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Capacity assessment of railway infrastructure

Tools, methodologies and policy relevance in the EU context

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Abstract

The transport sector is increasingly faced with several issues related to the rising of traffic demand such as congestion, energy consumption, noise, pollution, safety, etc.. Due to its low external and environmental costs, railway can be considered (together with inland waterways and short-sea-shipping) as a key factor for the sustainable development of a more competitive and resource-efficient transport system (European Commission, White Paper 2011). In order to reinforce the role of rail in European transport, there is a strong need of addressing the efficiency of the system and customers' satisfaction through targeted actions, i.e. rising reliability and quality of service. This becomes particularly pressing as many parts of the existing railway infrastructures are reaching their maximum capacity thus shrinking their capability to provide users and customers a higher or even adequate level of service. Taking also into account that transport demand forecasts for 2030 clearly show a marked increase of rail activity across the whole Europe, we aim to address the issue of rail congestion in the context of relevant policy questions***: Is the actual rail Infrastructure really able to absorb forecasted traffic, without significant impacts on punctuality of the system? Would the already planned interventions on the European railway infrastructure guarantee an adequate available capacity and consequently adequate reliability and level of service? To which extent would the coveted competition in an open railway market be influenced by capacity scarcity, mainly during peak hours or along more profitable corridors?***

An accurate estimation of capacity of the rail network can help answer these questions, leading policy makers to better decisions and helping to minimize costs for users. In this context this report explores the issue of capacity scarcity and sets this issue in the context of other relevant policy issues (track access charges, cost/benefit and accessibility measures, maintenance programmes, freight services' reliability, external, marginal congestion or scarcity cost for rail, impacts of climate changes, etc.), providing a methodological review of capacity and punctuality assessment procedures. To better explore the real applicability and the time and/or data constraints of each methodology, the study reports some practical applications to the European railway network. Finally in the last section the report discusses the topic from a modelling perspective, as the quantitative estimation of railway capacity constraints is a key issue in order to provide better support to transport policies at EU level.

1 Introduction

European transport is a key sector enabling growth and a driving force behind the internal market. The transport sector is increasingly facing several issues calling into question sustainability, from environmental protection to security of supply regarding energy sources, as well as economic efficiency and financial viability.

Due to its low external and environmental costs, railway can be considered (together with inland waterways and short-sea-shipping) as a key for the sustainable development of a more competitive and resource-efficient transport system (European Commission, White Paper (2011) [1]), particularly for medium- and long-distance travel.

In the recent years, the European Union has devoted significant efforts to improve the competitiveness of the rail mode at a European scale. Among the many issues identified by European policy makers, rail network bottlenecks are becoming a cause of concern particularly in certain corridors as increasing traffic eventually leads to congestion and degraded performance of the railway system. Delays and unreliability of services have a far-reaching impact, from Infrastructure Manager (IM) or Railway Undertakings (RU) to travellers and the overall society. There is thus the need to boost the productivity of infrastructure assets in order to improve the reliability and capacity of the whole system. Additional considerations arise from the fact that the objectives of the relevant stakeholders (IMs and RUs) are not always aligned: while the latter are mainly concerned with the provision of an efficient timetable and schedule of services, the former face the issue of capacity allocation and related infrastructure access charges.

An accurate estimation of capacity of the rail network is a starting point for a more efficient exploitation and deployment of railway infrastructure, better supporting policy and helping to minimize costs for users. Railway capacity is a complex issue depending not only upon infrastructure characteristics (e.g. signalling system, number of tracks, etc.), but it is also conditioned by a number of other elements such as speed reductions due to track conditions (so the maintenance program), length of trains, heterogeneity and frequency of services (timetable data), and so on. Therefore, capacity estimation requires a robust methodology and, unsurprisingly, very detailed data of the railway system (infrastructure and timetables). This report provides an extensive review and practical comparison of available capacity and punctuality assessment methodologies and their limitations in terms of level of detail of the required data; we also identify and evaluate a manageable and streamlined approach for a large-scale analysis based on well-established formulations for travel time, delay and utilized capacity. This becomes particularly relevant in the absence of detailed infrastructure and timetable data in order to evaluate fundamental operational and performance indicators.

Finally, we provide a summary of relevant aspects of rail traffic simulation in the context of large-scale network-based transport modelling, underlining the requirements regarding data and methodological constrains.

2 Why this report? Policy relevance of capacity scarcity

Railway capacity is a complex, multifaceted problem (McClellan (2006) [19]) affecting directly or indirectly Rail Undertakings (RUs), Infrastructure Managers (IMs) but also policy makers and above all users. A recent consultation carried out for the 4th Railway Package (see EC DG MOVE – European Commission, Directorate General for Mobility and Transport (2013) [23]) showed that there are still hitches with reliability and punctuality of rail services (mainly freight) all across Europe. Clearly this lack of predictability affects railway transport competitiveness by causing several inconveniences (also in terms of additional costs) to customers and other stakeholders. Of course the issue presents different characteristics across the various countries; some Member States (e.g. Greece, Romania and Portugal) are closing several lines due to budgetary constraints, while other parts of the European network are heavily congested. Set against this background, and taking also into account the forecasts of increasing rail traffic across the whole Europe from 2010 to 2030 (see for example EC DG ENER - Directorate General for Energy, EC DG CLIMA - Directorate General for Climate Action & DG MOVE (2013) [24] [25] or Sessa & Enei (2009) [26]), some policy questions draw our attention:

- Is the actual rail infrastructure really able to absorb the forecasted/expected traffic, without significant impacts on punctuality of the system?
- Would the already planned interventions on the European railway infrastructure (including the installation of the ERTMS, European Rail Traffic Management System where intended (see UIC - International Union of Railway (2008) [7], UIC (2010) [8], UNIFE – Association of the European Rail Industry (2012) [27] OECD – Organisation for Economic Cooperation and Development (2011) [28]), guarantee an adequate available capacity and consequently adequate reliability and level of service?
- Will the congestion on some parts of the network become an extremely limiting issue for passenger or freight trains?
- In which measure would the coveted competition in an open railway market be influenced by capacity scarcity (or limited availability) mainly during peak hours or along more profitable corridors?

An accurate estimation of capacity of the rail network can help to answer the previous questions, assisting policy makers in taking better decisions (notably investment prioritising) and contributing to minimize costs for users. However, one of the main difficulties faced in defining a broad analysis of capacity and related parameters for the entire European railway system (i.e., travel times, reliability, connectivity, benefits/costs, access charge, accessibility, etc.) stems from the lack of available or usable data. Although timetables are generally in the public domain, there is still the perception of such data as commercially sensitive information; hence the difficulty in identifying a harmonized, comprehensive and detailed European database. Various attempts to improve this situation are currently on-going, especially for infrastructure data (i.e. the UIC's Erim Project and RailTopoModel, the RailML initiative, the ERA-European Railway Agency's Register of Infrastructure, etc.).

From a methodological point of view, on the other hand, several studies already allow us to explore the issue of congestion and the trade-off between capacity and delay as well as related costs. As highlighted in RICARDO-AEA (2014) [29], it is still complex to identify a single method as best-practice procedure for the estimation of marginal congestion or scarcity cost for rail even if several efforts have already been made in this direction (see for example Jansson & Lang (2013) [30], Brons & Christidis (2013) [31] or Pérez Herreroa et al. (2014) [32]). Railway capacity estimation is therefore a challenging issue which impacts directly and indirectly on various policy areas and is in turn determined by several factors. Capacity availability depends not only upon the number of tracks or on the signalling system (see UNIFE (2012) [27]), but it is conditioned also by a number of other elements such as speed reductions due to track conditions (so the maintenance program), length of trains, heterogeneity and frequency of services, and so on. For example, the influence of maintenance and infrastructure condition on capacity is highlighted in several contributions (e.g. Famurewa et al. (2014) [36]) while the influence of rail buckling or failure risk (and related speed limitations) on the infrastructure network come to be relevant in case of extreme weather events and/or for the evaluation of the effects of climate change on performances or cost of infrastructure (e.g. Nemry & Demirel (2012) [5]).

This underlying difficulty is also evident when looking at the strategies of infrastructure access charging: although the allocation schemes adopted by some Member States take in account the fact that slot scarcity at peak hours and for some routes should have an impact on access charges (see Peña Alcaraz & Sussman (2015) [22], UIC (2021) [33], OECD (2008) [34] CESifo Group Database [35]), there is still a strong need for optimisation and harmonisation of these procedures across Europe. Figure 1 offers a summary of tariff concepts for each national scheme; as evident from the left table, 14 countries impose a charge for reserving capacity while 7 member states take in account the infrastructure's congestion in the calculation of the access fees. In particular *'saturation, bottlenecks or capacity'* levels are assumed as variables for estimation of the allocation charges in four countries, while the performances (in minutes of delay according to the compensation regime for performance, i.e. incentives for promoting efficiency and fines for penalising delays) are considered as input for the tariff system of 9 members of the Eurozone; Italy goes a step forward by considering traffic density of lines and assigning different weights (and thus fees) to congested lines. Obviously, uncoordinated charging policies can lead to an imbalanced use of capacity and cause delays.

Country	Access	Capacity Reservation	Train Movement	Energy/ Electricity	Maintenance	Safety/ Security	Congestion	Environment.	Total
Austria (AT)			√				√		2
Belgium (BE)	√		√	√				√	4
Bulgaria (BG)		√	√	√					3
Czech Republic (CZ)		√	√	√					3
Denmark (DK)	√[1]	√	√				√	√	5
Estonia (EE)			√						1
Finland (FI)	√[1]		√						2
France (FR)	√[12]	√	√	√					4
Germany (DE)			√				√		2
Greece (GR)		√		√	√				3
Hungary (HU)		√	√						2
Ireland (IE)		√	√	√					3
Italy (IT)	√	√	√	√					4
Latvia (LV)			√						1
Lithuania (LT)			√	√					2
Luxembourg (LU)		√	√	√			√		4
Netherlands (NL)	√[1]		√	√			√	√	5
Norway (NO)	√[1]		√	√					3
Poland (PL)			√						1
Portugal (PT)			√	√					2
Romania (RO)		√	√						2
Slovakia (SK)		√	√	√					3
Slovenia (SL)			√						1
Spain (ES)	√	√	√	√		√			5
Sweden (SE)	√[1]	√	√	√		√	√		6
Switzerland (CH)			√	√	√	√			4
United Kingdom (UK)	√	√	√	√			√		5
Total	10	14	26	17	2	3	7	3	

[1] – Access fee for special infrastructure only
[2] – Access fee for regional service concessions only

Variable Category		Variables	AT	BE	BG	CH	CZ	DE	DK	EE	ES	FI	FR	GR	HR	HU	IE	IT	LT	LU	LV	NL	NO	PL	PT	RO	SE	SK	SL	UK	Total	+/-
Rolling Stock and Traction Type	Electricity consumption	Days				•																									1	0
		Electric train-km											•				/		++	•											4	2
		KWh consumed									++											•	++		++					•	5	3
		Liters of diesel consumed																									•				1	0
	Traction Type	Diesel/electric/3rd rail traction	•				•					•			/		/		•	•	/			•	•	++	•	++	++	•	15	6
	Train characteristics/ wear and tear	Mass per axle/train						•						•				•		•			++	•							6	1
		Number of axles												•																	1	0
		Number of pantographs																•													1	0
		Number of trucks																		•											1	0
		Tilting train					•																								1	0
		Train speed												•				•		•				•							4	0
		Train type			/											•											•		•	•	5	1
Offered Services	Performance indicators	Ideal travel time												•		–															1	-1
		Performance regime (delay/min)	•	•	/			++						++	/			++		•					++						9	6
		Saturation, bottlenecks, capacity	•																	•		++								++	4	2
		Traffic density																•													1	0
	Stations	Distinction between O/D/Interm.	•	•		•							•			•				•		•			•						8	0
		Number of passengers									•																				1	0
		Stop time (at station/node)		•														•						++							3	1
	Unit Charges	Number of trains/train movements							•														•					•			3	0
		Route-km (total)		•	/						•			•				•		•		++									7	2
		seat-km									•																				1	0
		Ton-km or gross ton-km	•		/	•	•		++	•	++	•		•	/	++	/					•	•			++	•	•	++	++	19	9
		Train-km	•		/		•	•	•	•	•				/	•		++	•	•	/	•	•	•	•	•	•	•	•	•	22	4
Gen. Service Type	Agent	Operator/railway company																												•	1	0
	Domain	Domestic/international/regional/etc			/	•							•		/			•											++		6	3
		Geographic/tariff zone (Line/Stations)						++					++			++														•	4	3
		Traffic Type (passenger, freight, etc)	•	•	/	•	•	•	•		•	•	•		/	•		•	•	•	/		•	•	•	•	•	•	•	•	24	3

- – Removed between 2007 and 2012
- • Maintained between 2007 and 2012
- ++ Added between 2007 and 2012
- / New tariff system/concept or not considered before 2007

Figure 1: Summary of Tariff Concepts for Each Tariff System (source UIC (2012) [33], pag. 19 and pag. 23)

Last but not least, the experience gained in transport modelling at European level suggests that improving the representation of rail capacity constraints in large models supports sound transport policy analysis; in this context this report offers an overview of methodologies (with different degree of complexity and data requirements) aiming at filling this gap.

