASTA	IRCIM	LIPARI	MOM MALLAS	MULTIRAIL	OPENTIMETABLE	OPENTRACK	PETER	PTG	RADIS	RAILCAP	RAILNET II	RAILPLAN	RAILSIM	RAILSYS	RASIM	ROMAN	SAMFOST	SIM-OBAU	SIMONE	SIMON(TOPSim)/TTS	SISYFE	TNV	TPS/STRAX	TURNI	VILLON	VIRIATO	VirtuOS	XANDRA
		ID NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
input data	Infrastructure Parameters	Single/double tracks	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	?	✓	✓	✓	✓
		Moving Block System and signalling system	✓	?	✓	?	✗	?	✓	✓	?	✓	✓	?	✓	✓	✓	✓	?	?	✓	✓	✓	✓	✓	?	✓	✗	?	✓	?	✓	✓	✓	?	✓	✗	✓	?
		Definition of lines, routes	✓	✓	✓	?	✓	?	✓	✓	✓	✓	?	?	✓	✗	✓	✓	?	?	✓	✗	?	✓	✓	?	✓	✗	?	✓	?	?	✓	✓	?	✓	✓	✓	?
	Network Effects	Track structure and speed limits	✓	✓	✓	✓	✓	?	✓	✓	✓	✓	✓	✓	✓	?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Block occupation or blocking time	?	✓	?	?	✗	?	✓	✓	✓	✓	?	?	✓	?	✓	✓	?	?	✓	✓	?	✓	✓	?	✓	✗	?	✓	?	?	?	✓	?	✓	✗	✓	✓
		Headway distance	?	✓	?	?	✓	?	✓	✓	✓	✓	✓	✓	✓	?	✓	✓	?	?	✓	✓	✓	✓	✓	?	✓	✗	?	✓	?	✓	✓	✓	?	✓	✗	✓	✓
		Headway time	?	✓	?	?	✓	?	✓	✓	✓	✓	✓	✓	✓	?	✓	✓	?	?	✓	✓	✓	✓	✓	?	✓	✗	?	✓	?	✓	✓	✓	?	✓	✗	✓	✓
		Blocking time stairway	?	✓	?	?	✓	?	✓	✓	?	✓	?	✓	✓	?	✓	✓	?	?	✓	✓	✓	✓	✓	?	✓	✗	?	✓	?	?	✓	✓	?	✓	✗	✓	✓
		Signal headway	?	?	?	?	✓	?	✓	✓	?	✓	?	✓	✓	?	✓	✓	?	?	✓	✓	✓	✓	✓	?	✓	✓	?	✓	?	?	✓	✓	?	✓	✗	✓	✓
		Minimum Line Headway	?	✓	?	?	✓	?	✓	✓	✓	✓	?	✓	✓	?	✓	✓	?	?	✓	✓	✓	✓	✓	?	✓	✗	?	✓	?	?	✓	✓	?	✓	✗	✓	✓
		Buffer time	?	✓	?	?	✓	?	✓	✓	?	✓	?	✓	✓	✓	✓	✓	?	?	✓	✓	✓	✓	✓	?	✓	✗	?	✓	?	?	?	✓	?	✓	✗	✓	?
		Running time supplement	?	✓	?	?	✓	?	✓	✓	?	✓	?	✓	✓	✓	✓	✓	?	?	✓	✓	✓	✓	✓	?	✓	✗	?	✓	?	?	?	✓	?	✓	✗	✓	?
		Dwell time	?	✓	?	?	✓	?	✓	✓	?	✓	?	✓	✓	?	✓	✓	?	?	✓	✓	✓	✓	✓	?	✓	✓	?	✓	?	?	?	✓	?	✓	✗	✓	?
		Total consumption time	✓	✓	?	?	✓	✓	✓	✓	?	✓	✓	✓	✓	✓	✓	✓	?	✓	✓	✓	✓	✓	✓	✓	✓	✓	?	✓	?	✓	✓	✓	✓	✓	✓	✓	?
		Train mix / Rolling Stock	✓	✓	?	?	✓	?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	?	✓	✓	✓	✓	✓	✓	✓	✓	✗	?	✓	?	✓	✓	✓	✓	✓	✓	✓	✓
		Traffic peaking factor	✓	✓	?	?	✓	?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	?	✓	✓	✓	?	✓	✓	✓	✓	✗	?	✓	?	✓	✓	✓	?	✓	✓	✓	✓
		Priority	?	✓	?	?	✗	?	✓	✓	?	✓	?	✓	✓	✓	✓	✓	?	?	✓	✓	?	✓	✓	?	✓	✗	?	✓	?	?	?	✓	?	?	✓	?	?
	Operating Parameters	Track Interruptions	?	✗	?	?	✓	?	✓	✓	?	✓	?	✓	✓	✓	✓	✓	?	?	✓	✓	?	✓	✓	?	✓	✗	✓	✓	?	?	?	✓	?	?	✓	?	?
		Train stop time	✓	✗	✓	?	✓	✓	✓	✓	?	✓	✓	✓	✓	✓	✓	✓	?	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	?	✓	?	✓	✓	?	✓	?	✓
