MULTI-METHOD ANALYSIS FOR THE ASSESSMENT OF RAILWAY OPERATION ON THE WESTERN PART OF ROME'S RAILWAY NODE

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ABSTRACT

In the paper an assessment of railway operation on the western part of Rome's railway node is presented; the actual situation and possible future scenarios are analysed. A comparison among results given by different methods for carrying capacity evaluation and simulation models is described. The required input data and the different levels of detail that they can reproduce are explained.

Keywords: railway, carrying capacity, operation, synthetic and analytical methods, simulation

INTRODUCTION AND AIM OF THE STUDY

In the paper an analysis of the railway traffic situation related to the western part of Rome's railway node is presented, making a comparison among different methods for the evaluation of capacity and regularity. The present study investigates the problem of railway capacity evaluation by the identification of best performances and application fields of each method in view to use them in an integrated approach.

The aim of the paper is also to evaluate the carrying capacity by highlighting the actual network's problems and, if necessary, by identifying how to improve services by actions on signalling and operation, through the use of different operational models and limiting infrastructural modifications. Indicators which are able to underline critical situations concerning capacity and safety are defined.

Rome's railway node, like all urban railway nodes, must face many operational problems regarding railway management due to the coexistence of regional, long distance and freight services on a limited infrastructure. The carrying capacity of urban and regional services is not only limited by the layout configuration of stations and lines but also by the technological control solutions, operational rules and operational models.

The study takes into account the constraints given by the topology of the infrastructure and the technological level of interlocking and signalling system. The effects of these constraints

are obviously stronger in the stations, where the contrast between the need to concentrate the train running in a limited period of time (in order to have the most effective integration between regional fixed interval timetable services) and to distribute them in a large period (in order to avoid incompatibility among movement) is self evident.

The choice to analyse the western part of Rome's railway node is due to the complexity of services which work in this area, i.e. some important regional lines, relevant long distance and national/international freight traffic. The main regional services working on this area are the links with relevant poles such as Civitavecchia harbour and Fiumicino airport. Sharing tracks with variety of speeds, therefore, it is necessary to evaluate the present operational plan and to identify problems related to actual capacity and regularity. This detailed evaluation of capacity is important to define the future operational planning.

The study illustrates a comparison among a selection of methods for carrying capacity evaluation. These methods can be synthetic, analytical or based on simulation and in the paper the different levels of detail that the methods are able to reproduce are described. Synthetic methods [10] are not based on timetable and the results can be considered an upper limit of station capacity (e.g. Potthoff method [18]). Analytical methods use the timetable and the operational program of the station, check occupation and release of track circuits and calculate their utilization margins (e.g. method of assigned timetable [6]). Simulation models allow to identify conflicts and to calculate the occupation time of technological devices (switches and blocking sections) and the progressive elastic release of routes, which normally cannot be evaluated by synthetic and analytical methods.

The possibility to integrate the different methods is investigated, a detailed analysis of the actual situation is done and limits and future developments of the research are illustrated.

METHODS OF ANALYSIS

In literature there are lots of methods for the evaluation of the railway carrying capacity both for the stations and for the lines.

Potthoff method defines a set of indicators which evaluate the saturation of the station, the possible margins to increase the utilization rate and allows to compare different structural situations. It needs the topology of the station, works under a hypothesis of random arrivals distribution and doesn't need a scheduled timetable because it only gives a global evaluation of traffic in the reference time. Therefore it is very easy to apply and it represents a very simple method for preliminary calculation.

The method of assigned timetable is used to check the limits of Potthoff method. It considers the scheduled timetable, the random aspects and their consequences on the station capacity. It evaluates both the consequences of delays and the increase of traffic, which may produce remarkable cases of congestion. Several temporal axes are associated to trains movements. These movements are described by the dwell time, by the occupation of entry end exiting routes and by the interdiction of incompatible ones. The results can be summarised by indicators of operation quality, such as the topological distribution of switches where the most part of incompatibility cases are generated.

The class of simulation models can reproduce operational process and random aspects through the application of mathematical algorithms. One of the advantages of these models is the ability to reproduce the real circulation with a great precision, although they need a

higher level of detail for the process modelling with very heavy data processing needs and normally long simulation time. The modelling system [15] [16],developed within the research activity of *DITS – Department of Hydraulics Transports and Road of the University of Rome La Sapienza* (application of Petri Nets to the simulation of railway traffic in lines and stations) belongs to the Discrete Event Systems Class [3] and is based on Petri Nets [12] [14]. This choice is due to the natural vocation of this meta-language, used to solve problems regarding informatics, robotics and automatics, to represent complex discrete events systems, such as railway signalling and control systems.

Concerning the lines, a detailed analysis is done by using a simulation program called OpenTrack©, designed by the Polytechnic of Zurich, developed by the Institute for Transport Planning and Systems (*ETH Zurich*) and adopted by several European railway operators. The software is able to reproduce step by step the traffic on railway infrastructure and to give capacity indicators such as conflicts, delays, perturbations and so on [8].

Synopsis of Potthoff method

The main assumption of Potthoff method is the number of trains which run on the infrastructure and it considers that arrivals have the same probability along the research time. The probability of an arrival, for every line, is the ratio between the sum of occupation and interdiction times of trains which run in the research time. The method doesn't consider the actual timetable and ignores the effects of acceleration and deceleration due to red signals.

The capacity evaluation of the station is studied by making a comparison between the research time and occupation/dwell times. The value is verified if the difference isn't negative. For the resolution, characteristic matrixes and analytical tools are used. Every element of the matrixes identifies a couple of routes and conventional symbols are used to specify the compatibility or incompatibility between every couple.

Thanks to these matrixes it is possible to evaluate the mean number of movements $\bar{n}$ in the station, the mean occupation and interdiction time $\bar{t}$ and the delay R which is generated by N circulations. These mathematical elements define the total regular occupation/interdiction time.

Delays are globally studied as result of singular situations of real incompatibility and their analysis also permits an assessment of the operational quality of the station.

The number $\bar{n}$ is known as Potthoff number and its mathematical formula is:

$$\bar{n} = \frac{N^2}{\sum_{ij} n_i \cdot n_j}$$

where n_i and n_j indicate how often two itineraries i and j are occupied in the research time and the sum at the denominator is extended to all incompatible routes.

The mean occupation time $\bar{t}$ for each route includes decision, formation, running and release times. Interdiction times are generally different from occupation ones and indicate the time when trains cannot run on their route due to the incompatibility with other ones. These times can be reduced with the introduction of elastic release of routes.

The Delays Matrix R_{ij} is built from the matrix n_{ij} and t_{ij}.

To evaluate the operational quality of the station there are two main indicators: the regular utilization rate U_R, which is the ratio between the total occupation/interdiction time and the research time, and the total utilization rate U_T which considers, with the regular occupation/interdiction time, also the total delay generated in the station.

Synopsis of assigned timetable method

The method based on assigned timetable analyses the state of routes along the time. To consider the real railway operation it is necessary to consider the real sequence of arrivals in the station.

The uncertainty of arrivals times causes possible overlaps of occupation and interdiction times and related conflicts in function of the shifting of actual operational plan. To consider them it is possible to use probability distributions of arrivals based on statistic surveys. The assigned timetable doesn't provide with a deterministic capacity evaluation but it is able to manage uncertainties in arrivals as actual probabilistic methods.

The method proposes a graphical and analytical representation of station capacity and offers a simple evaluation tool for fast interpretation of results. It considers the real distribution of trains arrivals; the "arrival on time" must be considered as one of the most possible but not necessary the most probable.

The input data are the station layout, the operational plan and, if necessary, the arrivals distributions. The main results are width and number of free timeframes on each route with the aim to add new trains and the evaluation of delay generated in the station as a consequence of the perturbation on the operational plan.

The first step to apply the method is the schematisation of station and the individuation of routes, the position and typology of signals and track circuits. It selects all itineraries which start or end at a station track and calculates occupation and interdiction times, depending on trains kinematics and elastic (or not) release. The second step is the compilation of the *Routes Matrix* and the definition of arrival rules and timetable. It is possible to draw the occupation-interdiction diagram and evaluate capacity and punctuality indicators. This diagram represents the arrival of a train on a track and its dwell time. Occupation, interdiction and dwell times are drawn on the corresponding temporal axis with different symbologies (figure 1). Occupation and interdiction times are just rectangles whenever the probabilities of arrivals, departures and dwells time are not variable and it is simple to identify overlapped areas. The total delay of the station is the sum of all overlapped areas in the occupation-interdiction diagram and it is also possible to identify on it the delay generation location.