These methods intend to evaluate the carrying capacity of the railway system, i.e. the maximum number of trains which may run on a railway infrastructure in a specific period of time with a fixed level of service, and thus they do not refer to vehicle capacity constraints (i.e. maximum number of passengers that can be transported in a carrier) as often assumed/considered in transport models. In particular even if the following paragraphs and the presented methodologies are related to the first definition of rail congestion (evaluating the delays related to the saturation of lines), for completeness of the discussion the last section of this report gives a glance to the schedule or frequency based methodologies for assigning passengers to transport network. This kind of models take in account congestion aboard the vehicles by associating discomfort functions to different lines; they consider a *"fail-to-board"* probability as in some circumstances (e.g. during peak hours) passengers are not able to board the first service arriving due to overcrowding.

Regarding the structure of this report, after this short introduction and examination of the policy relevance of the topic, Sections 4 and 5 provide a methodological review of scientific literature and capacity and reliability assessment procedures. To better explore the real applicability and the time and/or data constraints of each methodology, section 6 reports some practical applications to the European railway network and finally the section 7 briefly discusses the topic from a modelling perspective, summarising capacity constraints algorithms and procedures.

3 Overview of previous studies on railway congestion

Scientific literature has recently devoted great efforts in defining and optimizing capacity and travel time (including waiting and delay times) for railway system; this key trade-off is dramatically increasing its relevance for the management of the available infrastructures and the tracks access process.

Several research projects have already tackled the topic of railway capacity from different perspectives (infrastructure access and charging, open market and competition, accessibility, reliability and cost for users, eco-driving and related energy consumption, etc.).

It is worth noticing that, due to growing demand, many parts of the existing railway infrastructure are reaching their maximum capacity thus shrinking their capability to provide users and customers a higher or even adequate level of service. The increasing number of operating trains saturates capacity and entails a congested, delay-sensitive network; moreover the high heterogeneity of the traffic aggravates even more the situation on some lines. Of course delays and unreliability of the services result in costs not only for Infrastructure Managers or Rail Undertakings but also for travellers and for the overall society. There is thus the need to boost the productivity of infrastructure assets in order to improve the reliability and capacity of the whole system; indeed this is one of the main aims of Shift2Rail (http://www.shift2rail.org/), the new born European rail joint undertaking (see in particular the third Innovation Programme - IP3: Cost Efficient and Reliable High Capacity Infrastructure and the IP5: Technologies for Sustainable & Attractive European Rail Freight).

Already in the 4th EU Research and Development (R&D) Framework Programme, the European Commission funded the project EUROPE-TRIP (2000) [2] (European Railways Optimisation Planning Environment - Transportation Railways Integrated Planning) with the aim, among others, to evaluate methods for assessing the capacity of rail lines; the 5th EU Framework Programme supported the IMPROVERAIL project (2003) [3] (IMPROVEd tools for RAILway capacity and access management). EURNEX [4] (EUropean rail Research Network of Excellence), turned from an EU research project within the Sixth Framework Programme into a self-standing legal entity in 2007; capacity management and optimisation is one of the main goals of its Pole 2 – Operation and System Performance.

Many other European projects are still ongoing (see http://www.transport-research.info/web/projects/search.cfm?isPostback=true&Themes=32#Results), for instance CAPACITY4RAIL (aiming at increasing the capacities of rail networks taking into account results from previous research projects and programmes), or OCTF (Optimisation of Railway Transport Capacity - Increase in capacity of the lower sector gauge).

Besides these EU-funded research projects and sectorial programmes, several other European studies have indirectly dealt with the issue of capacity or reliability. For example Nemry and Demirel in [5] estimated the impacts (in term of expected delays and costs) on the European railway network of climate changes; they focused on the issue of rail buckling risk and related speed reductions on the infrastructure network due to the increase in temperatures. The study provides also evidence of how capacity and delays (in this case associated to speed limitations) are not independent issues, but that they can be addressed from different perspectives, and are intertwined with other relevant aspects of the transport system.

Many remarkable projects and analyses in this field have been also proposed and supported by the UIC (International Union of Railway). The CAPMAN - Capacity Management - project [6] aimed at producing a common methodology to evaluate the capacity of railway infrastructure in order to assess the necessity of investments on the network; The *Influence of European Train Control System (ETCS) on line capacity* (2008)

[7] and the *Influence of ETCS on the capacity of nodes* (2010) [8] commissioned to the Institute of Transport Science of the RWTH University at Aachen that provide useful guidelines for the analysis and the calculation of capacity consumption (i.e., capacity usage) either along the lines or in the nodes (stations, teminals, junctions, etc.), providing also worthy comments related to the influence of the ETCS system. Last but not least the UIC Code 406R – *'Capacity'* (2004) [9] (or previously the UIC Code 405 (1996) [10]) providing a well-known standard methodology for rail capacity evaluation.

Taking a look overseas, besides the well-known TCRP (Transit Cooperative Research Program) Reports related to Rail Transit Capacity (including chapters of the several editions of the Transit Capacity and Quality of Service Manual) by the US Transportation Research Board (see references from [11] to [15]), quite interesting and complete analyses are presented, among others, in two studies conducted by Cambridge Systematic, Inc. and respectively related to the U.S.A. National Rail Freight Infrastructure Capacity and Investment Study (2007) [16] and to the Minnesota Comprehensive State-wide Freight and Passenger Rail Plan (2009) (see [17] and [18]).

4 Concept of capacity

As stated in the UIC Code 406 (2004) [9], *'Railway infrastructure capacity depends on the way it is utilised. The basic parameters underpinning capacity are the infrastructure characteristics themselves and these include the signalling system, the transport schedule and the imposed punctuality level'* (see Figure 2: Capacity balance according to UIC Code 406).

Capacity can be defined as the maximum number of trains that may be operated using concurrently a specific part of the infrastructure during a given time period and with a fixed level of service. As described in Dicembre & Ricci (2011) [40], it is conditioned by technical parameters, such as planimetry and altimetry of the infrastructure, speed limits, typology and number of tracks, signalling and control systems (e.g. block sections length), operational model (heterogeneity and succession of trains, level of service, commercial speeds, etc.) and priority rules.

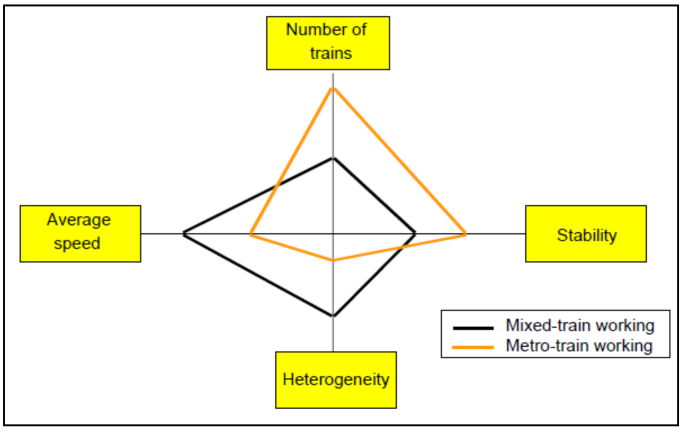


Figure 2: Capacity balance according to UIC Code 406

Taking into account such complexity, the UIC Code 406 identifies the most significant parameters influencing level of service, i.e. number of trains, average speed, heterogeneity of services and stability of timetable, and their relative trade-offs as determined by existing capacity limitations (see Figure 2). For example a low level of homogeneity of services implies differences in running time between consecutive trains and consequently a reduction in capacity (see Landex (2009) [41], Landex (2008) [42] and Figure 3).

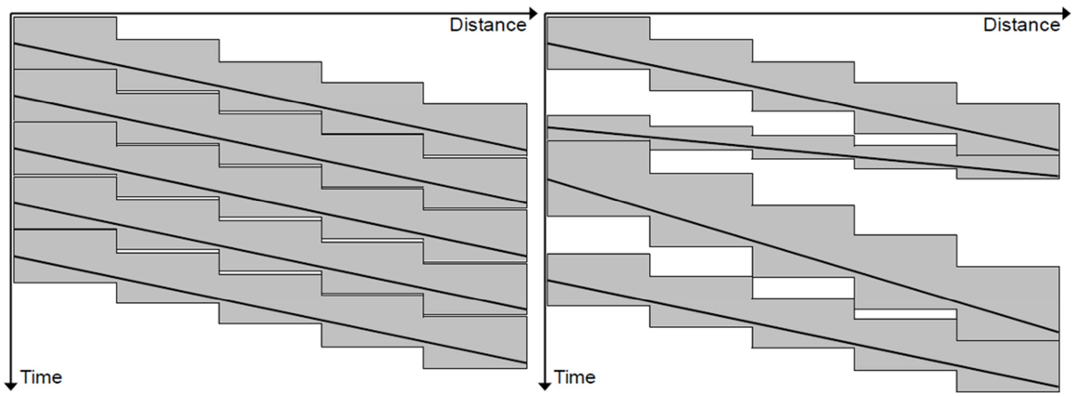


Figure 3: Capacity usage of homogenous timetable (left) versus heterogeneous timetable (right) (source Landex (2009) [41])

A remarkable review of capacity concepts and evaluation methodologies is reported in Abril et al. (2008) [43], Hansen & Pachl (2008) [44] and Hansen & Pachl (2014) [45]; in particular they provide a detailed distinction of capacity definitions:

- ***Theoretical Capacity*** is the number of trains that could run over a route, during a specific time interval, mathematically calculated using an empirical formula. It represents an upper limit for line capacity.
- ***Practical Capacity*** represents the practical limit of the number of trains (usually considering the current train mix, priorities, traffic bunching, etc.) that can be moved on a line in order to guarantee a reasonable level of reliability (see next figure). It is a more realistic measure than theoretical capacity, usually around 60%-75% of the latter.
- ***Used Capacity*** is the actual traffic volume over the network, usually lower than the practical capacity.
- ***Available Capacity*** *is the difference between the Used Capacity and the Practical Capacity and provides an useful indication of additional trains that could be handled by the network.*

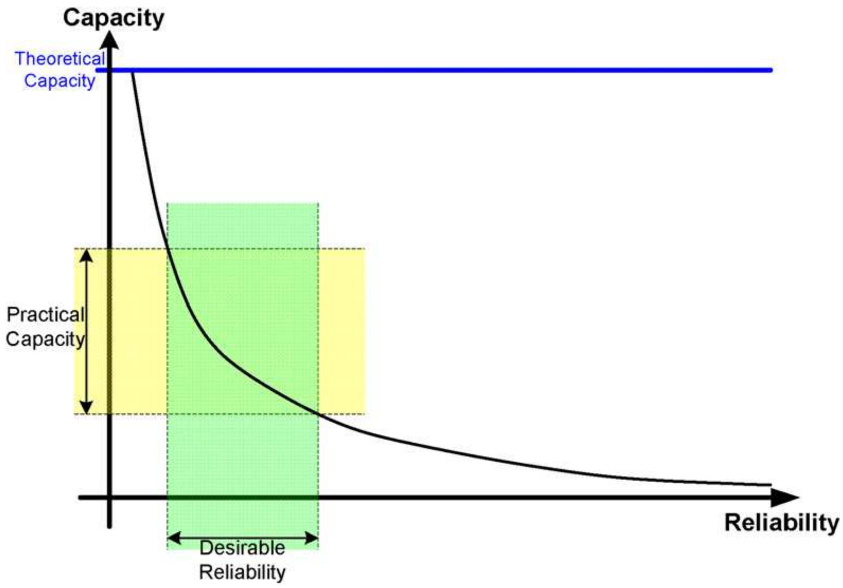


Figure 4: Correlation between theoretical capacity, practical capacity and reliability (source Abril et al. (2008) [43])

Starting from these definitions, it is possible to introduce different methods to evaluate capacity consumption requiring different level of data detail; while the theoretical capacity can be calculated by using empirical or analytical formulas, the calculation of the practical capacity requires the definition of a timetable and of a required level of service (e.g. admissible delays or percentage of on time trains). It is worth noticing that *"it is not possible to give a unique value to the whole railway network because of complexity and diversification of components (lines, stations or their subparts), which require different estimation of capacity itself. Anyway, at network's level it will be possible to estimate a global capacity value by referring to the lower local value"* (see IMPROVERAIL final report (2003) [3]). Indeed also UIC (2008) [7] and UIC (2014) [8] present a net distinction between line and node (stations, terminals, junctions, etc.) capacity, reporting a comparative analysis of different synthetic or analytical methodologies for their evaluation. Mussone & Calvo (2013) [49] and Malavasi et al. (2014) [50], instead, present two different approaches (beside useful literature reviews) for capacity evaluation of complex railway nodes.

As described in Dicembre & Ricci (2011) [40], Abril et al. (2008) [43], Hansen & Pach (2008) [44], Hansen & Pach (2014) [45], Kontaxi & Ricci (2009) [46], the most relevant approaches to evaluate railway capacity can be classified according to their methodology, the required data and the level of detail of the resulting estimations:

- *Synthetic and analytical methods* describe the problem by means of mathematical formulae and may represent a good start for identifying major capacity constraints; they are mostly applied for determining a preliminary solution in simple situations, for comparison purposes or as reference. Even if these methodologies often lead to useful results without the need of extensive simulations, it is worth noticing that the results vary from one method to another depending on the considered parameters (Kontaxi & Ricci (2009) [46]). Besides the well-known UIC [10] and TRB [11-16] approaches, detailed reviews and useful descriptions of several synthetic and analytical methods can be found in the scientific literature (e.g., see references from [40] to [48]).
- *Asynchronous methods* represent in more detailed way capacity estimation, modelling the dynamic scheduling processes by means of discontinuous events. The asynchronous approach often tries to optimize one or more variables; in practice optimisation methods for evaluating railway capacity focus on obtaining optimally saturated timetables, usually through mathematical programming techniques (e.g. Mixed Integer Linear Programming Formulations and Enumerative algorithms). A well-known example is represented by the UIC Code 406: by modifying the base timetable, existing train paths are set as close as possible to each other and the remaining unused time left in the timetable represents spare time theoretically available for additional train services.
- *Synchronous methods* (traffic simulation) are even more detailed; they are able to reproduce, by means of specific software, the processes of railway operation over the time and provide with values quite close to reality. Besides purely academic models, several simulation environments have been already produced and are commercially available on the market. They usually perform time-step simulations based on train motion equations. Few examples of these simulation environments are:

  - OpenTrack (OpenTrack Railway Technology) is a railway network simulation program developed as part of a Swiss Federal Institute of Technology Institute for Transport Planning and Systems (ETH IVT) research project (http://www.opentrack.ch/).