		Maximum trip time threshold	?	✗	?	?	✓	?	✓	✓	?	✓	✓	✓	✓	?	✓	✓	?	?	✓	✓	?	✓	✓	?	✓	✗	✓	✓	?	✓	?	✓	?	?	✓	?	?
		Quality of service, reliability, or robustness	✗	✗	?	?	✓	?	✓	✓	?	✓	✓	✓	✓	?	✓	✓	?	✓	✓	✓	?	✓	✓	✓	✓	✗	?	✓	?	✓	?	✓	?	?	✓	?	✓
output data	Capacity Analysis	Theoretical Capacity	?	✓	✓	✓	✓	?	✗	✓	?	✓	✗	✓	?	✓	?	✗	✗	?	✓	✗	✗	✓	✓	?	✗	✓	✗	?	✗	✗	✗	✗	✗	✗	✗	✗	✗
		Practical Capacity	✗	✗	✗	✓	✓	?	✗	✓	✗	✓	✗	✓	?	✗	?	✗	✗	?	✓	✗	✗	✓	✓	?	✗	✗	✗	?	✗	✗	✗	✗	✗	✗	✗	✗	✗
		Used Capacity	✗	✗	✗	✓	✓	?	✗	?	✗	✓	✗	✓	?	✗	?	✗	✗	?	✓	✗	✗	?	✓	✓	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗
		Available Capacity	✗	✓	✗	✓	✓	?	✗	?	✗	✓	✗	✓	?	✗	?	✗	✗	?	✓	✓	✓	?	✓	?	✗	✗	✗	?	✗	✗	✗	✗	✗	✗	✗	✗	✗
	Main Functions	Crew Scheduling	✗	?	?	✗	?	?	?	?	?	✗	✗	✗	?	✗	✗	?	✗	✓	?	?	✗	?	?	✓	?	?	✗	✗	✗	✗	✗	?	✓	✗	✓	✗	✗
		Infrastructure Manager	✓	✓	?	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✗	✓	✓	✗	✓	✓	✗	✗	✓	✓	✓	✓	✗	✓	✓	✗	✓	✗	✓	✓	✓	✓	✓	✓
		Station Manager	✓	✓	?	✓	✓	✓	✗	✓	✗	✗	✗	?	✓	✗	✗	✗	✗	✓	✗	✓	✗	✓	✓	✓	✗	✗	✓	✓	✗	✗	✗	✗	✓	✓	✓	✓	✓
		Timetable Manager	✗	✗	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✗	✗
		Timetable Optimization	✗	✓	✗	✓	✓	✓	✗	✓	✗	✗	✓	✓	✓	✗	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	?	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗
		Economic Evaluation	✗	?	✗	?	?	?	?	?	?	✗	?	?	?	?	?	?	?	✓	?	?	?	?	?	?	?	?	?	✗	?	?	?	?	✓	?	?	?	?
		Sensitivity Analysis	✗	?	✓	?	?	?	?	?	?	✓	?	?	?	?	?	?	?	✓	?	?	?	?	?	?	?	?	?	?	?	?	?	?	✗	?	?	?	?
		Simulation	✗	✗	✓	✓	✗	✓	✓	✓	✓	✓	✗	✗	✓	✗	✓	✗	?	✗	✓	✗	✓	✓	✓	✓	✓	✗	?	✓	?	✓	✗	✓	✗	✓	✗	✓	✓
	Statistical Analysis	elements	✓	✓	?	?	✗	?	?	✓	✓	✓	✗	?	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	?	?	?	?	✗	?	✓	?	?
		histograms of margins between trains	✓	✓	?	?	✗	?	?	✓	✓	?	✗	?	✓	✓	✓	✗	?	?	✗	✗	✓	✓	✓	?	✓	✗	✓	✓	?	?	?	?	✗	?	✗	?	?
		list of margins between trains	✓	✓	?	?	?	?	?	✓	✓	?	✗	?	✓	✓	✓	✗	?	?	✗	✗	✓	✓	✓	?	✓	✗	✓	✓	?	?	?	?	✗	?	✗	?	?
		statistics of train assignements by direction	✓	✓	?	?	✓	?	?	✓	✓	✓	✗	✓	✓	✓	✓	✓	?	✓	✓	✗	✓	✓	✓	?	✓	✓	✓	✓	?	?	?	?	✓	?	✓	✓	?
		Conflicts detection	✓	✓	?	?	✓	?	?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	?	✓	✗	✓	✓	?	?	?	✓	✓	✓	✓	✓	?
		Platform track occupation schedule	✓	✓	?	?	?	?	?	✓	✗	?	✗	?	✓	✗	✓	✗	✓	?	✗	✗	?	✓	✓	✓	✓	✗	✓	?	?	?	?	?	✓	✓	✓	✓	?