If we introduce the concept of probabilistic behaviour of trains, the rectangles in the occupation-interdiction diagram are replaced by real probability density of arrivals, dwells and departures.
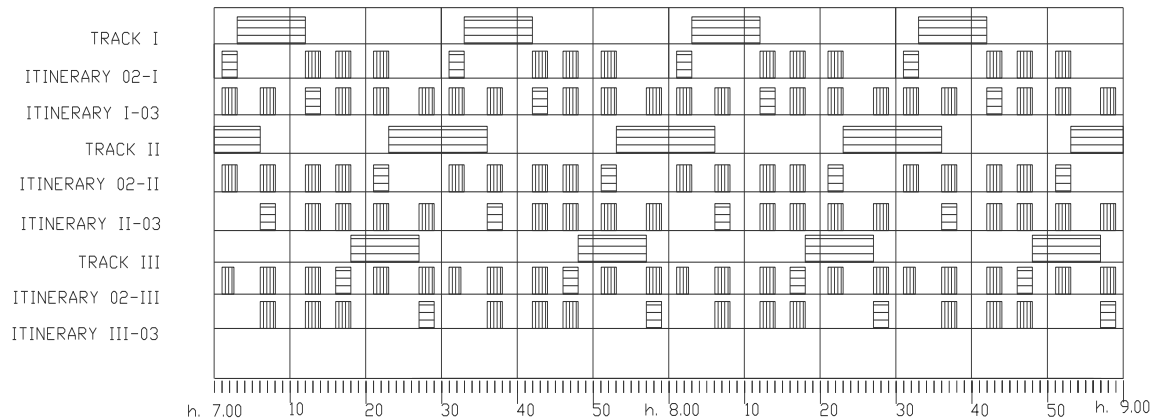
Figure 1 – Example of occupation-interdiction diagram for the method of assigned timetable (Fiumicino Aeroporto)

Petri Nets and simulation model

Synopsis of Petri Nets

The simulation model presented in this paper is based on Petri Nets, a graphical and mathematical modelling formalism used to analyse systems made by objects evolving in discrete events.

A discrete events system is a structure whose state space is discrete and whose state can only change as result of asynchronously occurring instantaneous events over time. A path in this kind of systems is typically linear constant function of time and conventional differential equations are not suitable for describing this discontinuous behaviour. The path can be merely a sequence of states, defining the class of *untimed models*, ore a sequence of states accompanied by the time instants at which state transition take place, which define the class of *timed models*.

In this framework Petri Nets are able to describe and study information processing subsystems which are characterized as being parallel, concurrent, distributed, asynchronous, deterministic or stochastic. Thanks to their simple graphical representation, Petri Nets are used as a visual-communication tool, such as block diagrams and flow charts; as a mathematical tool, they are described by state and algebraic equations and by other mathematical models which are able to control the behaviour of the whole system. Moreover the use of tokens allows to simulate the dynamic and concurrent activities of the different subsystems.

The fundamental elements of these nets are *places,* which define the condition or the state of the system, and *transitions*, which represent the event and modify the state, linked by *arcs*. The current state, or *marking,* is defined by t*okens* and their movement is caused by a change of a transition state. A change happens when all pre-conditions are active, i.e. there are tokens in the input places, and it actives the post-conditions, i.e. the tokens now occupy the output places.

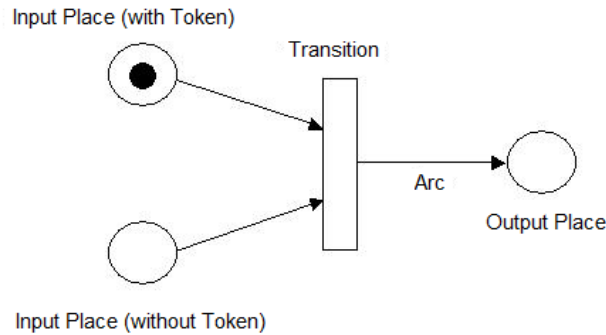In figure 2 a simple Petri Net is shown, with its basic elements.

Figure 2 – Example of Petri Net

In Petri Nets places are normally used to represent physical components of the system or the needed resources to develop some activities or to represent logical conditions. In particular an input place of a transition represents a condition to be satisfied to activate the transition itself. On the other side an output place represents a resource released after the transition action. The token represents the state of the system, the number of available resources, the availability of a machine or a logical condition.

There are different Petri Nets, e.g. condition/events (an element is active when all the conditions are satisfied), time depending and stochastic (when a time parameter is assigned to the transitions to make them firing with a delay, also estimated by stochastic distribution of probability).

Because of the high number of elements they have to take into consideration, the use of specialized software is compulsory. The software used in this paper is Faber© produced by Faber Corporation.

The Faber© language is integrated by standard informatics languages (such as C and C++); it is possible to use software databases to implement the algorithms and in the resolution of complex operation on data.

In Faber© it is possible to associate some attributes to tokens. Tokens become data structures with all net information. Moreover it is possible to attribute to transitions some predicates to be verified to fire, a level of priority, a firing delay (delayed firing after activation) and a releasing delay (delayed release after firing).

Another important feature in Faber© is the possibility to build class of objects and to define Extended Petri Nets. A model can contain a lot of objects of the same class potentially created in different models. The objects exchange tokens from the output places of an object to the input places of another one by links assembled in *portsets*. A link between two portsets is a *linkset*: portsets are connectors used to tie more links and all links between two objects forms a linkset.

In figure 3 portsets and linksets used to link two objects are shown.

In Faber© it is also possible to define a levels hierarchy: basis (places and transitions connected by arcs), intermediate (pages and sub-nets connected by common places), a *Top Level* (objects connected by linksets).

The simulation model presented in this paper is composed by several objects belonging to one class called *Class Units*.
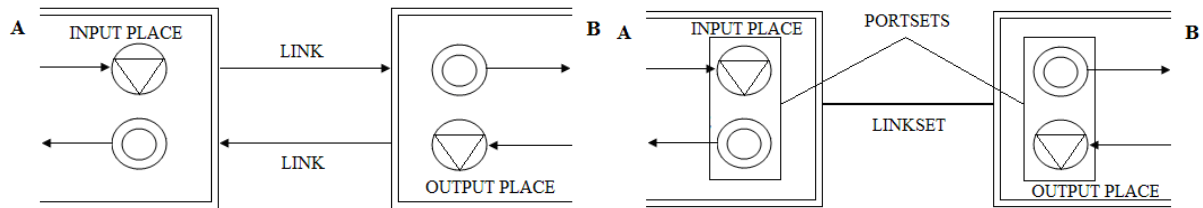
Figure 3 – Input and output places, linksets and portsets – Source: Faber©

Simulation model based on Petri Nets

The simulation model is built with particular Extended Petri Nets and the classes of objects (instances) which are used are:

- Track Circuit;
- Switch;
- Timetable.

The objects defined in these three classes are summarized in a fourth class, the Top Level, and linked by portsets.

In figure 4 the structure of the simulation model is represented.
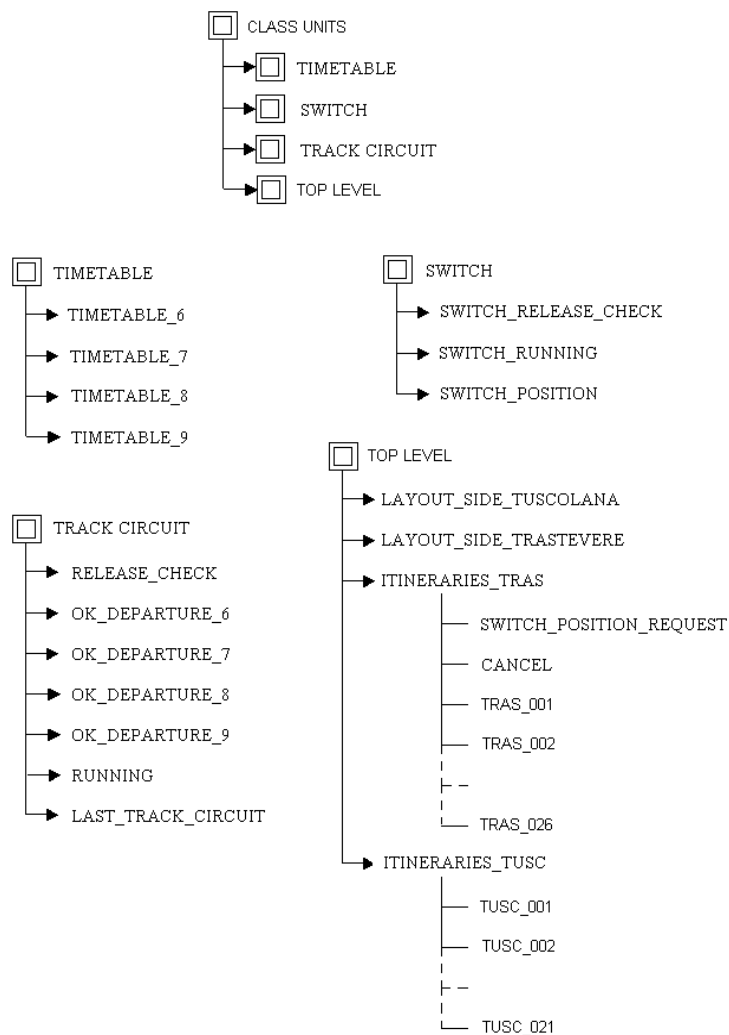

Figure 4 – Scheme of objects used for the simulation in Faber©

The track circuit class is divided into four main subnets; every subnet has a different logical function attributed to the corresponding object:

- Release check (RELEASE_CHECK), allowing to the circuit track to be run by another train because no more train exists on it;
- Confirmation of the possibility to depart for the actual train (OK_DEPARTURE);
- Physical running of the train on the track circuit (RUNNING);
- Occupation of the last track circuit (LAST_TRACK_CIRCUIT) of the route to operate release check and occupation.

The switch class is divided into three main subnets; every subnet has a different logical function which is attributed to the corresponding object:

- Release check (SWITCH_RELEASE_CHECK), allowing the switch to be used by another train because no more are running on it;
- Physical running of the train on the switch (SWITCH_RUNNING);
- Switch position on straight or reverse position (SWITCH_POSITION).