  - RailSys is a computer-based software system for analysis, planning and optimisation of operational procedures in railway networks developed by RMCON Rail Management Consultants (http://www.rmcon.de/en/products/railsys-classic-planning.html).

  - Rail Traffic Controller (RTC) is a Windows-based program developed by Berkeley Simulation Software (BSS) to simulate the movement of trains through rail networks (http://www.berkeleysimulation.com/).

A detailed description of simulation models is reported in TRB (2013) [14] and Hansen & Pach (2014) [45]: by reproducing the railway infrastructure and the rolling stock characteristics (see Figure 5) and after introducing the timetable data (see Figure 6), these software applications are able to simulate the railway system, providing different results related either to the operation of trains (Figure 6) or to the platform and track occupation in stations or nodes (Figure 7).

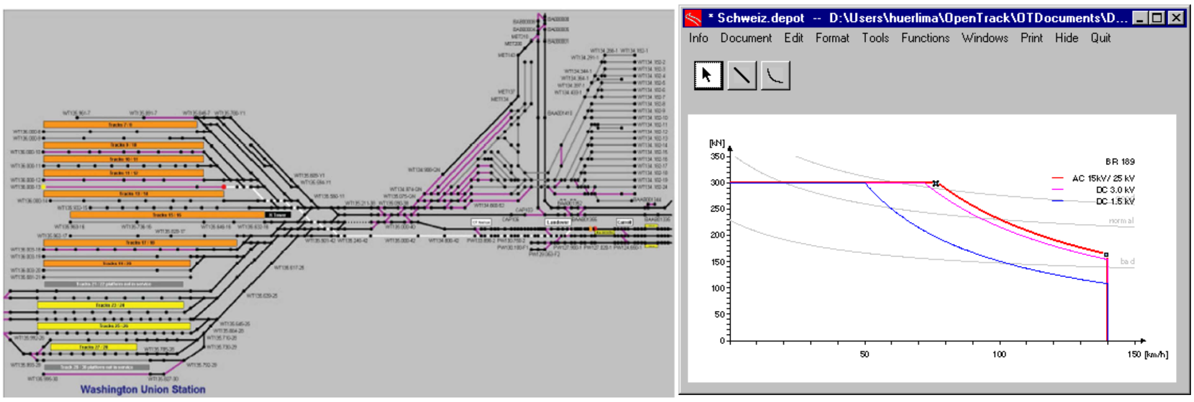


Figure 5: Washington Union Station scheme (left, source TRB (2013) [14]) and rolling stock data interface by OpenTrack (right)

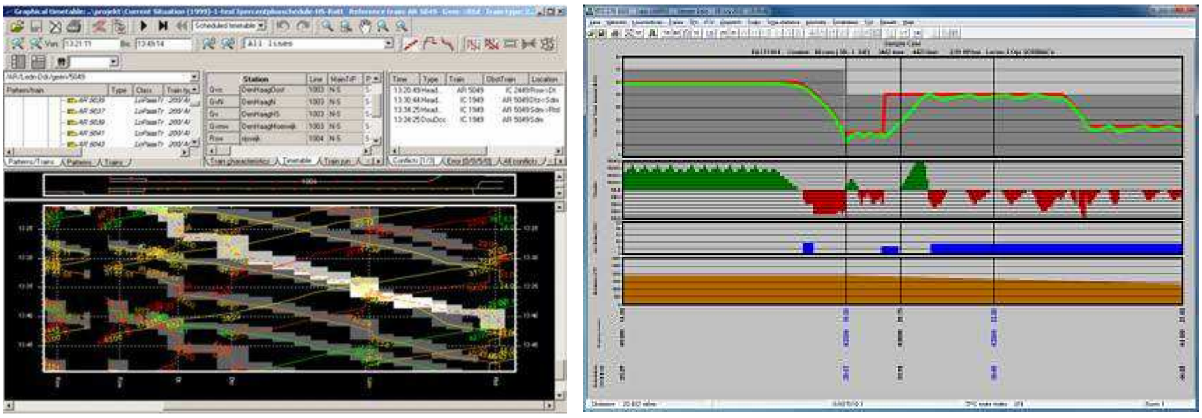


Figure 6: Timetable Manager Layout by RailSys (left) and Train Performance calculator by RTC (right)

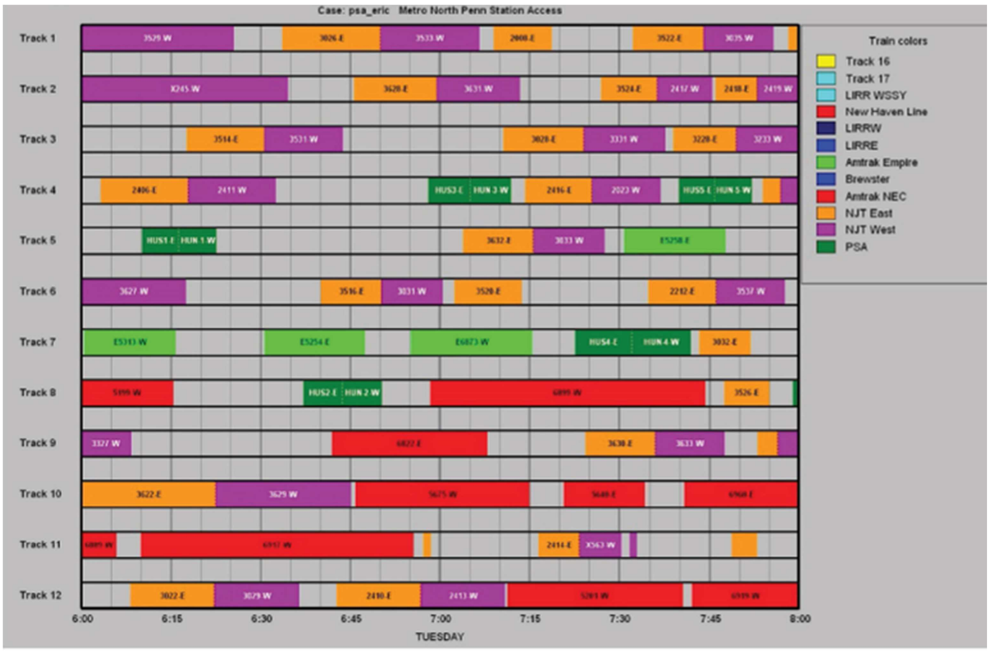


Figure 7: Example of occupation chart of station tracks (source TRB (2013) [14])

5 Review of methodologies

The recent EU Directive 2012/34/EU establishing a single European railway area underpins the need to identify congestion and to establish clear criteria for the allocation of rail infrastructure capacity. National Railway Network Statements are required to report in detail the physical and operational characteristics of the network, inter alia, the traction system, the length of lines, the number of tracks, the maximum permitted speed, load and train lengths; capacity of the rail network is therefore defined by the Infrastructure Manager based on the demand for rail transport and the technical characteristics of the network. For example, the Network Statements for Italy (2012 and 2014, see [85] and [86]), Spain (2015, see [87]) Germany (2015, see [88]) and UK (2015, see [89]) report indications of current traffic levels, used capacity and congested link of the rail network at national level. However, the approaches followed in order to estimate line capacity or evaluate congestion are not unified and in some cases, there is a lack of detailed explanations on the underlying calculation methods (the Italian Network statements for example assumed a capacity threshold of 190-200 trains/day on the double track lines, while the Spanish one offer different and detailed capacity limits for each line based on a calculation procedure).

In this section, different approaches to evaluate the capacity of a railway network are presented according to the level of detail and to the availability of data, describing also various methodologies (with varying degrees of complexity) to link the evaluation of utilized capacity to the probability and value of the expected delay; indeed depending on the data availability, synthetic, analytical or even simulation methods may be applied.

A detailed description of existing methodologies can be found in the Transit Capacity and Quality of Service Manuals [11] [12] [13] [14] and also in Abril et al. (2008) [43], Hansen & Pachl (2008) [44] Hansen & Pachl (2014) [45], while Kontaxi & Ricci (2009) [46] focus only on synthetic and analytical approaches. A comprehensive summary of all the possible procedures is beyond the purpose of this report; nevertheless, as stated in Kontaxi & Ricci (2009) [46], the results among the different approaches could slightly vary, mainly depending on input data and variables. In the following subsections we focus on several analytical and optimisation procedures. We also present some capacity threshold values as reported for example in Rothengatter (1996) [47], in the Rail Transit Manuals ([11]-[14]) or in several studies by United Nations (UN) and the International Union of Railway (UIC); in general they can be used as reference values, or in the case more accurate data is missing. In particular, to better understand the meaning of these empirical thresholds, Table 1, proposed by Sameni et al. (2011) [69], reports different metrics and indexes used for measuring capacity utilisation; they are grouped in three main categories (throughput, quality of service and asset utilisation) and the strengths and weaknesses of each type of metric are also briefly summarized.

Focusing on capacity thresholds, Table 2 and Table 3 report empirical and indicative values respectively for the minimum time interval between two trains by category and for the capacity of railway lines by number of tracks as suggested in Rothengatter (1996). The same article provides even the capacity limits depending upon infrastructure and traffic characteristics reported in table 4; in particular these *'practical'* thresholds try to take in account how the capacity of a line is influenced by infrastructure (number of tracks, signalling system), speed, heterogeneity of services, etc..

Table 1. Analysing metrics of capacity utilisation (source Sameni et al. (2011) [69])

Category		Examples	Description	Strengths	Weaknesses
Throughput	**Macro**	Number of trains, train-km	How many passengers can be transported over a period of time	Easily measurable and understandable	Does not reflect quality of service
	Micro	Number of passengers, Passenger-km, seat-km			
Level of service		Average delay, percentage of cancelled or late trains (e.g. Public Performance Measure in Great Britain)	Measures reliability and timeliness	Important for general public	Indirect measure heavily depends on how saturated the network is. Does not take scheduled waiting time and timetable supplements into account which are a waste of time for passengers
Macro Asset utilisation		Capacity Utilisation Index (CUI), Total time utilisation of infrastructure (UIC 406 method), Number of trains per km of infrastructure in a given time period	Estimating how saturated the network is	Important to estimate how efficiently the infrastructure is utilised	A measure of macro capacity utilisation, does not reflect the actual value of trains, load factor and how close the passengers are standing (micro capacity utilisation)
Micro asset utilisation		Load factor	Estimating how crowded the passenger trains are	Important to estimate how efficiently the rolling stock is utilised and the level of comfort for passengers	A measure of micro capacity utilisation, does not reflect how saturated the network is (macro capacity utilisation)

Table 2. Minimum time interval between two trains of different types in minutes (source Rothengatter (1996) [47])

i / j	Intercity	Express	Freight (fast)	Freight (slow)
Intercity	1.64	2.58	2.64	2.53
Express	9.25	1.49	2.49	2.39
Freight (fast)	5.96	3.88	1.68	2.57
Freight (slow)	5.10	4.09	3.14	2.24

Table 3. Capacity of railway lines by number of tracks (in total number of trains per day for both directions) (source Rothengatter (1996) [47])

Track type	Low	High
1 track	60	90
2 tracks	150	225
3 tracks	250	300
4 tracks	325	425

These figures were already presented in 1994 in the UNECE's (United Nation – Economic Commission for Europe) *'Draft report on the methodological basis for the definition of common criteria regarding bottlenecks missing links and quality of service of infrastructure networks'* (TRANS/WP.5/R.60) in order to provide *'an impression of magnitude'* of the capacity of railways lines; the table contains a sample of capacity levels as calculated and verified for operation of the European type express passenger trains with a maximum length of 400 m, goods trains with a maximum length of 700 m, and relatively high power-to-weight ratios and braking coefficients. Anyway, beside the Table 4, the mentioned UNECE report proposes general standard criteria to determine the capacity of railways; in particular it suggests the following practical values as capacity limits:

- *single track main lines: 1 x 60-80 trains/day;*
- *double track main lines: 2 x 100-200 trains/day;*

Table 4. Capacity of railway lines: number of trains per day, total both directions (source Rothengatter (1996) [47] or UNECE - United Nation, Economic Commission for Europe (1994) [48])

Type of line and equipment	Large differences in speed and mixing of trains of different speeds	Small differences in speed and grouping of trains of the same speed
Single track; determining distance between crossing (and overtaking) stations:		
5 km	60 – 80	80 – 120
10 km	40 - 60	60 - 90
20 km	20 - 50	30 - 40
Double track; block system with relatively long block sections (>2km); warning signals and block signals with two indications; siding at 20 km intervals	100 - 200	200 - 300
Double track; automatic block system with short block sections (1,5 km on the level); block signals with three or four indications; siding at 20 km intervals	100 - 200	250 - 400

These values only represent commercial trains, thus neglecting movements of locomotives, service transport, etc... Anyway, as also stated in the report, these capacity thresholds are only guiding figures, and often a more detailed analysis of the degree of occupation and the percentage of utilisation is absolutely necessary (by applying comparatively more complicated but also more accurate calculating methods, e.g. see next paragraphs).