Figure 3: Comparative analysis of the functionality of simulation tools for capacity calculation

TEST NETWORK

In order to perform a comparative application of the methods, it has been selected a line, which will result a common reference for the following analysis: the branch Sapri-Paola (Figure 4) located between the South of Campania and the North of Calabria regions, representing a part of Battipaglia - Reggio Calabria line, southern section of one of the main European North-South rail corridors and the most important rail link between Sicily, Calabria and the rest of Italy and Europe.



Data	Value
Type of Line	Double Track
Distance of stations[m]	13.209,00
Blocking System	BA cc
N of blocks[n°]	6
Block section[m]	2.430
Headway Time [min]	0:05:00
N° of categories of train speed	4
Running Time [min]	0:06:08

Figure 4: Data summary of the test network

On the line run all types of passenger and freight trains. The selected branch, with an overall length of 92.2 kilometres, has 11 stations and 9 intermediate stops. The critical section, with a total length of 13.2 kilometres, is between the stations Fuscaldo and Cetraro, with the presence of two intermediate stops. Figure 5 shows the schematic plan of the critical section, subject of test applications for the various methods hereby described.

PRELIMINARY COMPARATIVE ANALYSIS

In this section are shown the preliminary results of a comparative analysis carried out on the methodology outlined above, which highlights the main functions and application fields. The differentiated parameters intrinsically linked to the input and output data of each method are examined. The comparison identifies the ability to deal with the basic operations and standards of the railway system.

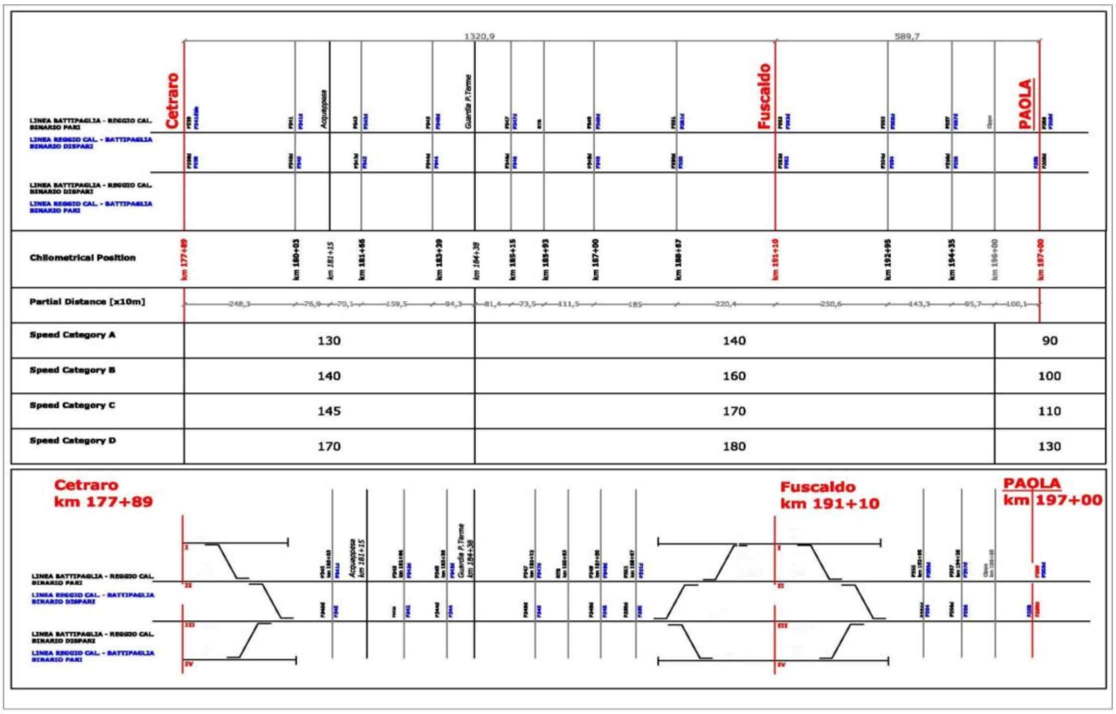


Figure 5: Schematic plan of the critical section Fuscaldo - Cetraro

The first result is their strong differentiation, not only because they are based on different mathematical models but mainly because they provide a range of output data corresponding to different service conditions and key features.

The ultimate goals of these activities of comparison and classification can be summarized in:

- to highlight the advantages and disadvantages of the methods from technical point of view and to formulate a clear indication to the operators, researchers and technicians of the instrument that fits on the basis of their needs;
- to develop and propose, as final result at a later stage, an unique tool capable to integrate the different approaches adopted to date.