The timetable class, which is also an object because it is composed by an only instance only, has one subnet, called TIMETABLE. In this object it is possible to define, in a parametric way, the departure times by the introduction of a release delay in the transitions, which simulate the scheduled train departure.

In the Top Level the station layout is represented; all infrastructural elements are able to reproduce the real layout but also the function defining the existing itineraries. This object is placed in the Class Unit, as it is known in Faber©.

The token's typology used in the proposed model are two: AM, which must verify route release and the correct switch position, and TRAIN, which analyses physical constraints such as the running of trains on track circuits and switches. Parametric files contain data regarding geometrical infrastructural properties (length of track circuits and switches) and kinematic features (running speed); so it is possible to calculate occupation times and total running time for every route.

The simulation starts from the timetable: an AM token is generated, one per each train, in the *Timetable* subnet. The corresponding route is called, a control of switch position is done and the first and last track circuits are identified; if the objects are occupied, a loop is present in the network regarding the route, it calls the same one until the release check is verified and the train is able to occupy the track. During the train running track circuits and switches are released and made available for other trains.

The output file is a list of data: in this file it is possible to read the number of the train which is simulated, occupation time, running speed, possible revocations of itinerary caused by concurrent trains, occupation and release times of track circuits and switches, call of track circuit and switches for the release check. It is possible to evaluate, on the basis of routes requests and cancellations, the number of trains delayed by others and the corresponding generated or suffered delays.

OpenTrack©

OpenTrack© is a simulation model for railway networks able to reproduce and elaborate the behaviour and the performances of all railway elements: infrastructure, signalling systems, rolling stock and timetable.

Railway traffic is modelled by solving the motion equation and by respecting the information about signals. The input data are divided into three different modules: rolling stock, infrastructure and timetable, as it is shown in figure 5. All the performances concerning train movement are calculated through the information given by the infrastructural layout and by the train features (motion resistances, curves radius, gradients, maximum speed, tractive effort, etc.). Signals regulate sections occupation by allowing or not the train running or by giving information about speed limitations. It is possible to follow the simulation step by step thanks to the animation of trains on the screen.

All the output data, such as acceleration, deceleration, speed, distance, tractive effort, energy consumption are recorded in apposite files which are simply queried to make several analyses, for instance the evaluation of delays. It is possible to identify the critical points of the infrastructure, to improve the traffic by changing the timetable, to plan improvements of services quality and so on.
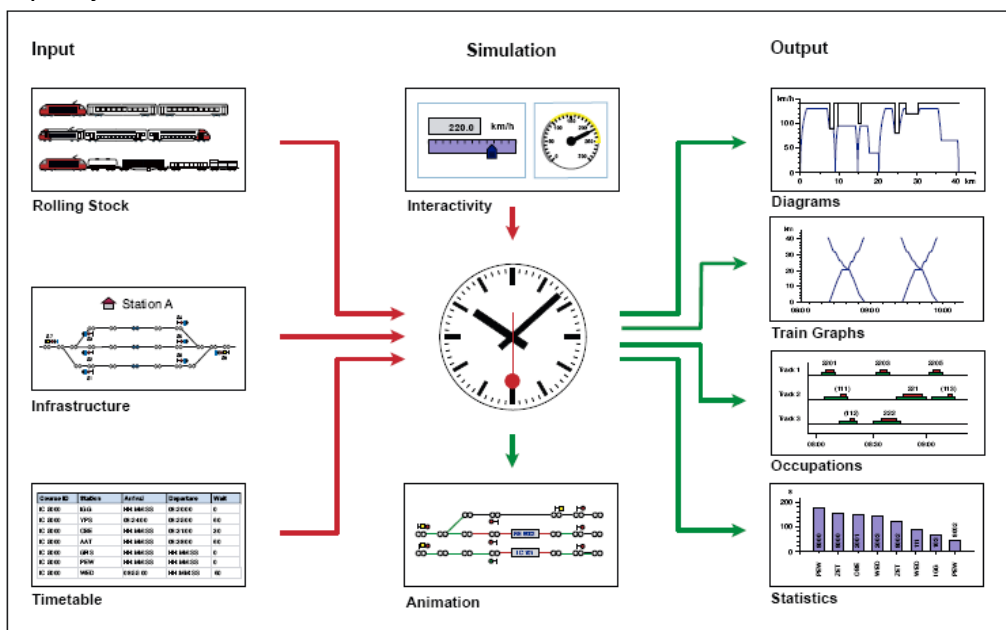

Figure 5 – OpenTrack© working scheme with its main features – Source: OpenTrack© User Manual

In figure 6 an example of station layout by OpenTrack© is shown. The signals define the start points and the end points for the construction of entry and exiting routes. The movements are organized into three different levels: the "signal-signal" route (*Route*), the "station-station" route (*Path*) and the "departure station-arrival station" route (*Itinerary*).
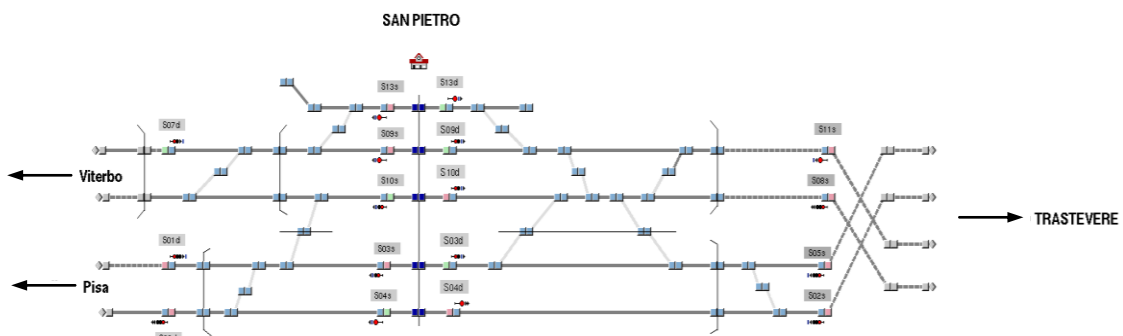

Figure 6 – Example of San Pietro station layout by OpenTrack© – Source: OpenTrack©

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Rolling stock is described by the definition of engines and trailed wagons. The required data are weight, length, maximum speed, adhesion in function of weather conditions and the tractive effort/speed diagram. The combination of these elements allows to model railway traffic by the definition of different trains belonging to different categories, i.e. regional, long distance and freight services. Each train, with its kinematic features, is associated to a course, and it is possible to define different route priority and a level of performance, which indicates the margins of time that a train can use when it is on time or delayed. Each course has got a defined timetable, with the information about the stations the train has to serve, arrival and departure times, dwell times, connections with other trains, distribution of departure delays and so on.

The real time simulation allows to visualize the run of trains on the infrastructure, so to evaluate the timetable features and to highlight conflicts. An iterative procedure between the timetable design and its verification is allowed. In case of criticalities it is possible to design changes in the timetable, the rolling stock or the infrastructure. The train run is drawn on the *train graph*, on which conflicts are self evident, the block section occupation is visualized and it is directly possible to modify the timetable moving the available train-paths.

OpenTrack© may also visualize the speed/distance chart to check the kinematic behaviour of each train.

APPLICATION TO ROME'S NODE

Configuration of the node and typologies of services

Rome's railway node, with its half-belt line, represents the main fulcrum of regional railway system and nation railway traffic (figure 7). The railway network has got a radial structure and the half-belt links regional and national lines. The node connects north lines ("Tirrenica" and "Dorsale Appenninica") to south lines ("Tirrenica sud", line to Cassino and high-speed line Roma – Napoli).

Regional services running the node define the Regional Railway Network (in Italian: rete Ferroviaria Regionale – FR). The lines are:

- FR1 Orte/Fara Sabina – Fiumicino Aeroporto;
- FR2 Roma Tiburtina – Guidonia – Tivoli;
- FR3 Roma Ostiense – Cesano – Viterbo;
- FR4 Roma Termini – Ciampino – Frascati/Albano/Velletri;
- FR5 Roma Termini – Ladispoli – Civitavecchia;
- FR6 Roma Termini – Frosinone – Cassino;
- FR7 Roma Termini – Campoleone – Latina – Formia;
- FR8 Roma Termini – Campoleone – Nettuno.

There is a direct link from Roma Termini to Fiumicino Airport (no stop service "Leonardo Express").

There are also other services both for passengers (long distance) and freight.

Figure 7 – Layout of Rome's node – Source: Italferr S.p.A – Gruppo Ferrovie dello Stato S.p.A.

The stations of the node represent concentration points of lines and trains and they are critical for regular railway operation, due to the variety of services and their different operational organization.

The main stations are Roma Termini, Roma Tiburtina, Roma Ostiense, Roma Tuscolana, Roma Casilina and Roma San Pietro.

The selected part of the network, which the pilot application focuses on, includes the western area of Rome's node, in particular the analysis of three main lines (and the stations which are served) branching from Roma Ostiense station: the Tirrenica line, with San Pietro and Maccarese stations, the links to Fiumicino airport, with Ponte Galeria and Fiumicino Aeroporto stations, and the line to Viterbo, with Cesano station.

The regional lines interested by the study are FR1, FR3 and FR5 and Leonardo Express Service. These services have a fixed interval timetables: FR1 and FR3 services have a frequency of 4 trains per hour per direction; the number of trains is reduced during the first and last hours of the day. FR5 service has a variable frequency from 1 to 2 trains per hour per direction during all the day and Leonardo Express service has a frequency of 2 trains per hours per direction.