These figures and their suggested capacity thresholds are still offered as valid reference values by UN or UIC, due to some extent to the long average lifetime of the fleet and the static nature of other limiting factors such as the signalling system (i.e. usual 3 aspects system and subsequent length of block sections) and infrastructure characteristics (i.e. gradients, maximum speeds, etc.).

5.1 UIC's Analytical Method – Code 405R

This section describes the analytical method proposed in its first edition by the International Union of Railway (UIC) in the Code 405R (1996) [10]; despite the fact that this methodology was officially replaced in 2004 by the so-called compression method (UIC's Code 406) as a standard measure of capacity, it offers an efficient estimation of the capacity of a line.

To summarise briefly the main characteristics of this approach, it is based on the following formula for the capacity:

$$P = \frac{T}{t_a + t_b + t_c} \tag{1}$$

- *P* is the capacity (daily, hourly, etc.) index
- *T* is the reference time (usually 24 hours for the daily capacity);
- t_a is the average minimum headway (the headway can be defined as the separation time between trains, i.e. the temporal interval between two consecutive trains on the same block section and in the same direction, see also Figure 9);
- t_b is an expansion margin, defined as a running time margin added to train headways in order to reduce knock-on delays and to achieve an acceptable quality of service.
- t_c is an extra time based on the number a of the intermediate block sections on the line and calculated by means of the formula $t_c=0.25*a$ (a block section can be defined as a section within/protected by signals, i.e. each track, in a fixed-block train control & signalling system, is divided in block sections that, for safety reason, can be occupied only by a train per time and are thus protected by signals, see Figure 9); this parameter takes into account that the increase of capacity on the determinant section, following its division into more block sections, is less than proportional to the reduction of the travel time.

The average minimum headway for each line is calculated by the following equation:

$$t_a = \sum_s \left(t_{h,ij} \times f_{ij} \right) \tag{2}$$

This expression requires the grouping of each possible succession of trains by classes of travel time; considering, for example, to have only two type of trains (slow and fast) with different allowed speed on the line, the minimum headway on the line will be different considering the four possible successions of trains: fast-fast, slow-slow, fast-slow and slow-fast. (see Figure 8).

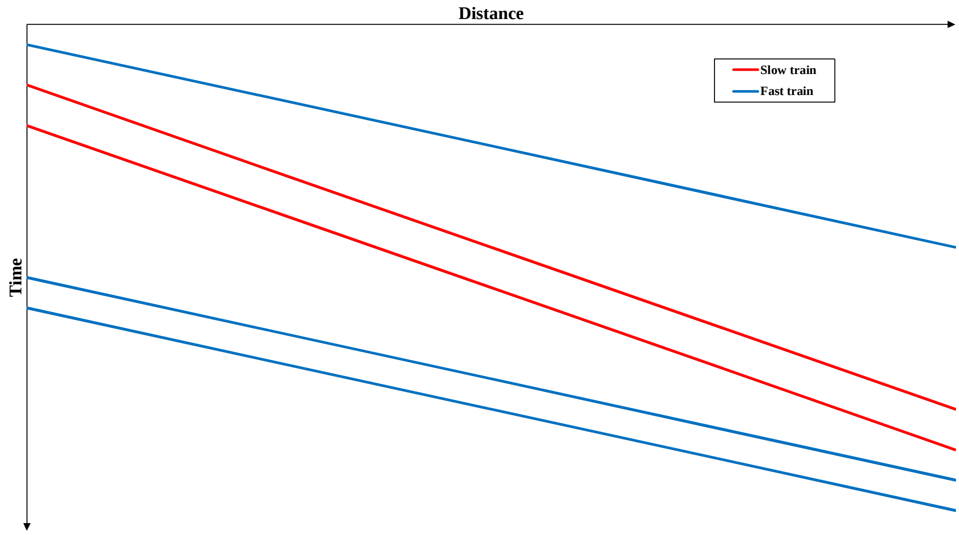


Figure 8: heterogeneous operation: different succession of trains (slow and fast)

In Eq. (2) s represents the number of different cases of succession (train of category j following train of category i), $t_{h,ij}$ is the minimum line headway for the specific case (category i preceding category j), and f_{ij} is the relative frequency of the specific succession; this last parameter is calculated as the ratio of the frequency F_{ij} (number of times the succession *'class i followed by class j'* appears in the timetable) on the total number of successions (total number of trains/services N minus 1):

$$f_{ij} = \frac{F_{ij}}{N-1} \tag{3}$$

The expansion margin t_b is calculated applying queuing theory to the relevant section, which is treated as a service. The most used approach involves an M/M/1 queueing system, where arrivals to the section are modelled as a Poisson process, service (transit) times have an exponential distribution and, obviously, the whole system works on a FIFO (*first-in, first-out*) basis. In particular the length of the queue for entering the block section is equal to the number of trains encountering a disturbance (delay) and it depends on the intensity of traffic Ψ (track occupation rate of the single channel) given by the ratio between the average number of arriving trains ($\lambda=1/(t_a+t_b)$, i.e. inverse of the expected inter-arrival time) and the maximum number of trains which utilize the section ($\mu=1/t_a$, i.e. inverse of expected service time):

$$\Psi = \rho = \frac{\lambda}{\mu} = \frac{t_a}{t_a + t_b} \tag{4}$$

An extensive test campaign, carried out by UIC, led to the identification of the following threshold values for Ψ:

- 0.60 (corresponding to 1.5 users waiting in the queue) valid for an unlimited period of time (normal operation of the system), hence the condition $t_b \geq 0.67 t_a$;
- 0.75 (corresponding to 3.1 users waiting in the queue) valid for a short period of time (peak hours), hence the condition $t_b \geq 0.33 t_a$;

Assuming a M/M/1 system, the mean queue length (average number of delayed trains) is be equal to:

$$L_q = \frac{\rho}{1-\rho} \tag{5}$$

while the average waiting time (average delay per train) can be evaluated as (see Ricci (2014) [51]):

$$w = \frac{\rho}{\mu - \lambda} = (t_a + t_b)\frac{\rho^2}{1-\rho} \tag{6}$$

The above approach is based on simple formulas and does not require a large amount of data besides values such as number of trains, reference period, etc. which are usually available. However the length (or the travel time) of the relevant block section of the line should be known or at least hypothesized, as this information involves a detailed knowledge of the infrastructure. In this context, we propose a simplified approach of this procedure in case of limited available data which is presented in the following section.

5.1.1 A Simplified Approach

As described in the previous section, the UIC Code 405R proposes an analytical method to be applied on the critical section of the line (based on blocking time sequences, see Figure 9). However, it is not always possible to find or collect information regarding the signalling system, particularly the length and the characteristics of all the sections along each line, as is the case in large-scale railway networks or for preliminary studies. Even if a simplified approach yields results that are to some extent less detailed and representative, it allows effectively estimating line capacity in the absence of a comprehensive, detailed set of data. In this respect, we have developed a *'simplified'* or *'ad hoc'* version of the UIC 405 method in order to obtain an indicative value of utilised capacity and possible delay per train, relying only on data such as distance, scheduled travel time and number of trains between consecutive nodes. The headways are calculated based on the scheduled running times between stations, i.e. each line section between consecutive stations (and per direction in case of double track lines) can be occupied only by a single train, neglecting missing infrastructure information related to the characteristics of the block sections. This assumption, also applied in other consolidated procedures (e.g. Capacity Utilisation Index, see next subsection), will lead to more restrictive and less representative values of capacity due to systematically longer line sections and headways. Anyway, in absence of further details (as for example in case of the analysis of very large network), it could still provide a valuable indication of capacity and related delay.

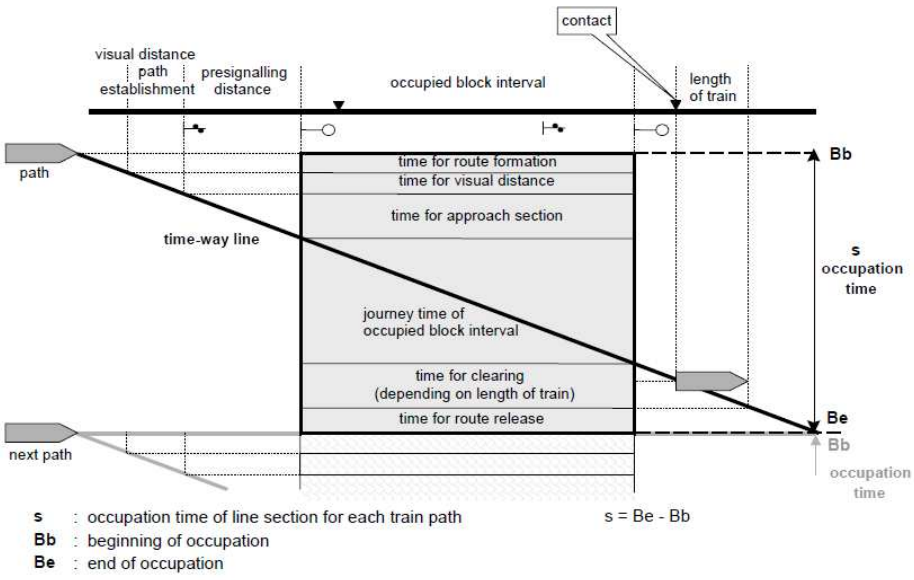


Figure 9: Scheme of blocking time occupation (source UIC Code 406 (2004) [9])

Trying to limit to some extent the effects described above, especially the underestimation of capacity, we suggest considering the section divided into blocks of fixed length (e.g. 2 km) in case of long distances between consecutive stations (more than 3-4 km) and evaluating the occupation time of the resulting block intervals; in order to guarantee a conflict-free timetable it should be considered at least a distance of two blocks plus *'sight and reaction'* time (see also Figure 18 in section 6.1). The number of intermediate hypothesised block sections will also enter in the calculation of the extra time t_c.

5.2 Capacity Utilisation Index (CUI) Method

Whenever the scheduled timetables for analysed lines are available, this approach provides an effective solution to the problem of capacity calculation; the Capacity Utilisation Index is defined as *'the time taken to operate a squeezed or minimum technically possible timetable compared to the time taken to operate the actual timetable'*.

This method is used in UK by Network Rail for capacity analysis based on minimum headways and it requires less detail compared to the UIC's 406 method described below; the main idea is to take a train graph and to compress it so as to let the trains running as close each other as possible, with only a headway between them.

The capacity utilisation is evaluated as a proportion of the time taken to operate the squeezed timetable compared to the time taken to operate the actual timetable (e.g. in Figure 10, CUI = 45/60 = 75%). Of course the method, even if worthy, provides only an estimate of capacity sensitive to the way the timetable is compressed.

It has been shown (see Gibson et al. (2002) [52] or Armstrong, J. Preston, J. (2013) [54]) that there is a relationship between CUI and the Congestion Related Reactionary Delay (CRRD) per train km; this subset of delay is the portion that would be expected to increase more-than-linearly with an increase in traffic.

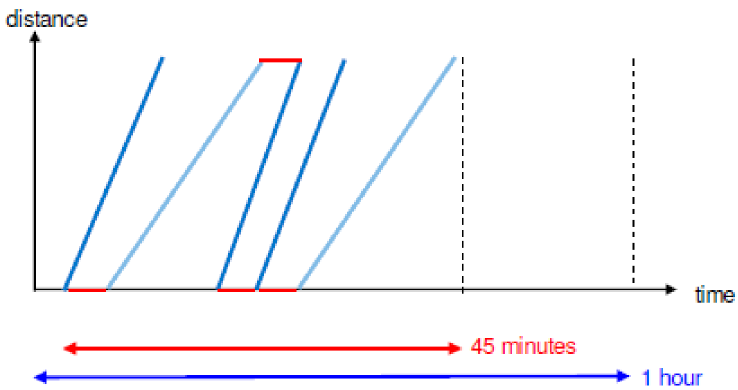


Figure 10: Capacity utilisation calculation according to CUI method (Faber Maunsell-Aecom (2007) [53])

Based on a fitting test with observed real data, the method proposes an exponential function to link the CUI and the CRRD:

$$D_{it} = A_i \times \exp(\beta \times C_{it}) \qquad (7)$$

where are:

- D_{it} the reactionary delay on track section i in time period t;
- A_i a route section specific constant;
- β a route specific constant;
- C_{it} the capacity utilisation index on section i in time period t.

The values of *Ai* and *β* have been calculated and are regularly updated for the UK network (see Gibson et al. (2002) [52]) and they could be generalised to other networks only based on a specific investigation; for the purpose of the present analysis a hypothetical shape of the function includes a range of coherent values for *Ai* and *β* (see applications in the section 6).

As already noticed, the capacity utilisation index is calculated by compressing the timetable based on the occupation time between two consecutive stations, whereas the UIC 406 method considers each block section along the line, which requires more detailed information on infrastructure and signalling systems.

5.3 UIC's Compression Method – Code 406

As the UIC Code 406 (2004) [9] states: '*capacity consumption shall be analysed within a line section through compressing timetable train paths in a pre-defined time window. The effects of the compression on neighbouring line sections are not taken into account. This is acceptable because the analysis must be done for the limiting section of the line, and no conclusions concerning the timetable feasibility on neighbouring line sections shall be derived from this analysis*'. In order to assess capacity and identify bottlenecks in a line, the capacity consumption on every single section has to be calculated: the highest value of capacity consumption shall determine the reference value for the whole line.