LINE CAPACITY METHODS APPLICATIONS

As previously mentioned, the methods were applied for comparative purposes to the critical section of the Sapri-Paola line and to Fuscaldo station. For the line the applied methods made possible to calculate a wide set of values of theoretical capacity, in some cases significantly different each other, with values ranging between 100 and 170 trains per day for each direction (Figure 6). It is pointed out how the values of the capacity have the same order of magnitude for the methodologies by Bianchi (1964) and the FS formula (1968), easy to apply but with the limitation not to take into account perturbed traffic and not homogeneous speeds. In fact by including these two factors Bianchi, in his second formulation, significantly reduces the value of the theoretical capacity. DB and UIC formulas introduce elements explaining the influence of speed classes' alternation in the actual operation by providing lower values of capacity.

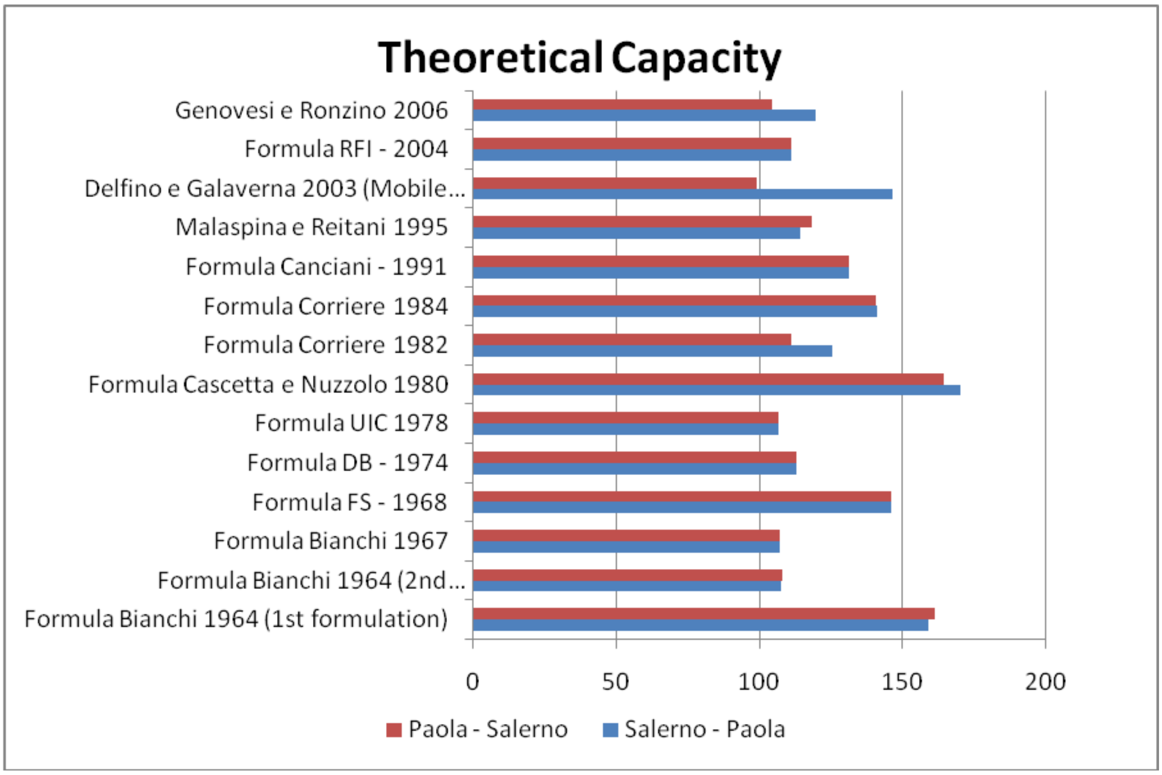


Figure 6: Theoretical capacity (trains/day) per direction according to different methodologies

The remaining methods, with the single exception of Cascetta and Nuzzolo one, lead to define capacity values in a similar order of magnitude, anyway depending upon the multiple parameters taken into account. The Cascetta and Nuzzolo methods suffers of the introduction of several new factors normally justifying lower capacity values as actually resulting by more recent methods considering them. The advantages and disadvantages of all methods shown in figure 6 are currently under examinations in order to define their variability on different test cases and proceed with their final validation. The authors remain at complete disposal for any information on this preliminary stage if necessary.