In total there are about 500 trains per day which run on this part of the network.

Roma Ostiense, equipped with 15 tracks, is the largest station analysed in this study, interested by regional (FR1, FR3, FR5 and Leonardo Express), long distance and freight services.

San Pietro station represents the point of convergence of regional services FR3 and FR5, also run by long distance and freight services.

Maccarese station can be considered the north-west door to Rome's node run both by FR5, long distance and freight services.

Ponte Galeria station is a transit station along the line to Fiumicino Airport and it is run only by the regional service FR1 and Leonardo Express (except some special freight trains in the early hours of the morning).

Fiumicino Aeroporto station is the terminal station of the line to the airport, equipped with 3 tracks and served by the regional services FR1 and Leonardo Express.

Cesano station is the door station on the line to Viterbo, served only by the regional service FR3. It is the terminus of trains (50% of the total number of trains) which do not continue to Viterbo and is equipped with 4 tracks linking a double track line section (from Rome) with a single track section (to Viterbo).

The pilot application includes the description of infrastructural and technological systems and the calculation of railway capacity making, at the end of the study, some assumptions about possible traffic increases and operational situation.

Actual railway carrying capacity assessment

A first analysis about the number and typologies of trains running the western area of Rome's node is summarized in table I.

Data are divided by line, period of the day (2 hours periods) and typology of services, in particular regional (R), Leonardo Express (LEO), Intercity (IC), Interregional (INT), Eurostar (ES) and freight (F).

The data in the table are referred to Roma Ostiense timetable (valid from December 2008 to December 2009) and a working day is considered.

The application of Potthoff method provides with the results shown in figure 8.

Table I – Number of trains on each line during the day (by Roma Ostiense Timetable)

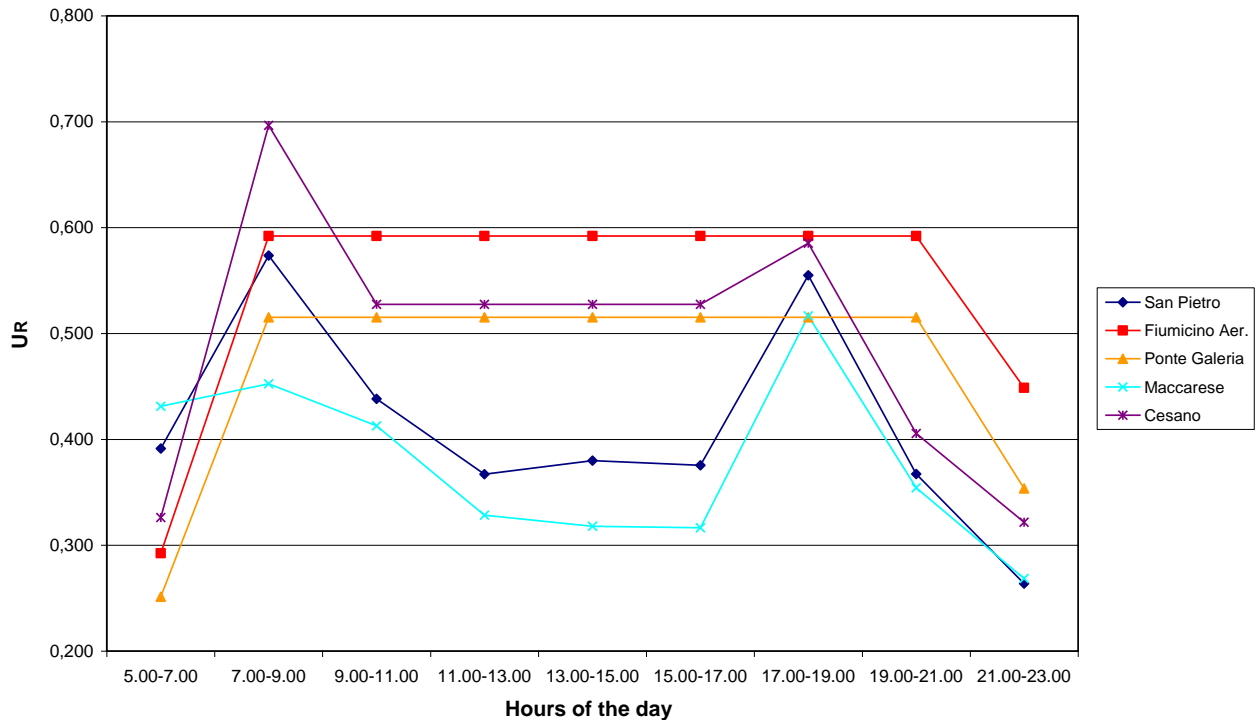|	Line									
	Viterbo		Fiumicino			Tirrenica Line					
Hours	R	TOT	R	LEO	TOT	R	IC	INT	ES	F	TOT
03.00-05.00	1	**1**	0	0	**0**	0	0	0	0	1	**1**
05.00-07.00	7	**7**	4	3	**7**	5	3	0	0	3	**11**
07.00-09.00	22	**22**	16	8	**24**	7	3	3	0	0	**13**
09.00-11.00	16	**16**	16	8	**24**	6	1	2	1	2	**12**
11.00-13.00	16	**16**	16	8	**24**	6	4	2	0	2	**14**
13.00-15.00	16	**16**	16	8	**24**	7	1	1	0	1	**10**
15.00-17.00	16	**16**	16	8	**24**	6	2	2	0	3	**13**
17.00-19.00	20	**20**	16	8	**24**	7	3	2	0	2	**14**
19.00-21.00	14	**14**	16	8	**24**	6	1	2	1	3	**13**
21.00-23.00	9	**9**	12	8	**20**	6	3	2	0	1	**12**
23.00-05.00	2	**2**	5	6	**11**	2	1	1	0	0	**4**
TOT	**139**	**139**	**133**	**73**	**206**	**58**	**22**	**17**	**2**	**18**	**117**

Figure 8 – Utilization rate for each station by daily periods

Fiumicino Aeroporto and Ponte Galeria stations present a similar trend because they are run by the same line and by the same typology of services. Fiumicino Aeroporto has the same value of utilization rate during the central part of the day. The same considerations are valid for Ponte Galeria, which has lower utilization rates than Fiumicino Aeroporto, which is a terminal station, because of the topology of the station and the occupation and interdiction times of routes.

Cesano station has higher values of utilization rates during the peak period in the morning and in the evening. The higher value obtained in the case of Cesano are due to the high traffic and to the particular structure of the station, which is terminus for the urban trains and connects a double track line on a side with a single track line on the other side.

Maccarese and San Pietro stations have similar utilization rates, higher during the peak periods (5.00 – 7.00 p.m.).

Potthoff method only gives a synthetic analysis of a station and it is not able to explain, for instance, the real distribution of trains and the consequent free intervals when new paths might be added. To provide to this limit the assigned timetable method is used; it is able to give additional graphical and numerical solutions for a very simple analysis of the state of occupation of each route and station track.

In this point of view the assigned timetable method is used to evaluate the situation of Fiumicino Aeroporto and San Pietro stations (figure 9). The selected period of analysis (7.00 – 9.00 a.m.) includes the highest number of trains and occupied routes. The choice to apply the pilot application on these stations is due to the possible comparison between two different station typologies, a terminal station (Fiumicino Aeroporto) and an interconnection/transit station (San Pietro).

In table II for each route the occupation time, caused by the physical running of trains or by the occupation due to trains which run on incompatible itineraries, and the rate compared to the total available time are reported.
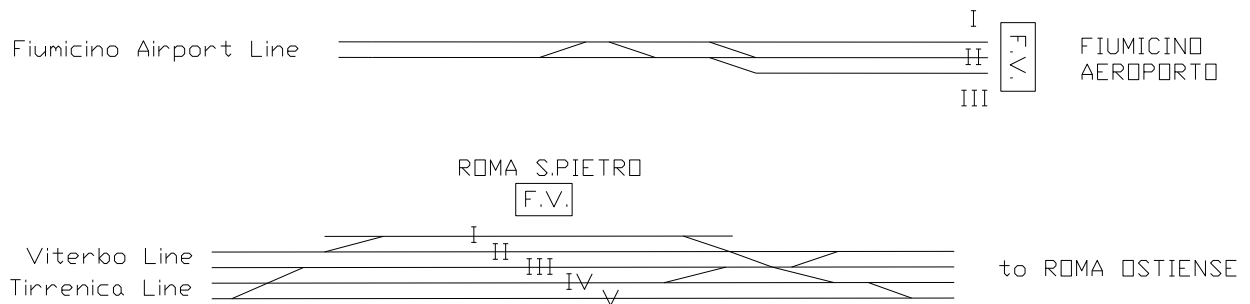

Figure 9 – Layout of Fiumicino Aeroporto and San Pietro stations

Table II - Occupation times and occupation rates by route for Fiumicino Aeroporto and San Pietro stations

Station	Route		Occupation time	%
	From	To	[s]	[/]
FIUMICINO AEROPORTO	F. Airport Line	Track I	2084	28,9
	Track I	F. Airport Line	3156	43,8
	F. Airport Line	Track II	2620	36,3
	Track II	F. Airport Line	2640	36,6
	F. Airport Line	Track III	2992	41,5
	Track III	F. Airport Line	2124	29,5
SAN PIETRO	Viterbo Line	Track II	4130	57,4
	Track II	Roma Ostiense	4130	57,4
	Roma Ostiense	Track III	1968	27,3
	Track III	Viterbo Line	1968	27,3
	Tirrenica Line	Track IV	3068	42,6
	Track IV	Roma Ostiense	3068	42,6
	Roma Ostiense	Track V	1076	14,9
	Track V	Tirrenica Line	1076	14,9

By a careful analysis of the obtained data, it is also possible to understand the distribution of trains during the analysis period, in particular for the pilot application on San Pietro (peak hour of the morning) it is possible to notice that the inbound trains are more than the outbound trains due to the commuting movements to the city.