The first step of the methodology is to build up the infrastructure layout and the timetable of the line and then to compress the timetable in order to obtain the overall capacity consumption. The block sections remain occupied, depending on signalling systems, as long as the point behind them (cleared for safety reasons) becomes free and the route is released (Figure 11).

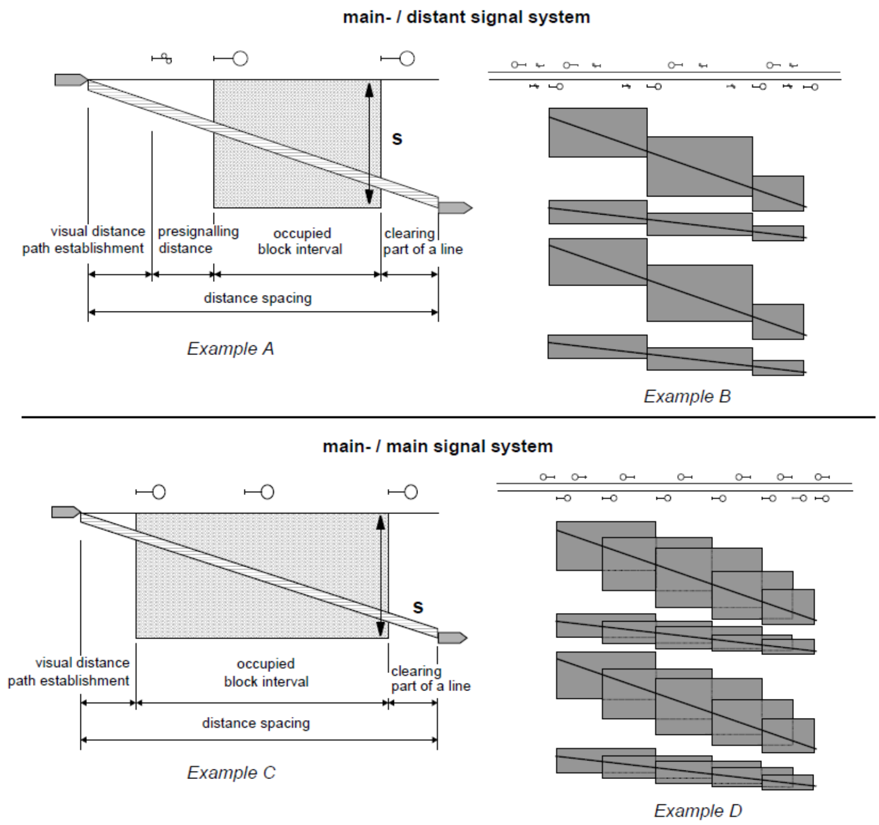


Figure 11: Example of occupation times in different signalling system; source: UIC Code 406 (2004) [9]

The calculation method suggested in UIC Code 406 is based on blocking time sequences: for each block section, the occupation time is a sum of times for (see Figure 9 and Figure 11):

- *route formation;*
- *of the block itself;*
- *clearing time;*
- *visual distance/driver reaction;*
- *approach the section;*
- *track occupation*

all depending on the timetable, infrastructure and vehicle characteristics. UIC (2008) [7] reports some samples of practical values of operational times to apply for various signalling systems.

In order to estimate the total capacity consumption it is necessary to consider time reserves for timetable stabilisation (i.e. buffer time *B*) and for maintenance (i.e. *D*) besides the minimum occupation time *A* and supplement for single-track lines (i.e. crossing buffer *C*); hence the total consumption time *k* will be:

$$k = A + B + C + D \tag{8}$$

Part of the remaining slots are not usable due to market requirements, while a second share of the unused capacity represents still available capacity (see Figure 12).

Given a reference time t_u (chosen window time), the capacity consumption *K [%]* is defined as:

$$K = \frac{100 \times k}{t_u} \tag{9}$$

UIC specifies a guideline for standard values of infrastructure occupation in order to achieve a satisfying operating quality. These values are a function of the type of line and the infrastructure use (see Table 5).

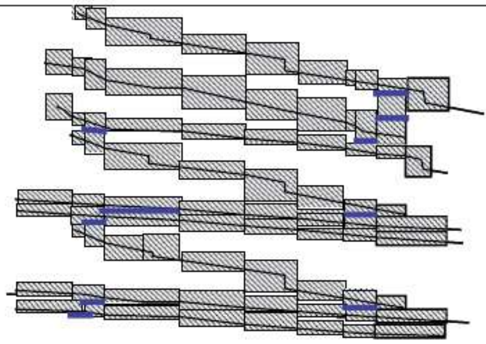
I	Capacity conumption	A	(minimum) infrastructure occupation 
		B	buffer time
		C	supplement for single-track lines
		D	supplement for maintenance
II	Unused Capacity	E	usable capacity
		F	lost capacity

Figure 12: Determination of capacity consumption; source: UIC Code 406 (2004) [9]

Table 5. UIC's Recommended Values for Infrastructure Occupation (Source: UIC Code 406 (2004) [9]).

Type of line	Peak hour	Daily period
Dedicated suburban passenger traffic	85%	70%
Dedicated high-speed line	75%	60%
Mixed-traffic lines	75%	60%

The method does not consider an explicit interrelation between capacity and quality; thus as it is, can be used for a rough benchmark calculation of capacity consumption, but not for an estimation of performance of the railway infrastructure.

5.4 STRELE Formula (Method of Schwanhäußer)

In order to calculate the average buffer time $\underline{t}_p$ to achieve an adequate level of service the following equation can be used:

$$\underline{t}_p = \frac{\underline{z} \times (1-\rho)}{\rho} = \frac{A}{N} \times \frac{(1-\rho)}{\rho} \tag{10}$$

where is:

- ρ recommended value for the infrastructure occupation by UIC 406 (Table 5);
- $\underline{z}$ average minimum headway time;
- A minimum infrastructure occupation and N actual number of running trains.

The method considers that both the entering delays and primary delays (generated on the section itself) induce new secondary delays; these last ones arise from threading trains into the line section. According to Schwanhäußer, the average secondary delays (unscheduled waiting times) on line sections can be expressed by the formula (see UIC (2008) [7]):

$$ET_W = \left(p_{ve} - \frac{p_{ve}^2}{2}\right) \frac{\underline{t}_{ve}^2}{\underline{t}_p + \underline{t}_{ve}\left(1 - e^{-\underline{z}/\underline{t}_{ve}}\right)} \times \left(p_g \left(1 - e^{-z_g/\underline{t}_{ve}}\right)^2 + (1-p_g)\frac{\underline{z}_v}{\underline{t}_{ve}}\left(1 - e^{-2z_v/\underline{t}_{ve}}\right) + \frac{\underline{z}}{\underline{t}_p}\left(1 - e^{-\underline{z}/\underline{t}_{ve}}\right)^2 \right) \tag{11}$$

with:

- $\underline{t}_p$ average buffer time, given in Eq. (10);
- $\underline{z}$ average determinative minimum headway time;
- $\underline{z}_g$ average determinative minimum headway time of equal-ranking successions of trains;
- $\underline{z}_v$ average determinative minimum headway time of different-ranking successions of trains;
- $\underline{t}_{ve}$ average delay at entry;
- p_{ve} probability of delay at entry;

- p_g probability of an occurrence of equal-ranking successions of trains.

The average buffer time to reach a satisfying operating quality can be defined by assuming an acceptable value of the unscheduled waiting time.

It is worth noticing that Eq. (11) requires the definition (by measurements or assumptions) of the average delay $\underline{t}_{ve}$ and of the probability of delay p_{ve} at entry.

5.5 Further Methods for the Evaluation of Train Delays

In the last decades, several other contribution have been presented on the trade-off between number of running trains (or directly capacity) and trains' delays (e.g. Hansen & Pachl (2014) [45], Huisman et al. (2002) [55] and Wendler (2007) [56] report different queuing models for this scope).

Hertel (see Hansen & Pachl (2014) [45], Hansen (2009) [57] Pachl (2002) [58] Schmidt (2009) [59]), instead, presented an analytical approach for the waiting time as a function of traffic flow, related waiting time sensitivity (partial derivative of average waiting time with respect to track occupancy) and maximal traffic energy, defined as product of train intensity and speed:

$$E_{traffic\ energy} = \frac{n}{s} v^2 = \frac{n}{t} v \tag{12}$$

with:

- n number of trains;
- s length of the line;
- t time;
- v average speed;

According to Hertel (Figure 13) the recommended area of train intensity as function of waiting time sensitivity and traffic energy of a track operated in one direction would be within 150 and 200 trains per day and the waiting time per train may increase up to 10 min.

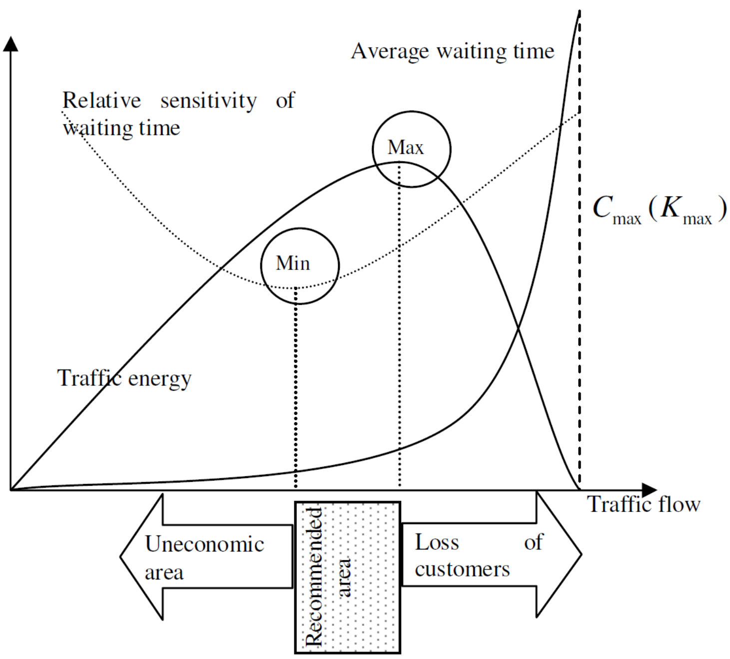


Figure 13: Hertel's approach, source Hansen & Pachl (2014) [45]

Finally Landex (2008) [42] proposed another approach following an idea by Kaas: the total amount of delay Σt_d along a given train's path can be calculated based on the initial delay $t_{d,1,i}$ and a delay propagation factor $y(t_{d,1,i})$:

$$\sum t_d = t_{d,l,i} \times y \tag{13}$$

By expressing the initial delay $t_{d,1,i}$ as a multiple of the minimum headway time $t_{h,min}$:

$$t_{d,l,i} = n \times t_{h,\min} \tag{14}$$

as also reported in Figure 14, the propagation factor (and so the total delay) could be calculated in function of the capacity consumption K and the size of the minimum headway time $t_{h,min}$ (by means of n):

$$y = \frac{n}{\left|\left(\frac{1}{K}-1\right)\right|} + 1 - \frac{\left(\frac{1}{K}-1\right)}{2n} \frac{n}{\left|\left(\frac{1}{K}-1\right)\right|} \left(\frac{n}{\left|\left(\frac{1}{K}-1\right)\right|} + 1\right) \tag{15}$$

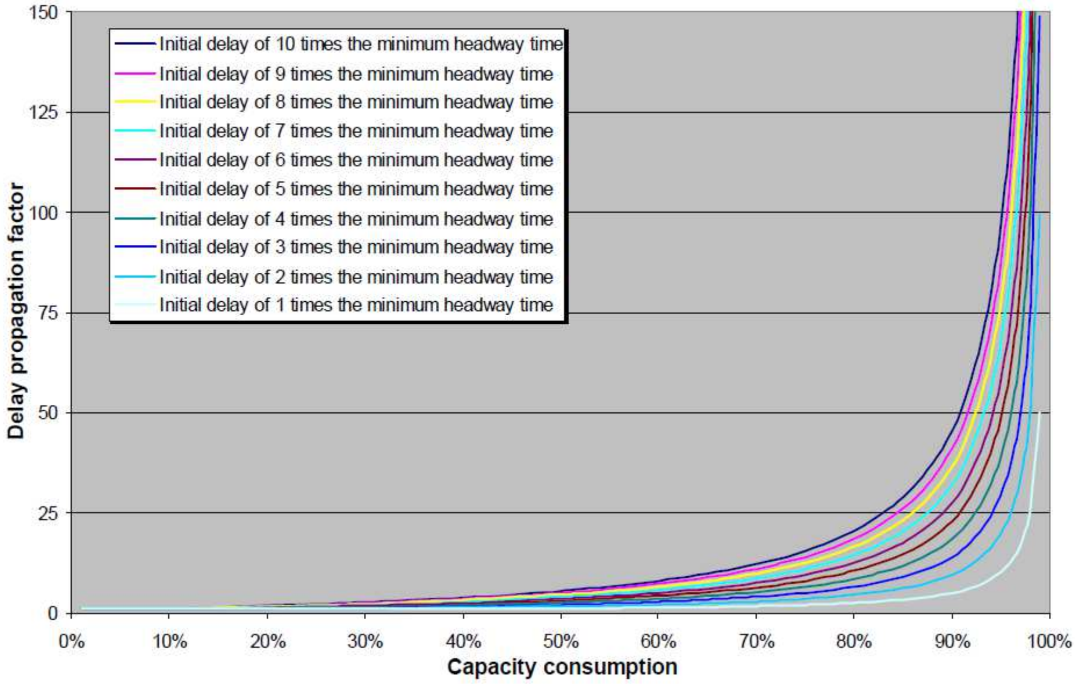


Figure 14: Delay propagation factor as a function of capacity consumption and initial delays; source: Landex (2008) [42]

As evident from Figure 14, delay increases as capacity consumption intensifies and the propagation starts growing dramatically when the capacity consumption is over 80%.