NODE CAPACITY METHODS APPLICATIONS

For the nodes the results of the application of the Potthoff method to the Fuscaldo station, along with sensitivity analysis which allows defining the capacity margins, are shown in Table 1. The application of the method based on Assigned Timetable by Giuliani, Malavasi and Ricci (1989), which moves beyond the empiric approach of Potthoff method, provides interesting results which are shown in Table 2. It is revealed that the introduction on the actual distribution of the arrivals and the calculations of delays based on the actual timetable of the trains in the Fuscaldo station not only reduces the capacity margins of station itself but also points out the critical situation in which it stands given the results of a Utilization Coefficient equal to 141%. In fact, the total numbers of 69 trains which are considered in the planned timetable of the station assume a total delay of 1931 minutes/day which, in average, corresponds to 28 minutes for a single train. Actually the most part of the (1185 minutes) is attributed to 8 freight trains which are travelling with delay from their origin and simply acquire an additional a delay in their departure from the Fuscaldo station. If the assumption of not considering these delays is made and only passenger trains are considered (second column of Table 2) the results are not so far from those obtained by Potthoff method. Figure 7 show a chart which provides a comparison of the obtained results in terms of residual movements.

		Current Situation	Traffic increase 5%	Traffic increase 10%	Traffic increase 13%
Average Number of Movements	*n average*	1,73	1,73	1,73	1,73
Average Time [min]	*t average*	9,31	9,31	9,31	9,31
Regular Occupation [min]	*B*	743,00	780,15	817,30	839,59
Coefficient of Regular Utilization	*Cut reg.*	56%	59%	62%	64%
Sum of Delays [min]	*Sum R*	730	766	803	825
Coefficient of Total Utilization	*Cut tot.*	88%	93%	97%	100%
Time of Reference [min]	*T*	1320	1320	1320	1320
Total Number of Movements	*Nm*	138	145	152	156
Total Number of Trains	*Nt*	69	72	76	78
Additional Movements			**7**	**14**	**18**

Table 1: Application of the Potthoff Method to the Fuscaldo railway node.

		All trains	Passengers trains only
Average Number of Movements	n (average)	1,73	1,73
Average Time [min]	t average	9,31	9,31
Regular Occupation [min]	B	743,00	840,45
Coefficient of Regular Utilization	**Cut.reg.**	**56%**	**64%**
Sum of Delays [min]	Sum R	1931	730
Coefficient of Total Utilization	**Cut.tot.**	**141%**	**105%**
Time of Reference [min]	T	1320	1320
Total Number of Movements	Nm	138	122
Total Number of Trains	Nt	69	61
Additional Movements		**-40**	**-5**

Table 2: Application of Assigned Timetable (Giuliani, Malavasi and Ricci) method to the Fuscaldo station

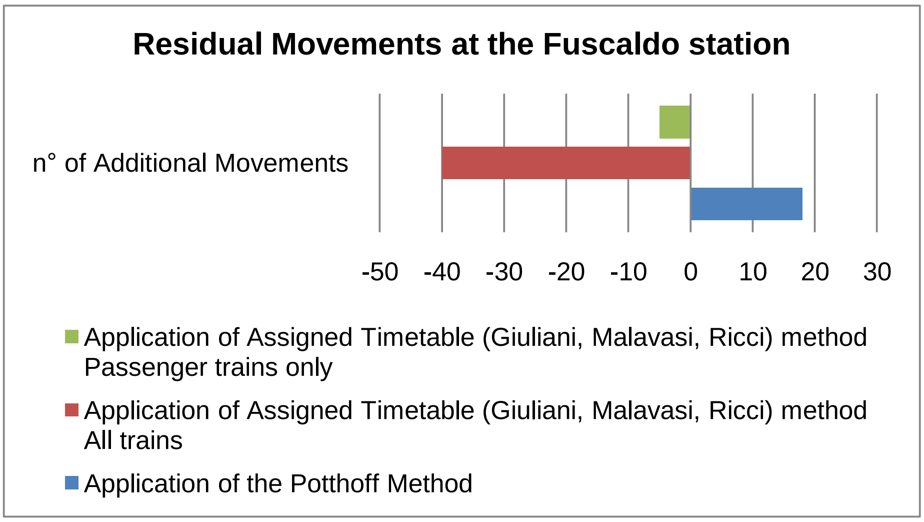


Figure 7: Residual Movements at the Fuscaldo Station.

FINAL COMMENTS AND CONTRIBUTIONS TO RESEARCH

In the framework of the concerned railway research area, a contribution has been proposed, specifically focusing on the following topics:

- development of the concept of capacity in combination with the development of the railway network in the last 60 years, through the analysis of existing methodologies and evolution perspectives in this area;
- correlation between the methods developed by researchers and the data normally managed by infrastructure managers and railway operators;
- support to full development of calculation procedures allowed by the diffusion of the personal computers;
- relationship between theories developed and progressively evolved and accuracy of the results provided as well as their comparison with modern simulation tools, with the further aim to highlight their application and theoretical problems;
- link between different operators and researchers in order to obtain an updated picture of state of the art and use of different theories and methods in Europe;
- contribution towards the development of an integrated instrument characterized by different levels of detail, therefore useful for technical-scientific and operational scopes.