The comparison among methods is done on the basis of different indicators (table III):

➤ number of conflicts (N_C);

➤ total delay (D_T);

➤ mean delay per delayed train (D_{mdt}), i.e. rate between the total delay and the number of conflicts;

➤ mean delay (D_m), i.e. the rate between the total delay and the total number of trains in the research time.

Table III – Results of Potthoff and assigned timetable methods for Fiumicino Aeroporto and San Pietro stations (7.00 – 9.00 a.m.)

	Fiumicino Aeroporto		San Pietro	
	Potthoff	**Assigned T.**	**Potthoff**	**Assigned T.**
N_c	/	0	/	0
D_T [s]	27	0	3,8	0
D_{mdt} [s]	/	0	/	0
D_m [s]	1,2	0	0,1	0

Potthoff method, working under hypothesis of random arrivals, gives an upper limit to the definition of station capacity and it can only give a global evaluation of traffic in the research time. The assigned timetable, considering the scheduled timetable, is able to define with higher precision the operational situation by verifying the presence of conflicts. In fact results shown that there are no conflicts situations in the period of analysis.

More comparative elements are provided by the more complex station of Roma Ostiense [4]. The simulation model based on Petri Nets is applied to this pilot application. The period of analysis is from 7.00 to 9.00 a.m., when there are the major number of trains and used routes. The theoretical timetable is applied.

The regular utilization rate U_R and the total utilization rate U_T calculated by Potthoff method are respectively 0,41 and 0,45.

In table IV obtained results are shown.

Table IV – Comparison between methods for Roma Ostiense station (7.00 – 9.00 a.m.)

	Potthoff	**Assigned Timetable**	**Simulation (Petri)**
N_c	/	3	3
D_T [s]	1835,7	91	76
D_{mdt} [s]	/	30	25
D_m [s]	16	0,79	0,66

To evaluate the stability of results, the same analysis is done on the basis of effective timetable referred to a working day and on the basis (perturbed scenario) of a timetable with the application of mean delays to the theoretical scheduled timetable. The applied mean delays are calculated on the basis of measured delays for a working day; they are registered for all trains entering and leaving from Roma Ostiense, depending on the running line and on services typology (long distance, regional, freight).

Moreover, to underline the topological constraints of the station layout, i.e. the points which generate higher delay values, the station is divided into five sub-stations (called A, B, C, D and E) which can be critical parts of the station layout (bottlenecks). For each sub-station the three methods are applied considering them independently.

The analysed results are *n* (number of used itineraries), *N* (number of circulations), U_R (regular utilization rate), U_T (total utilization rate), D_T (total delay), N_C (number of conflicts) and D_{mdt} (mean delay for delayed train). In tables V and VI results are shown and in figure 10 and 11 obtained mean delays are represented.

Potthoff method gives the same values for the sub-stations for the two scenarios because the number of total trains doesn't change. Sub-station E has higher regular and total utilization rates. The assigned timetable and the simulation model confirm the results

obtained by Potthoff method and highlight that also sub-station A and C have high delay values.

Table V – Effective timetable of a working day of Roma Ostiense – results

Sub-station	n	N	Potthoff				Assigned T.				Simulation (Petri)			
			U_R	U_T	D_T	D_m	N_c	D_T	D_{mdt}	D_m	N_c	D_T	D_{mdt}	D_m
A	11	38	0,29	0,30	211	6	4	281	70	7	3	176	59	5
B	6	20	0,31	0,34	306	15	1	96	96	5	2	97	97	5
C	7	29	0,29	0,30	211	7	4	281	70	10	1	85	85	3
D	5	19	0,21	0,22	127	7	1	105	105	6	0	0	0	0
E	10	33	0,45	0,53	813	25	6	497	83	15	8	466	58	14

Table VI – Timetable with the application of mean delays to the theoretical scheduled timetable of Roma Ostiense – results

Sub-station	n	N	Potthoff				Assigned T.				Simulation (Petri)			
			U_R	U_T	D_T	D_m	N_c	D_T	D_{mdt}	D_m	N_c	D_T	D_{mdt}	D_m
A	11	38	0,29	0,30	211	6	6	288	48	8	3	197	66	5
B	6	20	0,31	0,34	306	15	2	118	59	6	1	37	37	2
C	7	29	0,29	0,30	211	7	4	215	53	7	0	0	0	0
D	5	19	0,21	0,22	127	7	2	156	78	8	0	0	0	0
E	10	33	0,45	0,53	813	25	4	394	98	12	6	303	50	9

Figure 10 – Effective timetable of a working day of Roma Ostiense – mean delays D_m
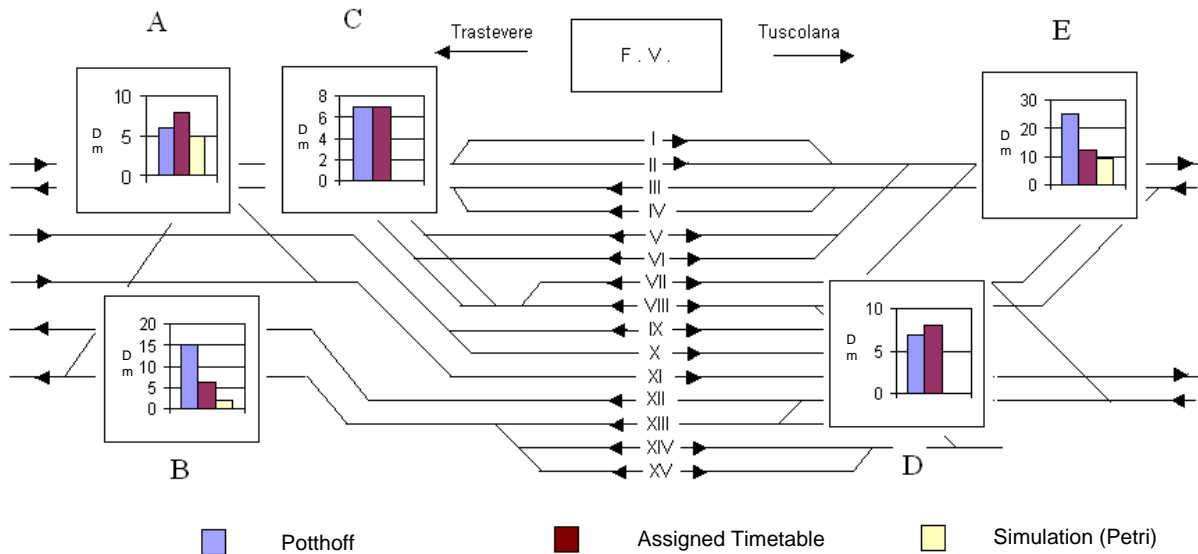
Figure 11 – Timetable with the application of mean delays to the theoretical scheduled timetable of Roma Ostiense – mean delay D_m

OpenTrack© is applied to analyse railway traffic along all the lines, in particular the conflicts between trains which generate delays. The analysis is performed from Roma Ostiense to Fiumicino Aeroporto, Maccarese and Cesano covering the whole day (24 hours). By the train graph it is possible to define when and where conflicts are generated and responsible trains, their entity and the block sections with their occupation time (in OpenTrack© different colors indicate different train categories).

In figure 12 an example of train graph is shown as well the results by indicators for all the lines in table VII.
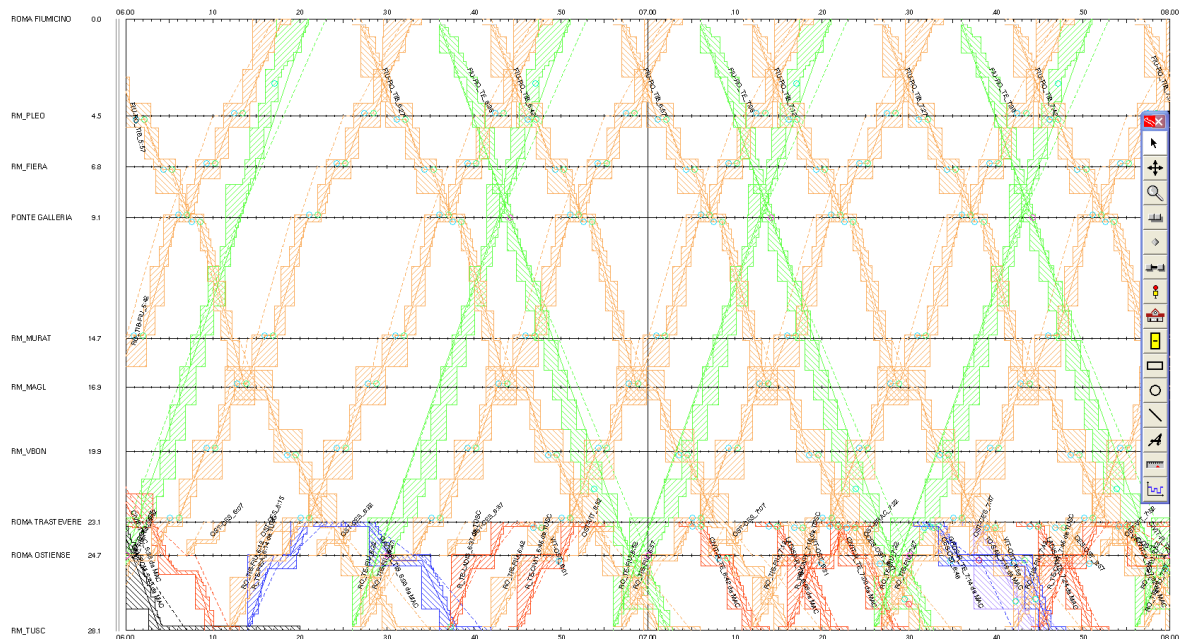