6 Comparative analysis of capacity estimation methodologies: an empirical assessment

This section describes the practical application of capacity estimation methodologies presented in Section 5, in particular the simplified approach (SA), on specific European railway networks in order to investigate the robustness of such approach as compared to other methods and the extent to which data requirements may limit actual applicability in a wide European context. We first report a detailed application to a specific line in order to explore how the results may vary using different methodologies (Rotoli et al. (2015) [60][61]); the second sample reports the main outcome of our analysis on the Italian railway network using general data and the proposed 'ad hoc' simplified approach (SA) (Rotoli et al. (2015) [61][62]). Lastly, a third application shows how the concepts of capacity and punctuality are closely interrelated to several other issues; specifically we focus on a succinct accessibility analysis (Rotoli et al. (2015) [61][62]) but as described also below, the calculated travel time can be seen as a parameter for evaluating benefit and cost for users, as a factor to take into account in the infrastructure access charge and so on. Even more interesting would be to try to represent how exogenous changes (investments or the effects of extreme weather, for example) would impact the actual capacity/punctuality scenario and the user's ability to move by rail. Finally it is worth to point out that despite the analyses presented here have focused on passenger trains, issues like capacity availability and punctuality or reliability are crucial to redirect freight traffic on rails and for more efficient and eco-sustainable logistic chains; such kind of problems can also be addressed with a similar methodology.

6.1 Napoli Centrale – Salerno line

A first application to the Italian line Napoli Centrale – Salerno (see Figure 15) was set in order to test the applicability of some of the methods presented above. The objective of this exercise lies on the estimation of the difference in data needs and results by applying the various capacity and punctuality assessment procedures.

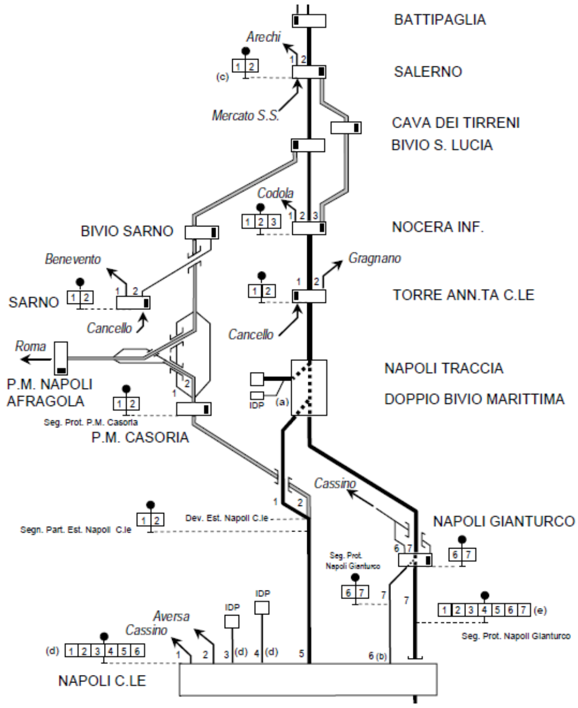


Figure 15: Schematic layout of the Napoli Centrale- Salerno line by RFI

The line includes several parallel sections with different characteristics used by various types of passenger trains (High Speed, Intercity and Regional):

- the long established line from Napoli Centrale to Salerno passing by Torre Annunziata is mainly used by regional trains and it is further divided into two (double track and electrified) lines between Nocera Inferiore and Salerno; the section via Cava dei Tirreni is a complementary line offering mostly local services;
- the High Capacity & High Speed line from Napoli Centrale to Salerno passes by P.C. Vesuvio and reconnects with the traditional line at Bivio Santa Lucia; Intercity and High Speed trains run on it.

Since the High Capacity line is still used by a limited number of trains, we have concentrated our attention on the more congested and critical traditional line passing by Torre Annunziata. Detailed data related both to the infrastructure and to the timetable of the line are available from the RFI (Rete Ferroviaria Italiana) website (Figure 16 and Figure 17.

Grado di Presta-zione	Ascesa ‰	Progressive Chilometriche	Distanze Parziali	LOCALITA' DI SERVIZIO	Posti di Blocco	INDICAZIONI DI SERVIZIO E PROTEZIONE PL	Numero e capacità binari
24	23	36.039		(da Napoli) **NOCERA INF.** (per Codola e Bivio S.Lucia)	15	(1) (4) 3 9.5 40 9	714-273
		36.328	0.289	P.L.		Segn. Part. Est. Nocera Inf. - Pagani	
		36.834	0.506	P.L.		Segn. Part. Est. Nocera Inf. - Pagani	
		37.000	0.166	Cippo			
		37.038	0.038	P.L.A.		Segn. Part. Est. Nocera Inf. - Pagani	
		37.416	0.378	P.L.A.		Segn. Part. Est. Nocera Inf. - Pagani	
		38.772	1.356	P.L.		Segn. Prot. Nocera Sup.	
	25	39.113	0.341	**Nocera Superiore**	16	(2) (4)	-
		39.160	0.047	P.L.		Segn. Prot. Nocera Sup.	
		39.350	0.190	P.L.		Segn. Part. Nocera Sup.	
		40.436	1.086	P.L.A.		Segn. Part. Nocera Sup.	
		40.725	0.289	P.L.A.		Segn. Part. Nocera Sup.	
		42.606	1.881	P.L.A.		Segn.Km. 42+550 Disp.Com.Km.39+750	
1	0	44.624	2.018	**Cava dei Tirreni**	17	(2) (4) 40 9	1 / 345
		47.000	2.376	Cippo			
		48.494	1.494	*Vietri sul Mare*			-
		48.592	0.098	P.B.I.	18	(3)	
		50.000	1.408	Cippo			
		51.992	1.992	*Duomo – Via Vernieri*		(4)	-
		53.090	1.098	Dev. I (da Mercato S.S. e Biv.S.Lucia) **SALERNO**		(4) (21) 100 13	450-272

Figure 16: Schematic layout of the Napoli Centrale- Salerno line by RFI

Km		NA653	NA113	34533	NA411	799	35799	701	34509	NA413	NA115	34601
		2	2 3 11	2 2 5	2 3	R 2 14	R 2 15	R 2	2	2 1	2 1	2 4
	Provenienza	■	■	■	■	Torino	Torino	Roma	■	■	■	■
0	**Napoli Centrale**	e 08.30	.	.	e 08.30	**08.35**	**08.35**	**08.45**	08.50	e 09.00	.	.
5	Napoli S. Giovanni-Barra	08.45	.	.	08.45	.	.	.	.	|	.	.
7	Pietrarsa-S.Giorgio a Cr.	f 08.55	.	.	f 08.55	.	.	.	.	|	.	.
9	Portici-Ercolano	09.05	.	.	09.05	.	.	.	.	|	.	.
12	Torre del Greco	g 09.20	.	.	g 09.20	.	.	.	.	|	.	.
18	S. Maria La Bruna	.	.	.	|	.	.	.	.	|	.	.
23	**Torre Annunziata C.le** 326-327	.	.	09.25	09.40	.	.	.	.	09.30	.	09.55
26	Pompei	.	.	09.31	.	.	.	.	.	.	.	10.01
28	Scafati	.	.	09.37	.	.	.	.	.	.	.	10.07
32	Angri	.	.	09.42	.	.	.	.	.	.	.	10.12
36	Pagani	.	.	09.46	.	.	.	.	.	.	.	10.16
37	**Nocera Inferiore** 325	.	09.35	09.51	.	.	.	.	.	.	10.05	10.21
40	Nocera Superiore	.	c 09.40	09.55	.	.	.	.	.	.	c 10.10	10.25
46	Cava de' Tirreni	.	09.50	10.00	.	.	.	.	.	.	10.20	10.30
50	Vietri sul Mare-Amalfi	.	d ♦ 10.00	10.05	.	.	.	.	.	.	d 10.30	10.35
53	Salerno Duomo Via Vernieri	.	|	10.11	.	.	.	.	.	.	|	10.41
54	**Salerno** a	.	a b 10.15	10.15	.	**09.12**	**09.12**	**09.21**	09.28	.	a b 10.45	10.45
	Salerno 87	.	***10.29***	***10.29***	.	***09.31***	***09.31***	***09.31***	09.31	.	.	.
	Paola 88 a	.	***12.25***	***12.25***	.	***12.47***	***12.47***	***12.47***	12.47	.	.	.
	Lamezia Terme C.le a	.	***12.57***	***12.57***	.	.	.	.	.	.	.	.
	Reggio Cal. C.le a	.	.	.	.	.	.	.	.	.	.	.
	Destinazione	■	■	■	■	■	■	Taranto	Cosenza	■	■	■

Km		34625	34603	NA305	34647	NA655	NA265	NA267	22233	NA415	723	1911
		2 3	2 2	2 1	2 3	2	2 3	2 3	2 16 17	2 3	R 12	R 2 18 19
	Provenienza	■	■	■	■	■	■	■	■	■	Roma	Torino
0	**Napoli Centrale**	.	.	e 09.05	09.13	e 09.15	e 09.20	e 09.20	09.30	e 09.35	**09.50**	**09.55**
5	Napoli S. Giovanni-Barra	.	.	09.20	.	09.30	|	|	.	09.50	.	.
7	Pietrarsa-S.Giorgio a Cr.	.	.	f 09.30	.	f 09.40	|	|	.	f 10.00	.	.
9	Portici-Ercolano	.	.	09.40	.	09.50	|	|	.	10.10	.	.
12	Torre del Greco	.	.	g 09.55	.	g 10.05	|	|	.	g 10.25	.	.
18	S. Maria La Bruna	.	.	h 10.10	.	.	|	|	.	h 10.40	.	.
23	**Torre Annunziata C.le** 326-327	09.57	10.10	10.20	.	.	09.50	09.50	.	10.50	.	.
26	Pompei	10.04	10.16	10.30	.	.	.	.	.	.	.	.
28	Scafati	10.10	10.22	10.40	.	.	.	.	.	.	.	.
32	Angri	10.16	10.27	10.50	.	.	.	.	.	.	.	.
36	Pagani	10.20	10.31	11.00	.	.	.	.	.	.	.	.
37	**Nocera Inferiore** 325	10.25	10.36	11.05	.	.	.	.	.	.	.	.
40	Nocera Superiore	.	10.40	.	.	.	.	.	.	.	.	.
46	Cava de' Tirreni	.	10.45	.	.	.	.	.	.	.	.	.
50	Vietri sul Mare-Amalfi	.	10.50	.	.	.	.	.	.	.	.	.
53	Salerno Duomo Via Vernieri	.	10.56	.	.	.	.	.	.	.	.	.
54	**Salerno** a	10.40	11.00	.	09.52	.	.	.	10.08	.	**10.26**	**10.32**
	Salerno 87	.	.	.	***10.29***	.	.	.	***10.29***	.	**10.29**	.
	Paola 88 a	.	.	.	***12.25***	.	.	.	***12.25***	.	**12.25**	.
	Lamezia Terme C.le a	.	.	.	***12.57***	.	.	.	***12.57***	.	**12.57**	.
	Reggio Cal. C.le a	.	.	.	.	.	.	.	.	.	.	.
	Destinazione	■	■	■	Vallo L.	■	■	■	Sapri	■	Palermo	■

Figure 17: Extract of the timetable of the Napoli Centrale - Salerno line by RFI

An initial capacity and punctuality analysis has been carried out by means of the UIC's analytical method (Code 405), considering an operational time T of about 18 hours (taken from the timetable); in particular Table 6 reports the values obtained applying the methodology to the block sections, while Table 7 reports the results of the simplified approach.

In the first case, the block interval depends on the signalling system: considering a conventional signal system (i.e. with three possible aspects), the block interval along the line will be constituted by 2 consecutive blocks (Figure 18).

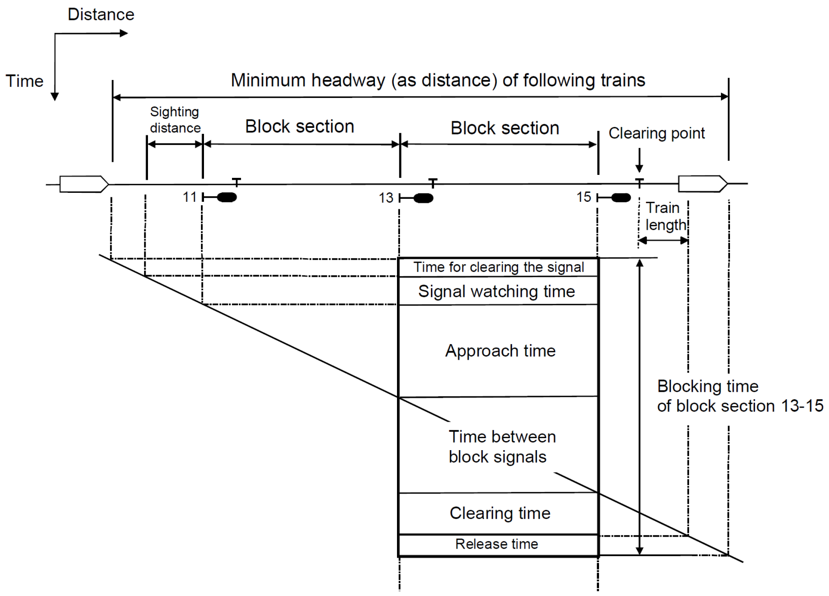


Figure 18: Blocking time by Hansen & Pachl (2014) [45]

Exemptions are required for block intervals entering stations with more shunting platforms besides the running tracks (one train can enter the station even if another train is waiting or departing in the same direction from another platform). Regarding the simplified application (SA), in case of long distance between two consecutive stations we have hypothesized the section divided into more intermediate blocks of length equal to 2 km.