In order to present in an as much as possible systematic way the most significant results of the developed analysis, in Figure 8 are summarized the first results of a SWOT (Strengths, Weaknesses, Options and Threats) analysis, which will be enriched on the basis of additional evidences to be acquired in further research steps.

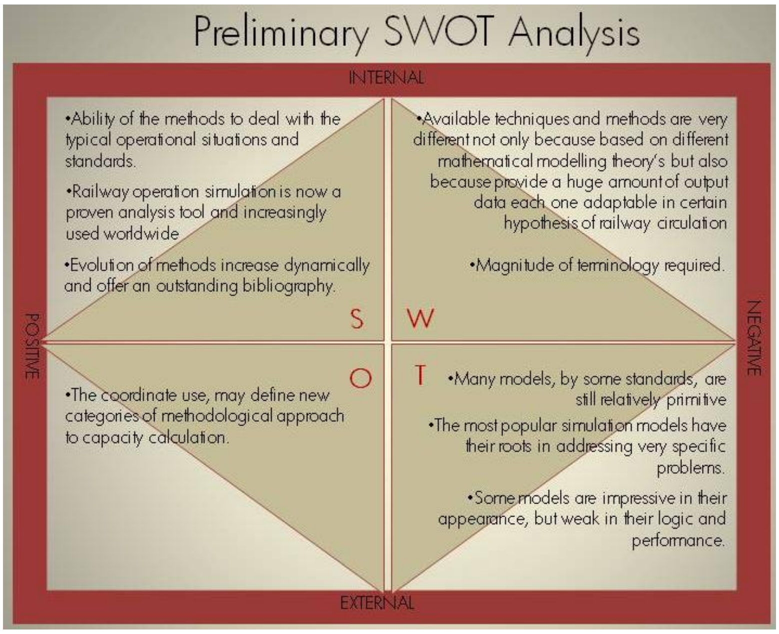


Figure 8: SWOT Analysis – Preliminary status

REFERENCES

[1] Bianchi M. – Potenzialità di linee ferroviarie – Ingegneria Ferroviaria (Dicembre 1964)
[2] Potthoff – Verkehrsstromungslehre – Transveb, Berlin, (1965)
[3] Bianchi M. – Circolazione di treni a velocità diverse su linee a doppio binario – Ingegneria Ferroviaria (Dicembre 1967)
[4] Szpigel, B., - Optimal Train Scheduling on a Single Track Railway, in Operational Research 72, 343-352. (1972)
[5] Petersen E. R.,Over the road transit time for a single track railway. Transportation Science, 8, 65-74, (1974)
[6] G.R.Corazza - L.Florio - Il problema del nodo e la verifica degli impianti di stazione, Ingegneria Ferroviaria, (Aprile 1979)
[7] UIC Leaflet 405-1 R, Methode Destinee a determiner la capacite de lignes. UIC International Union of Railways, France (1979)
[8] E.Cascetta - A.Nuzzolo - Un modello analitico per il calcolo della capacità di circolazione delle linee ferroviarie, Ingegneria Ferroviaria, (Febbraio 1980)
[9] Bonora G., Giuliani L. – I criteri di calcolo di potenzialità delle linee ferroviarie, Ingegneria Ferroviaria, (Aprile 1982)
[10] Kraft, E.R. - Capacity of Single Track Rail Lines, Proceedings of the Transportation Research Forum 23 (1) 461-471.(1982)
[11] Corriere F. – Potenzialità e regolarità di esercizio nelle linee ferroviarie - Ingegneria Ferroviaria (Gennaio/Febbraio 1982)
[12] [UIC, 1983] UIC leaflet 405-1, Method to be used for the Determination of the Capacity of Lines. UIC International Union of Railways, France, (1983).
[13] Corriere F. – Sulla potenzialità dei sistemi di trasporto in sede propria, Ingegneria Ferroviaria (Gennaio/Febbraio 1984)
[14] Florio L., Malavasi G. – Principi teorici per la verifica di un impianto complesso e determinazione dei margini di potenzialità – Ingegneria Ferroviaria, (Dicembre 1984)
[15] G.Viguna – Organizzazione etecnica ferroviaria, CIFI (1986)
[16] G.R.Corazza - A.Musso - Gli impianti di stazione e la loro analisi topologica, (Novembre 1987)
[17] L.Giuliani - G.Malavasi - S.Ricci - Analisi di un impianto di stazione sulla base del programma di Esercizio, Ingegneria Ferroviaria, (Ottobre1989)
[18] G.R.Corazza - A.Musso La Circolazione Ferroviaria e gli Impianti di stazione, Ingegneria Ferroviaria , (Luglio/Agosto 1991)
[19] Canciani G. – Criteri progettuali di rinnovo e potenziamento delle line ferroviarie : modello di calcolo e di verifica della potenzialità di circolazione (Giugno 1991)
[20] G.R.Corazza - A.Musso - La Circolazione Ferroviaria e gli Impianti di stazione. La Verifica a Lungo Termine, Ingegneria Ferroviaria, (Ottobre 1991)
[21] Ricci S. - Metodologia di analisi e verifica dei regolamenti di circolazione ferroviaria , Ingegneria Ferroviaria, (Gennaio 1992)
[22] G.Reitani - R.Malaspina - La potenzialità di circolazione ferroviaria su linee a singolo binario- un modello di calcolo, Ingegneria Ferroviaria, (Agosto 1995)
[23] G.Reitani - R.Malaspina - Un criterio di calcolo della potenzialità di circolazione ferroviaria su linee a doppio binario, Ingegneria Ferroviaria, (Agosto1995)
[24] Poggio A. – Analisi comparata dei sistemi di controllo e regolazione della circolazione sulle linee ferroviarie , Ingegneria Ferroviaria (Agosto 1995)
[25] Cappelli - S.Ricci - P.Staffini - Un Modello di Simulazione dei Nodi Ferroviari complessi, Ingegneria Ferroviaria, (Marzo 1996)
[26] L.Florio, L.Mussone – A new approach to the analytical formulation of the capacity of complex railway systems (1998).
[27] M.Galaverna , G.Sciutto – Influenza delle stazioni nella potenzialità di ferrovie a traffic