Figure 12 – Train graph with block sections (Fiumicino line) by OpenTrack©

Table VII – Results obtained for the actual timetable with OpenTrack©

	Viterbo Line	**Fiumicino Line**	**Tirennica Line**
N_c	3	1	6
D_T [s]	341	212	2215
D_{mdt} [s]	114	212	369
D_m [s]	2,45	1,04	18,93

The delays which actually exist are due to the conflicts in the scheduled timetable. In particular in the case of Viterbo line the delays are due to direct trains scheduled during the peak periods conflicting with the trains with fixed interval timetable, as it occurs for the Tirrenica line, where the delays are caused by the coexistence between regional and long distance traffic.

Study of possible future scenarios

The considered scenarios include an increase of Leonardo Express service on Fiumicino Line and an increase of the regional service FR5 on Tirrenica line. Moreover a further study is the extension of these scenarios by considering delays for entering and exiting trains (perturbed situation); differences from the situation without delays are explained.

The comparison among the different scenarios is carried out by the total delay D_T (calculated for Potthoff, assigned timetable and simulation based on Petri Nets), the total utilization rate U_T (calculated by Potthoff method) and the mean delay per train D_{mdt} (calculated for the three methods). It is also possible to associate the total utilization rate U_T and mean delay D_m, making feasible a correlation between capacity evaluation and traffic regularity. In the study the peak period from 7.00 to 9.00 a.m. of a working day is considered.

The global panel of planned scenarios includes the three scenarios analysed before for the actual carrying capacity assessment ("scenario 1" based on the theoretical scheduled timetable, "scenario 2" based on actual timetable referred to a working day and "scenario 3" based on the application of mean delays to scenario 1) plus:

> ➢ Scenario 4: theoretical scheduled timetable with increase of Leonardo Express service (from 2 to 4 trains/hour per direction);
> ➢ Scenario 5: application of mean delays to scenario 4;
> ➢ Scenario 6: theoretical scheduled timetable with increase of Leonardo Express service (from 2 to 4 trains/hour per direction) and the regional service FR5 (from 3/5 to 6 trains/hour per direction);
> ➢ Scenario 7: application of mean delays to scenario 6.

In figure 13 the trend of mean delays per train for scenarios 1-4-6 (without perturbations) is shown.

In figure 14 the trend of mean delay per train for scenarios 3-5-7 (with perturbations) is shown.
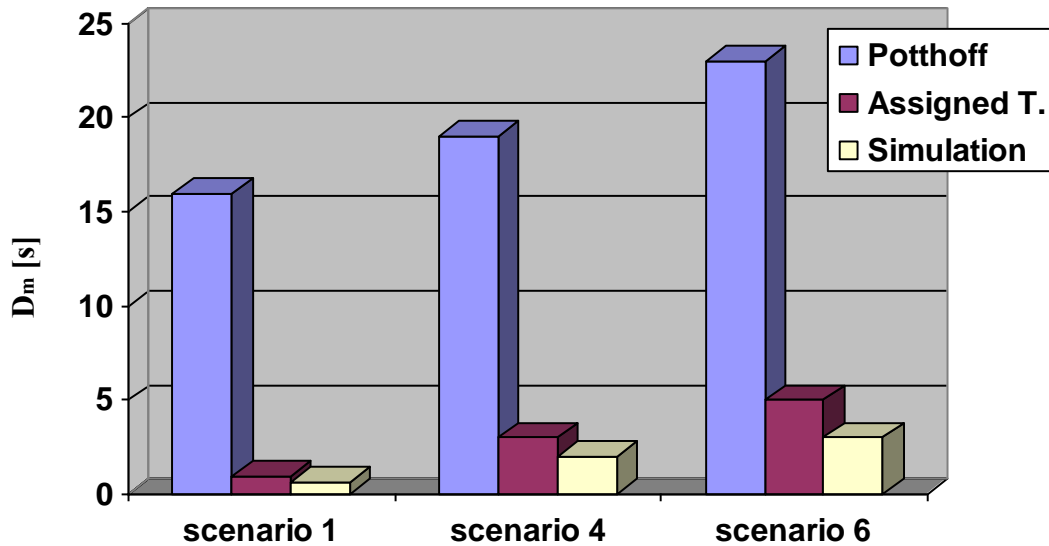
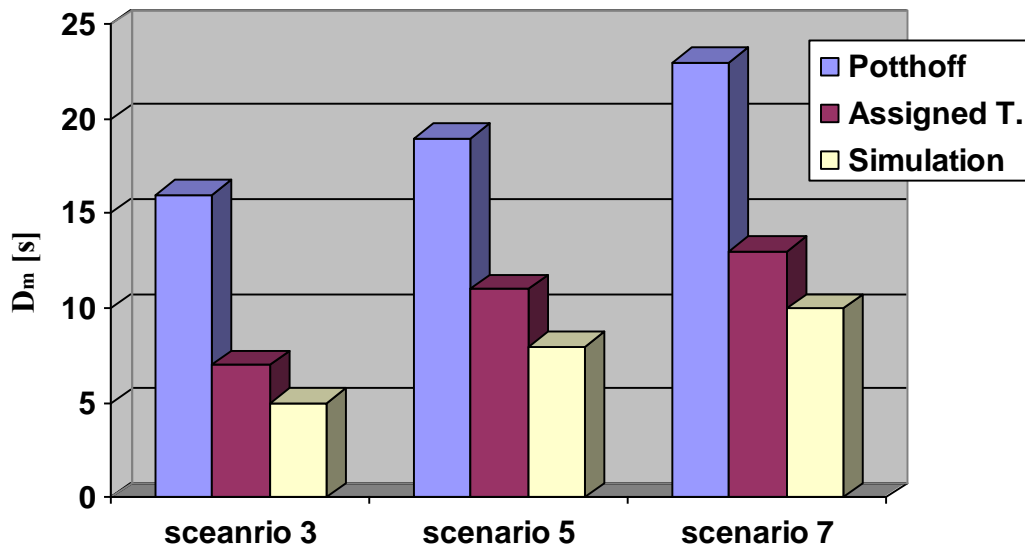Figure 13 – Mean delays for scenarios 1-4-6 (timetable without perturbations)

Figure 14 – Mean delays for of scenarios 3-5-7 (timetable with perturbations)

Potthoff method provides with higher values of mean delay than the other two methods because it evaluates delays independently upon the timetable. This operational condition, which represents the maximum operational disorganisation, can be considered an upper limit to the possibility to generate delays.

For all methods, the introduction of delays, i.e. a perturbation, causes an increase of total and mean delays compared to scenarios with unperturbed timetable; it shows a worsening of traffic quality because trains don't respect the scheduled timetable, which is considered one of the "best" possible operational plan.

A more detailed comparison between assigned timetable and simulation methods shows that the first one gives higher values than the second one. Simulation is able to reproduce timetable flexibility because it is able to perform in real time a dynamic evaluation of delays and to update operation due to perturbations which is not possible with the assigned timetable method.

A difference between Potthoff and assigned timetable methods is due to the fact that the first one distributes low delays in a lot of conflicts, as well as the second one highlights a few conflicts with high delays. A higher number of simulated scenarios should confirm this statement.

Figure 15 illustrates the trend of utilization rate U_T calculated by Potthoff method versus the mean delay D_m for unperturbed scenarios 1-4-6.

For a fixed utilization rate U_T it is possible to calculate the corresponding value of mean delay D_m for the three methods (Potthoff, assigned timetable and simulation based on Petri Nets). On the other side if we set a feasible value of mean delay D_m it is possible to valuate for the three methods the expected total utilization rate U_T.