This approximation applies to the sections:

- Napoli – Torre Annunziata (we have information on the intermediate stations only by the infrastructure data of the line but not by the timetables i.e. no train stops at the stations along this section);
- Nocera Inferiore - Salerno via Bivio Santa Lucia.

In both Table 6 and Table 7 we have reported:

- Actual used capacity (utilisation rate) and the related results for queue's length and delays;
- Outcomes corresponding to the UIC's recommended value for the infrastructure occupation, i.e. the expansion margin and the average delay per train assuming a maximum intensity of traffic of 0.60 and thus 1.5 trains in queue.

As it becomes evident, all the results in the two tables (ρ, P, w, t_b) are remarkably similar on average, even if not identical; the major differences, as expected, appear on the longest sections. For the section between Napoli Centrale and Torre Annunziata, we have presented three different types of analysis in Table 7:

- A first approach considering each section between consecutive stations (rows from 1 to 5);

- A second approach considering this entire part of the line as a unique section (row 18);
- A last one hypothesizing this part of the line divided into blocks of a fixed length of 2 kilometres (row 19).

The results of first and last assumptions can be compared with each other and with the results from Table 6.

When applying the last two described assumptions even to the line from Nocera Inferiore to Salerno via Bivio Santa Lucia (rows 12 and 20 in Table 7), the outcomes are less precise due to the actual big distances between signal P141 and P143 and between this last one and the Salerno station (rows 22 and 23 in Table 6).

The results confirm the importance of having access to more detailed data (length of the block sections) to identify bottlenecks or for specific analysis, but on average they could still be considered comparable (see Figure 19) and valuable for large-scale analysis in case of unavailability of comprehensive data. Indeed, it is worth noticing that the relative influence of the waiting time is minor for very long section, due to the prevalent travel time.

Table 6. Application of the UIC's Method (Code 405) to the Napoli –Salerno Line

Section			Length [km]	Average speed [km/h]	Number of trains				Inter-arrival time [mm:ss]	Blocking time [mm:ss]	Actual values			t_c	$\rho = \Psi = 0.6$, $L_q = 1.5$		
N	**From**	**To**			**All**	**Reg**	**IC**	**HS**			**ρ**	**L_q**	**w [mm:ss]**		**t_b [mm:ss]**	**P**	**w [mm:ss]**
1	Napoli Centrale	103 - B.Marittima	2.700	42.0	28	28	-	-	38:34	04:17	0.111	0.125	00:32	-	02:52	151	06:26
2	103 - B.Marittima	Napoli S. Giovanni	2.190	80.3	28	28	-	-	38:34	03:22	0.087	0.096	00:19	-	02:15	192	05:03
3	Napoli S. Giovanni	P107	1.305	119.2	28	28	-	-	38:34	03:31	0.091	0.101	00:21	-	02:22	184	05:18
4	P107	Portici	2.067	150.0	28	28	-	-	38:34	04:37	0.120	0.136	00:38	-	03:06	140	06:57
5	Portici	Torre del Greco	3.473	140.0	28	28	-	-	38:34	04:03	0.105	0.117	00:29	-	02:43	160	06:05
6	Torre del Greco	P113	1.466	140.0	28	28	-	-	38:34	02:48	0.073	0.078	00:13	-	01:53	231	04:13
7	P113	P115	1.160	143.2	28	28	-	-	38:34	03:45	0.097	0.108	00:24	-	02:31	172	05:38
8	P115	S. Maria La Bruna	2.549	145.0	28	28	-	-	38:34	03:42	0.096	0.106	00:24	-	02:29	175	05:33
9	S. Maria La Bruna	P119	1.320	145.0	28	28	-	-	38:34	02:19	0.060	0.064	00:09	-	01:33	279	03:29
10	P119	P121	1.171	145.0	28	28	-	-	38:34	03:19	0.086	0.094	00:19	-	02:13	195	04:59
11	P121	Torre Annunziata	2.694	145.0	28	28	-	-	38:34	02:28	0.064	0.068	00:10	-	01:39	262	03:42
12	Torre Annunziata	Pompei	3.168	130.0	68	68	-	-	15:53	05:26	0.342	0.520	02:50	-	03:38	119	08:10
13	Pompei	Scafati	1.831	150.0	68	68	-	-	15:53	04:35	0.288	0.405	01:51	-	03:04	141	06:53
14	Scafati	PL129	1.908	150.0	68	68	-	-	15:53	04:50	0.304	0.437	02:07	-	03:14	134	07:16
15	PL129	Angri	2.510	150.0	68	68	-	-	15:53	02:58	0.186	0.229	00:41	-	01:59	218	04:27
16	Angri	P133	1.218	150.0	68	68	-	-	15:53	04:07	0.259	0.349	01:26	-	02:45	157	06:11
17	P133	Pagani	2.298	150.0	68	68	-	-	15:53	02:52	0.180	0.220	00:38	-	01:55	226	04:18
18	Pagani	Nocera Inferiore	1.631	150.0	68	68	-	-	15:53	03:41	0.232	0.301	01:07	-	02:28	176	05:32
19	Nocera Inferiore	P.C. Grotti	1.660	150.0	43	43	-	-	25:07	03:44	0.148	0.174	00:39	-	02:30	173	05:36
20	P.C. Grotti	Bivio S. Lucia	2.222	133.8	43	43	-	-	25:07	03:49	0.152	0.179	00:41	-	02:33	170	05:44
21	Bivio S. Lucia	P141	1.630	147.7	66	43	13	10	16:22	05:42	0.348	0.534	03:03	-	03:49	114	08:34
22	P141	P143	4.147	150.0	66	43	13	10	16:22	08:52	0.542	1.182	10:29	-	05:56	73	13:20
23	P143	Salerno	5.152	139.9	66	43	13	10	16:22	05:08	0.314	0.457	02:21	-	03:26	126	07:43
24	Nocera Inferiore	Nocera Superiore	3.074	115.0	35	35	-	-	30:51	04:49	0.156	0.185	00:53	-	03:14	134	07:14
25	Nocera Superiore	Cava dei Tirreni	5.511	140.0	35	35	-	-	30:51	06:20	0.205	0.258	01:38	-	04:14	102	09:31
26	Cava dei Tirreni	Vietri sul Mare	3.968	87.0	35	35	-	-	30:51	05:56	0.192	0.238	01:25	-	03:58	109	08:55
27	Vietri sul Mare	Duomo	3.400	83.8	35	35	-	-	30:51	06:30	0.211	0.267	01:44	-	04:21	99	09:46
28	Duomo	Salerno	1.098	90.0	35	35	-	-	30:51	04:32	0.147	0.172	00:47	-	03:02	143	06:48

Table 7. Application of the Simplified Approach (SA) to the Napoli –Salerno Line

Section			Number of trains				Inter-arrival time [mm:ss]	Blocking time [mm:ss]	Actual values			Distance [km]	Intermediate blocks		t_c [mm:ss]	$\rho = \Psi = 0.6$, $L_q = 1.5$		
N	From	To	All	Reg	IC	HS			ρ	L_q	w [mm:ss]		Hp.	Real		t_b [mm:ss]	P	w [mm:ss]
1	Napoli Centrale	Napoli S. Giovanni	28	28	-	-	38:34	04:17	0.11	0.13	00:32	5	2	1	00:30	02:52	141	06:23
2	Napoli S. Giovanni	Portici-Ercolano	28	28	-	-	38:34	03:31	0.09	0.10	00:21	4	1	1	00:15	02:22	176	05:16
3	Portici-Ercolano	Torre del Greco	28	28	-	-	38:34	02:46	0.07	0.08	00:13	3	1	0	00:15	01:51	222	04:08
4	Torre del Greco	S. M. La Bruna	28	28	-	-	38:34	05:02	0.13	0.15	00:45	6	2	2	00:30	03:22	121	07:31
5	S. M. .La Bruna	Torre Annunziata	28	28	-	-	38:34	04:17	0.11	0.13	00:32	5	2	2	00:30	02:52	141	06:23
6	Torre Annunziata	Pompei	68	68	-	-	15:53	05:26	0.34	0.52	02:50	3	1	0	00:15	03:38	116	08:07
7	Pompei	Scafati	68	68	-	-	15:53	04:35	0.29	0.41	01:51	2	0	0	00:00	03:04	141	06:50
8	Scafati	Angri	68	68	-	-	15:53	04:50	0.30	0.44	02:07	4	1	1	00:15	03:14	130	07:13
9	Angri	Pagani	68	68	-	-	15:53	04:07	0.26	0.35	01:26	4	1	1	00:15	02:45	152	06:08
10	Pagani	Nocera Inferiore	68	68	-	-	15:53	03:41	0.23	0.30	01:07	1	0	0	00:00	02:28	176	05:29
11	Nocera Inferiore	Bivio. S.Lucia	43	43	-	-	25:07	03:44	0.15	0.17	00:39	4	1	1	00:15	02:30	167	05:34
12	Bivio S.Lucia	Salerno	66	43	13	10	16:22	10:20	0.63	1.71	17:42	11	5	2	01:15	06:55	58	15:25
13	Nocera Inferiore	Nocera Superiore	35	35	-	-	30:51	04:49	0.16	0.19	00:53	3	1	0	00:15	03:14	130	07:11
14	Nocera Superiore	Cava de' Tirreni	35	35	-	-	30:51	06:20	0.21	0.29	01:38	6	2	0	00:30	04:14	98	09:27
15	Cava de' Tirreni	Vietri sul Mare	35	35	-	-	30:51	05:56	0.19	0.24	01:25	4	1	0	00:15	03:58	106	08:51
16	Vietri sul Mare	Salerno Duomo	35	35	-	-	30:51	06:30	0.21	0.27	01:44	3	1	0	00:15	04:21	97	09:42
17	Salerno Duomo	Salerno	35	35	-	-	30:51	04:32	0.15	0.17	00:47	1	0	0	00:00	03:02	143	06:46
18	Napoli Centrale	Torre Annunziata	28	28	-	-	38:34	17:53	0.46	0.87	15:28	23	11	10	02:45	11:59	33	26:42
19	Napoli Centrale	Torre Annunziata	28	28	-	-	38:34	05:28	0.14	0.17	00:54	23	11	10	02:45	02:27	122	05:28
20	Bivio S.Lucia	Salerno	66	43	13	10	16:22	05:25	0.33	0.50	02:41	15	7	4	01:45	02:13	148	04:56

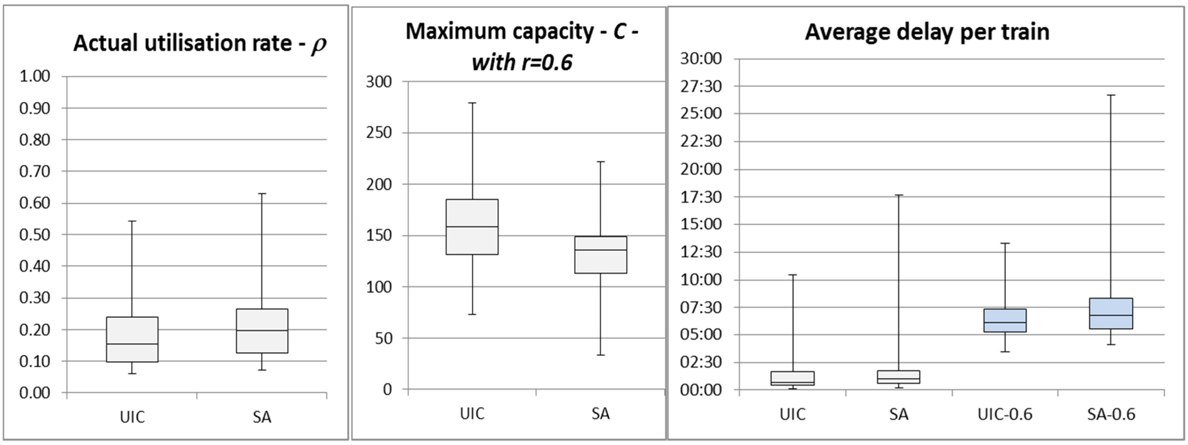


Figure 19: Variability across sections of actual utilisation rate, maximum capacity and delays (actual in grey while assuming ρ=0.6 in light blue) applying the UIC Method (Code 405) and the Simplified Approach

In order to further compare these results we have applied the CUI approach and the UIC's procedure by the Code 406 to the line Nocera Inferiore – Salerno via Bivio Santa Lucia (the most critical one as suggested by the described outcomes of the UIC'405 analytic method).