misto, Ingegneria Ferroviaria , (Dicembre 1999)
[28] Malavasi G., Ricci S. – Carrying capacity of railway networks: interaction of line and node models – Computers in Railways VII, WIT Press, Southampton, (2000)
[29] Di Marco G. - Malavasi G. - Ricci S. - Affidabilità dei sistemi ferroviari. Analisi e valutazione mediante modelli di simulazione, Ingegneria Ferroviaria , (Gennaio/Febbraio 2000)
[30] M.Antognoli - G.R.Corazza - P.Guida - Analisi di un impianto di stazione mediante osservazioni in condizioni reali di esercizio, Ingegneria Ferroviaria, (Luglio 2001)
[31] EC (2001). White paper: European transport policy for 2010: time to decide. European Commission, http://ec.europa.eu/transport/white-paper/documents/doc/lb-textecomplet-en.pdf. , (2001).
[32] Galatola M. - Gli indici di criticità : Un metodo per l'analisi dei nodi ferroviari, Ingegneria Ferroviaria , (Marzo 2002)
[33] Delfino A. - Galaverna M. Blocco fisso e blocco mobile: analisi di potenzialità Ingegneria Ferroviaria, (Giugno 2003)
[34] Fiche UIC 406 R – Liens entre capacitè des infrastructures ferroviaires et qualità de l'exploitation, (September 2004)
[35] [UIC, 2004a], Capacity management (capman phase 3), summary report. Technical report, UIC International Union of Railways, France. (2004) http://www.uic.asso.fr/download.php/infra/2004-Capman- 3-Summary.pdf.
[36] [UIC, 2004b] UIC leaflet 406 R, Capacity. UIC International Union of Railways, France, (2004)
[37] Nash A., Huerlimann D., "Railroad simulation using OpenTrack", In: Allan, J., Hill, R.J., Brebbia, C.A., Sciutto, G., Sone, S. (eds.), Computers in Railways IX, pp. 45- 54, WIT Press, Southampton, (2004)
[38] Nash A., Ullius M., "Optimizing railway timetables with OpenTimeTable", In: Allan, J., Hill, R.J., Brebbia, C.A., Sciutto, G., Sone, S. (eds.), Computers in Railways IX, pp. 637-646, WIT Press, Southampton, (2004)
[39] Nash A., Huerlimann D., Schuette J., Krauss V.P, "RailML – a standard data interface for railroad applications", In: Allan, J., Hill, R.J., Brebbia, C.A., Sciutto, G., Sone, S. (eds.), Computers in Railways IX, pp. 233-240, WIT Press, Southampton, (2004)
[40] Diego d'Elia - Il software CAPRES per lo studio della potenzialità di reti ferroviarie - Applicazione ai casi di Genova e della Sardegna, Ingegneria Ferroviaria , (Gennaio 2004)
[41] Galatola M. - Analisi della circolazione ferroviaria - Gli indici di compattezza e di qualità, Ingegneria Ferroviaria , (Luglio/Agosto2004)
[42] Kozan E. and Burdett R. L., A Railway Capacity Determination Model and Rail Access Charging Methodologies. Transportation Planning and Technology, 28(1), 27-45, (2005).
[43] Estimation Of Railway Capacity Consumption Using Stochastic Differential Equations, XIX Ciclo Del Dottorato Di Ricerca In Ingegneria Delle Infrastrutture, Delle Strutture E Dei Trasporti, Università Di Trieste (2005)
[44] Galatola M. - La potenzialità delle linee ferroviarie e la qualità del servizio offerto - Ingegneria Ferroviaria, (Gennaio 2005)
[45] Evaluation of railway capacity , Alex Landex, Centre for Traffic and Transport, Technical University of Denmark (2006)
[46] Techniques for absolute capacity determination in railways. Transportation Research Part B: Methodological 40(8):pp. 616-632, Burdett, Robert L. and Kozan, Erhan (2006)
[47] Genovesi P. – Ronzino C.D - Flussi e capacità delle linee ferroviarie a doppio binario, Ingegneria Ferroviaria, (Luglio/Agosto 2006)
[48] An Assessment of Railway Capacity - M. Abril, F. Barber, L. Ingolotti, M.A. Salido, P. Tormos, A. Lova , (Aprile 2007)
[49] Survey of automated systems for railway management, Universidad Politécnica De