In figure 16 the trends of total utilization rate U_T for the perturbed scenarios 3-5-7 are shown.
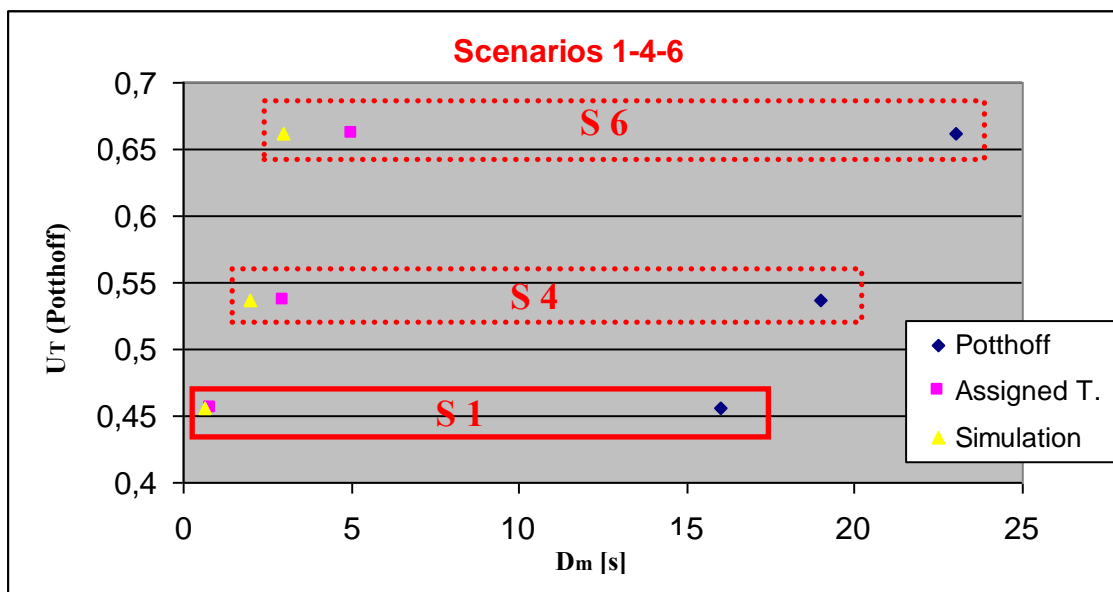

Figure 15 – Utilization rate versus mean delay per scenario S (timetable without perturbations)
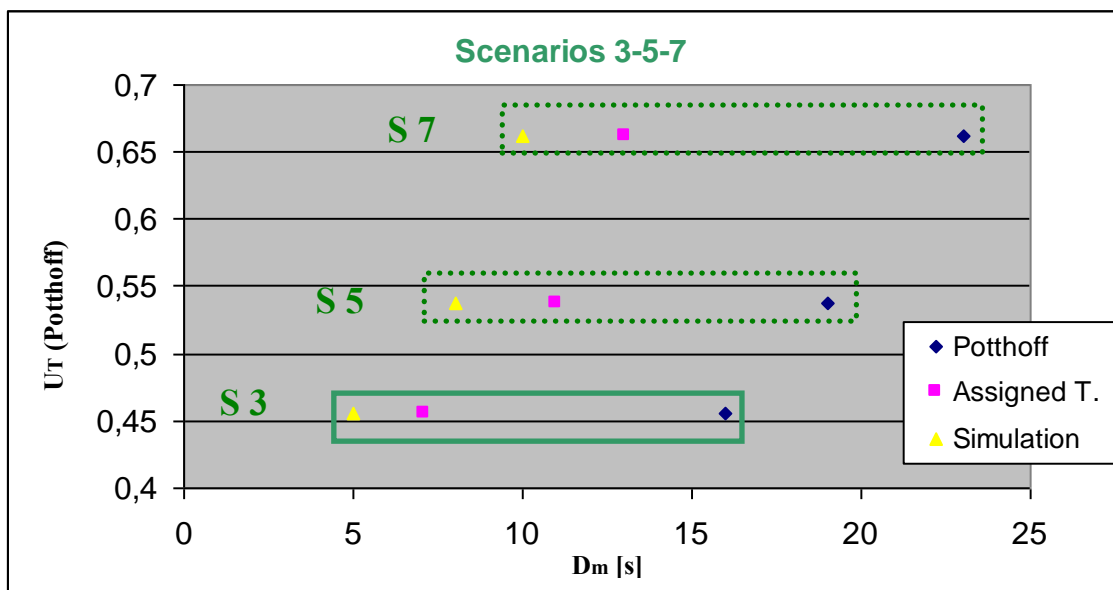

Figure 16 – Utilization rate versus mean delay per scenario S (timetable with perturbations)

It is self evident that today (scenario 1, i.e. scheduled timetable), Roma Ostiense station has a total utilization rate U_T of about 45% (calculated by Potthoff); the corresponding mean delay D_m is 16 seconds for Potthoff, less than 1 second for the others. On the other side in case of perturbed operation (scenario 3) the corresponding mean delay is 16 seconds for Potthoff, about 7 seconds for the assigned timetable and 5 seconds for the simulation model based on Petri Nets.

In the first case (scenario 1) the mean delays obtained with assigned timetable method and the simulation model are nearly the same and the mean delay for Potthoff is higher. In the second case (scenario 3) the difference between the mean delay for Potthoff and the mean delay calculated with assigned timetable method and the simulation model is reduced; on the other hand the difference between the mean delay for the assigned timetable and the simulation model is increased.

A further development of the study is the increase of regional traffic by using fixed interval timetables; different increases are studied for the three lines (Viterbo, Tirrenica and Fiumicino).

In table VIII the mean delays obtained by OpenTrack© simulation are shown.

It is possible to notice that the situation on the Tirrenica line is more critical than the other ones: in fact on this line different services (regional, long distance and freight) are running with different technical and operational features, e.g. speed, length, weight and stops, which cause higher values of delay and difficulties for their integration.

In figures 17÷20 the correlation between increase of frequency and number of conflicts N_C, total delay D_T, mean delay for delayed train D_{mdt} and mean delay for train D_m for the three lines are shown.

Table VIII: mean delays for train obtained for the increased scenarios with OpenTrack©

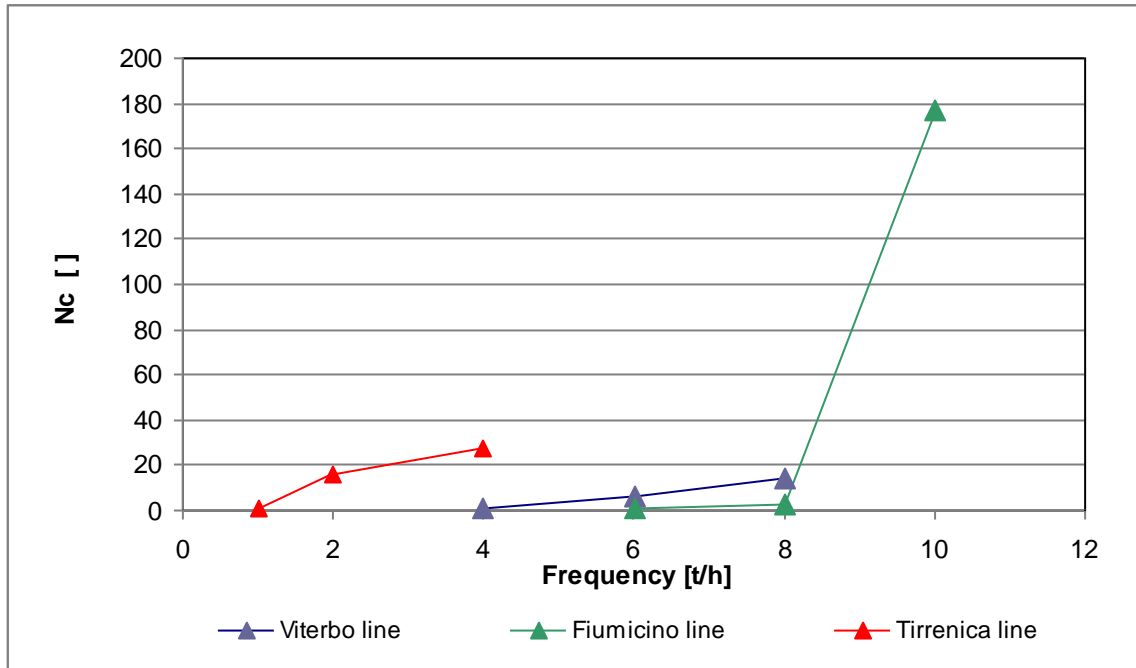|		Timetable		
		Actual Situation	**Scenario I**	**Scenario II**
Viterbo Line	**Frequency [t/h]**	4	6	8
	N_c	3	6	14
	D_T [s]	341	1186	2574
	D_{mdt} [s]	114	197,6	183,85
	D_m [s]	2,45	6,14	10,4
Fiumicino Line	**Frequency [t/h]**	6	8	10
	N_c	1	3	177
	D_T [s]	212	302	26832
	D_{mdt} [s]	212	100,7	151,6
	D_m [s]	1,04	1,1	74,5
Tirrenica Line	**Frequency [t/h]**	1	2	4
	N_c	6	16	27
	D_T [s]	2215	5101	9747
	D_{mdt} [s]	369	319	364,7
	D_m [s]	18,93	38,35	55,3