Valencia, (2007)
[50] L.Landex, A.H.Kaas – Practical use of the UIC 406 leaflet by including timetable tools in the investigations, Computer in Railways X (2007)
[51] Understanding the Timetable Planning Process as a Closed Control Loop, Marco Luethi, Daniel Huerlimann, Andrew Nash - Swiss Federal Institute of Technology (ETH Zürich)
[52] RailSYS: http://www.rmcon.de/englisch/uber_railsys.html
[53] PETER: http://www.citg.tudelft.nl/live/pagina.jsp?id=52fc8b1d-d494-4d579cb0-8865c0de8a85&lang=en
[54] ROMAN: http://w2.siemens.at/roman//
[55] VIRIATO: http://www.sma-partner.ch/vp/vstart.php?lang=e
[56] CAPRES: http://www.fasta.ch/capres/capres_english.htm
[57] FASTA: http://www.fasta.ch/fasta/fasta_english.htm
[58] AFAIG: http://www.fasta.ch/afaig/afaig_english.htm
[59] DEMIURGE:http://recherche.sncf.com/uk/la_recherche_et_ses_domaines/exploitation/demiurge.html
[60] SISYFE:http://recherche.sncf.com/uk/la_recherche_et_ses_domaines/exploitation/sisyfe.html
[61] FAST TRACK II: http://www.multimodalinc.com/prodserv.php?item=mrpass
[62] RAILCAP: http://www.stratec.be/site/FichesEtudes/PlanGBrailcap.htm
[63] LIPARI: http://recherche.sncf.com/uk/projets/uk_lipari.html
[64] OPENTRACK: http://www.opentrack.ch/opentrack/opentrack_e/opentrack_e.html
[65] OPENTIMETABLE: http://www.opentimetable.ch/opentimetable_e.html
[66] VISION :http://www.aeat.co.uk/rail/what/products/vision_fr.htm
[67] TPS/STRAX: http://www.hacon.de/tps_e/index.shtml
[68] CMS: http://www.aeat.co.uk/rail/what/products/cms_fr.htm
[69] PTG : http://www.aeat.co.uk/rail/what/products/ptg_fr.htm
[70] FALKO:www.siemens.com/transportation.
[71] DONS: L. Ingolotti, P. Tormos , A. Lova - A DECISION SUPPORT SYSTEM (DSS) FOR THE RAILWAY SCHEDULING PROBLEM
[72] IRSIM: M.Jelaska - Railway line capacity planning support model
[73] MOM MALLAS: http://www.dsic.upv.es/grupos/gps/MOM/
[74] RADIS: http://www.hacon.de/radis_e/index.shtml
[75] RAILSIM: http://www.railsim.com/
[76] RAILNET II: http://www.fasta.ch/railnet_II/railnet_II_english.htm
[77] RAILPLAN: http://www.comreco-rail.co.uk.html

[15]
[16] Ricci S. - Metodologia di analisi e verifica dei regolamenti di circolazione ferroviaria , Ingegneria Ferroviaria (Gennaio 1992)
[17] Reitani G. - Malaspina R. - La potenzialità di circolazione ferroviaria su linee a singolo binario- un modello di calcolo, Ingegneria Ferroviaria (Agosto 1995)
[18] [19] Florio L., Mussone L. – A new approach to the analytical formulation of the capacity of complex railway systems (1998).
[20] Galaverna M., Sciutto G. – Influenza nella potenzialità di ferrovie a traffico misto, Ingegneria Ferroviaria (Dicembre 1999)
[21] Delfino A. - Galaverna M. Blocco fisso e blocco mobile: analisi di potenzialità Ingegneria Ferroviaria (Giugno 2003)

[22] RFI COM NI ORG 001° del 07 Aprile 2004
[23] Genovesi P. – Ronzino C.D - Flussi e capacità delle linee ferroviarie a doppio binario, Ingegneria Ferroviaria (Luglio/Agosto 2006)
[24] Ferrovie dello Stato – Prefazione Generale all'Orario di Servizio – Ministero dei Trasporti, (2004-2008)