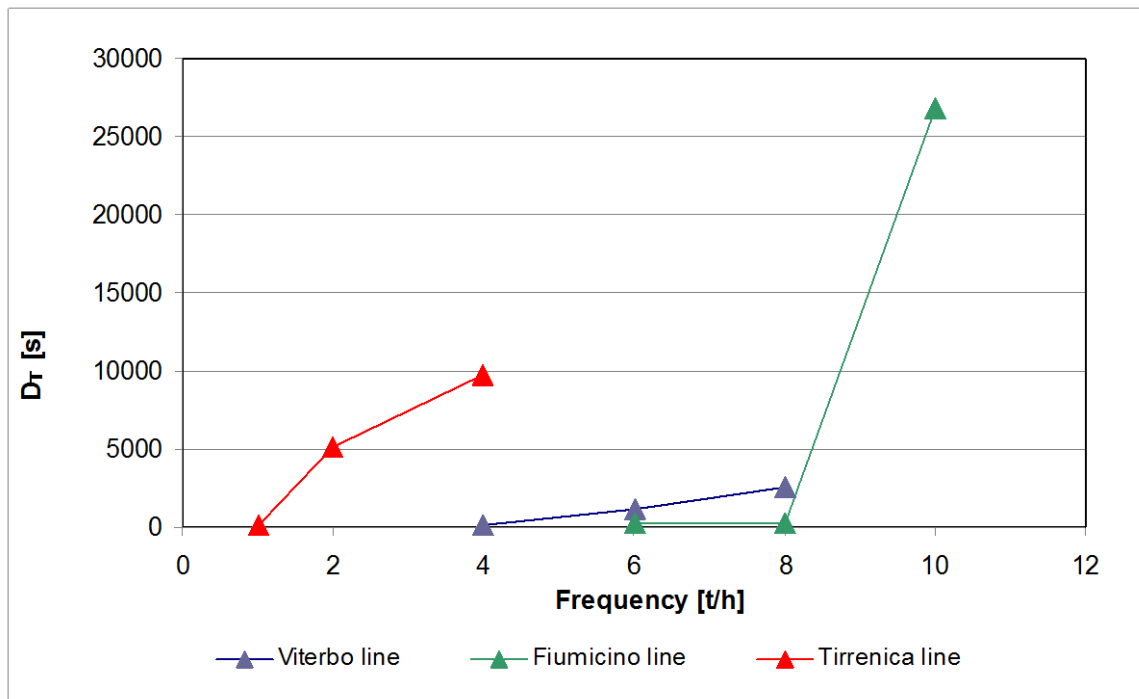Figure 17 – Number of conflicts in future scenarios by OpenTrack©

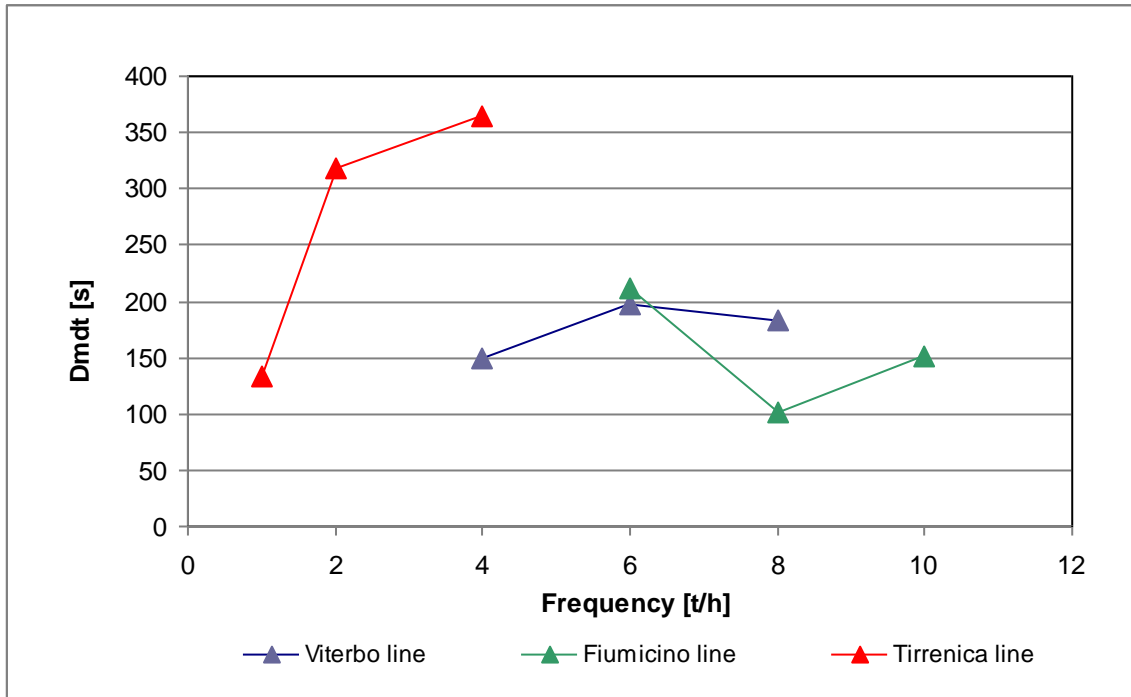Figure 18 – Total delay in future scenarios by OpenTrack©

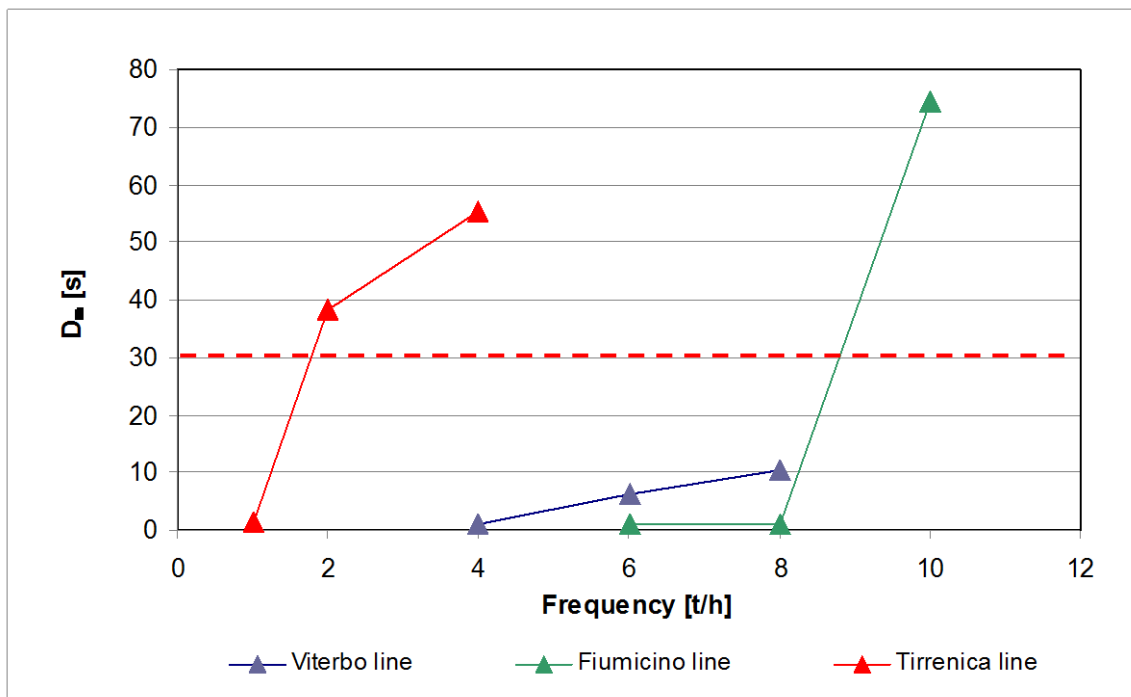Figure 19 – Mean delay for delayed train in future scenarios by OpenTrack©

Figure 20 – Mean delay for train in future scenarios by OpenTrack©

The increase of traffic may be considered feasible if the corresponding increase of mean delays D_m is not exceeding a fixed threshold. In this study this threshold is established at 30 seconds per train (red dotted line) as entity not relevant for the passengers perception (usual timetable approximation at 1 minute).

On this basis the increases of frequency are feasible within this limits (figure 20):

- Viterbo line: from 4 to 8 trains/hour;
- Fiumicino line: from 6 to 8 trains/hour;

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- Tirrenica line: from 1 to 2 trains/hour (anyway with mean delay per train exceeding 30 seconds)

CONCLUSIONS AND FUTURE DEVELOPMENTS

In the paper a study on the western part of Rome's node is presented.

The capacity analysis has been carried out by using different methods and by highlighting analogies and differences among them. The problems concerning the infrastructural situation of the node, the carrying capacity limits of stations and lines are studied in the present and in future operational scenarios.

The innovative contribution of the paper to the problem of railway capacity estimation is based on the identification of best performances and application fields of each method in view to use them in an integrated approach.

Potthoff method produces results which can be considered an upper limit of station capacity because it considers the traffic independently by the timetable. On this basis a new station may be designed, saturation levels may be identified and the operational situation may be sketched.

Assigned timetable method works on the real timetable and calculates with greater precision the marginal capacity of the station; it is valid for the check of a timetable, the occupation of single routes and the identification of paths available for new trains.

The simulation allows to identify the conflicts and to calculate the occupation time of technological devices (switches and block sections) and the progressive elastic release of routes, which normally cannot be evaluated by synthetic and analytical methods but, often, with very heavy data processing systems and very long simulation time.

Values of capacity and regularity may be verified by a larger amount of simulations particularly for the assessment of possible traffic increases, both for the scenarios studied in the paper and for the other services operated in the node.

Moreover local analyses on the station layouts will be helpful to highlight critical parts of the station, e.g. by splitting the station in sub-stations, as it is shown for the case of Roma Ostiense.

Concerning the operational situation, the results show the difficulty to increase traffic on line run by trains of different typologies, such as on Tirrenica line. A solution to improve and increase railway traffic might be to adopt signalling systems with reduced block sections near stations. This fact will allow to increase capacity, with as much as possible constant headway between trains, drawing them up near stations and spacing them on line. On the other side it is possible to think to specialize the lines depending on traffic typology and to limit interferences among them. It will allow to increase the global carrying capacity thanks to the concept of homogeneous speed timetable with possible higher regularity and increase of frequencies.

The study has finally highlighted some infrastructural and technological problems, in particular concerning Roma Ostiense station, capable to cause bottlenecks.

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