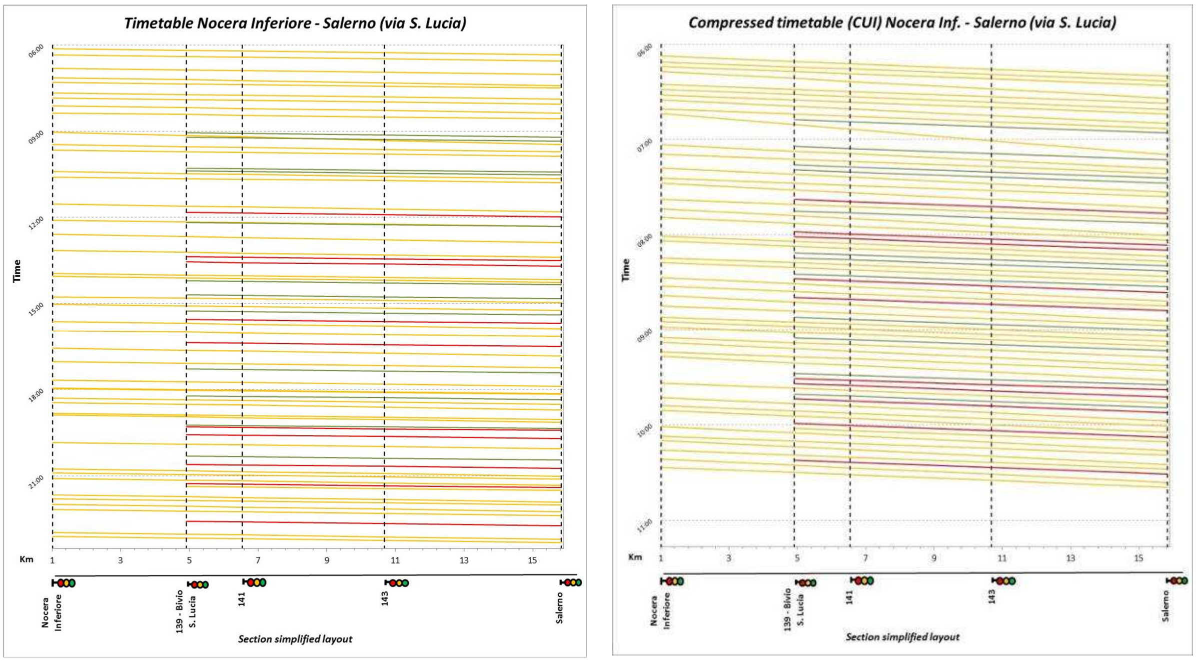


Figure 20: Nocera Inferiore – Salerno (Via S. Lucia): Actual timetable (left) and Compressed timetable with minimum headway of 7 minutes (right)

The regional trains departing from Nocera towards Salerno and the Intercity or High Speed trains entering the line at Bivio Santa Lucia have only a scheduled stop in Salerno.

Therefore, in order to evaluate the minimum headway, we could not refer to the dwelling time (i.e. time a train spends at a scheduled stop without moving for boarding and deboarding passengers or while waiting for traffic ahead to clear, for example) in the intermediate stations (as suggested in Faber Maunsell-Aecom (2007) [53]) but we can only calculate the occupation time corresponding to the different block sections (see Figure 18). In the face of missing or limited infrastructure data, we have assumed for each scenario a different value of minimum headway along the whole line (respectively 3, 5, 7 or 9 minutes).

Nevertheless, we have also calculated this time for the application of the UIC' methods (around 9 minutes, see row 22 in Table 6).

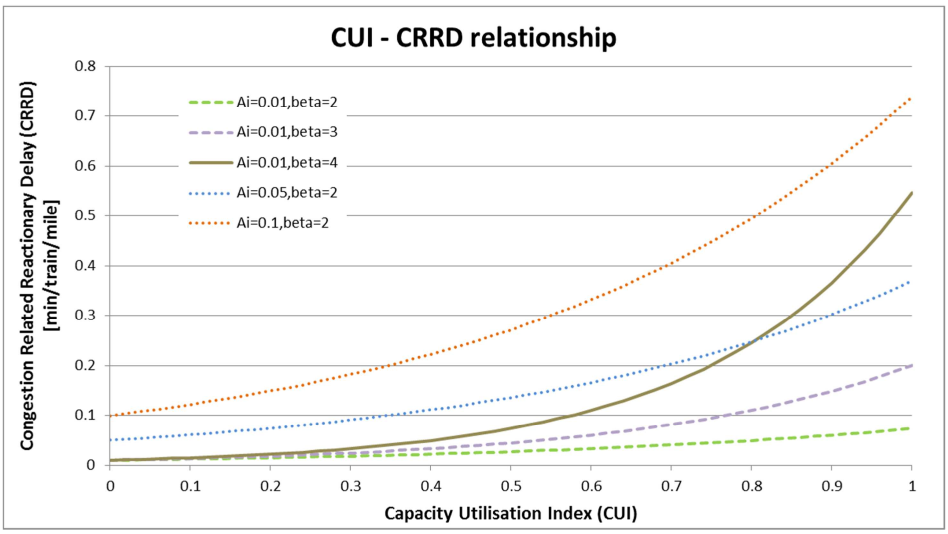


Figure 21: CUI- CRRD Relationship for various values of *Ai* and *β*.

Table 8. CUI Approach Results for the Section Nocera Inferiore – Salerno (via Bivio Santa Lucia).

Headways [minutes]	**CUI**	***A_i***	***β***	**CRRD per train mile [min]**	**CRRD [min] Nocera – Salerno (via Bivio S. Lucia)**
3	0.26	0.01	2	0.017	0.25
			3	0.022	0.33
			4	0.029	0.43
		0.05	2	0.085	1.25
			3	0.11	1.63
			4	0.144	2.13
		0.1	2	0.169	2.51
			3	0.221	3.27
			4	0.287	4.25
5	0.39	0.01	2	0.022	0.32
			3	0.032	0.48
			4	0.048	0.70
		0.05	2	0.109	1.61
			3	0.161	2.38
			4	0.238	3.52
		0.1	2	0.218	3.23
			3	0.322	4.77
			4	0.475	7.04
7	0.52	0.01	2	0.028	0.42
			3	0.047	0.70
			4	0.079	1.17
		0.05	2	0.14	2.08
			3	0.235	3.48
			4	0.393	5.83
		0.1	2	0.28	4.15
			3	0.47	6.96
			4	0.787	11.65
9	**0.64**	0.01	2	0.036	0.53
			3	0.069	1.02
			4	0.13	1.93
		0.05	2	0.18	2.67
			3	0.343	5.08
			4	**0.651**	**9.65**
		0.1	2	0.361	5.35
			3	**0.686**	**10.15**
			4	1.302	19.29

Figure 20 reports the actual timetable and the compressed timetable in the hypothesis of minimum headway of 7 minutes, while Table 8 reports the calculated values for the capacity utilisation index and the reactionary delay.

Regarding the CRRD parameters, NetworkRail has evaluated the values of Ai and β on the entire railway network in Great Britain. As these can only be extrapolated to other networks based on specific studies, for the scope of this analysis we have assumed a set of significant values (see Figure 21).
The assumptions Ai=0.01 and β=3 will lead to a congestion related reactionary delay per train along a section of 100 miles equal to 1 minute with a CUI=0, equal to 4.5 minutes with a CUI=0.5 and finally a delay of around 20 minutes per train every 100 miles with a CUI value of 1. It is interesting to observe that the relative variation of CRRD between two scenarios is independent from A (due to the ratio between the compared values), while it depends only on β.
The next figure reports the compressed timetable (UIC's 406 procedure) with the buffer time for the considered line section.
The total occupation time A (see Eq.(8)) results equal to about 10 hours and 50 minutes, corresponding to an infrastructure occupation (A/T) referred to the whole day of 45%, lower than the UIC's recommended value of 60%. The average minimum headway (A/N) is equal to 9 minutes and 50 seconds and considering the STRELE formula with ρ=60%, we obtain an average determinative buffer time of around 6,5 minutes. The final capacity consumption K (including both A and B, i.e. the total infrastructure occupation and the total buffer time) is 75% and the optimal number of trains will be:

$$N = \frac{T}{\bar{z} + \bar{t}} = 87.8 \tag{16}$$

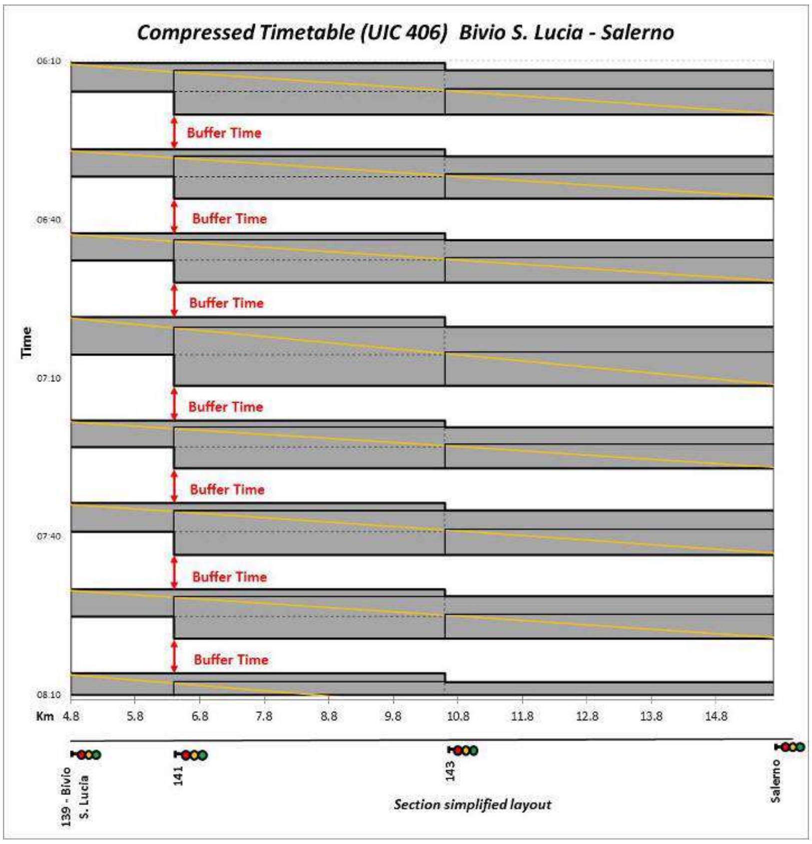


Figure 22: Extract of the compressed timetable with buffer times for the line section Bivio Santa Lucia – Salerno (UIC''s 406 procedure).

Comparing these results with the outcomes of the UIC 405 (row 22 Table 6) and of the CUI (Table 8), they are quite similar; moreover, they are also more or less of the same order of magnitude of the results obtained by applying the proposed simplified method with accuracy/precision depending on the real lengths of the neglected block sections (see Table 9).

Table 9. Brief comparison of the main results with the different approaches

			Average minimum headway [mm:ss]	Average determinative buffer time – t_b [mm:ss]	Capacity - Optimal number of trains (ρ=0.6)
Section 1			***Napoli Centrale - Torre Annunziata***		
a	**UIC 405**		04:37	03:06	140
b	**Simplified Approach -2km**		05:28	02:27	122
c	***Absolute variation (a-b)***		-00:51	*00:39*	*18*
d	***Relative deviation (c/a)***		-18%	*21%*	*13%*
Section 2			***Bivio Santa Lucia – Salerno***		
e	**UIC 405**		08:52	05:56	73
f	**Simplified Approach**	**whole section**	10:20	06:55	58
g		**2km sections**	05:25	02:13	148
h	**CUI Method (*A* = 0.1 , *β*= 2)**		09:00	05:35	75
i	**UIC 406**		09:50	06:34	88
Relative deviations	***(e – f) / e***		*-17%*	*-17%*	*20%*
	(e – g) / e		*39%*	*63%*	*-103%*
	(e – h) / e		*-2%*	*6%*	*-3%*
	(e - i) / e		*-11%*	*-10%*	*-20%*
	(f – g) / f		*48%*	*68%*	*-155%*
	(f - h) / f		*13%*	*19%*	*-29%*
	(f – i) / f		*5%*	*5%*	*-51%*
	(h - g) / h		*40%*	*60%*	*-97%*
	(h – i) / h		*-9%*	*-17%*	*-17%*
	(i – g) / i		*45%*	*66%*	*-69%*

6.2 Simplified analysis of the member states railway networks: an application to Italy

The ultimate objective of this section is to provide with a straightforward method in order to assess congestion on broad-scale railway networks, notwithstanding the lack of detailed infrastructure data at link level. The analysis is based on the UNECE's rail census data for 2005 [63] providing information regarding length, traffic (annual and daily), number of tracks, etc. for the European railway network at corridor level. Since the database does not contain any information regarding travel time, it has been enhanced with speed values for each link from the ETISPLUS dataset for 2005 [64].

Finally for section length, a key factor in the estimation of congestion as discussed in the previous sections, we have assumed each line divided into sections of around 2 kilometres (for the single lines, instead, we have assumed a determining distance between crossing or overtaking stations of 8 kilometres).

For each section, it was possible to calculate a restrictive travel time based on this conventional length, on the maximum allowed speed and assuming a time of 30 seconds for sighting, clearing and release of the signalling system. Of course in case of more detailed information on different allowed speeds for trains per category (e.g. Intercity, Regional, Freight, etc.), it could therefore be possible to calculate the running time for each section based on actual operation.

The UNECE database provides information for each corridor only on the eventual length of segments with one or two tracks; this means that is not possible to split the single or double-track sections and that in our analysis the capacity of the whole corridor is conditioned by the capacity of single track sections, if any (Figure 23).

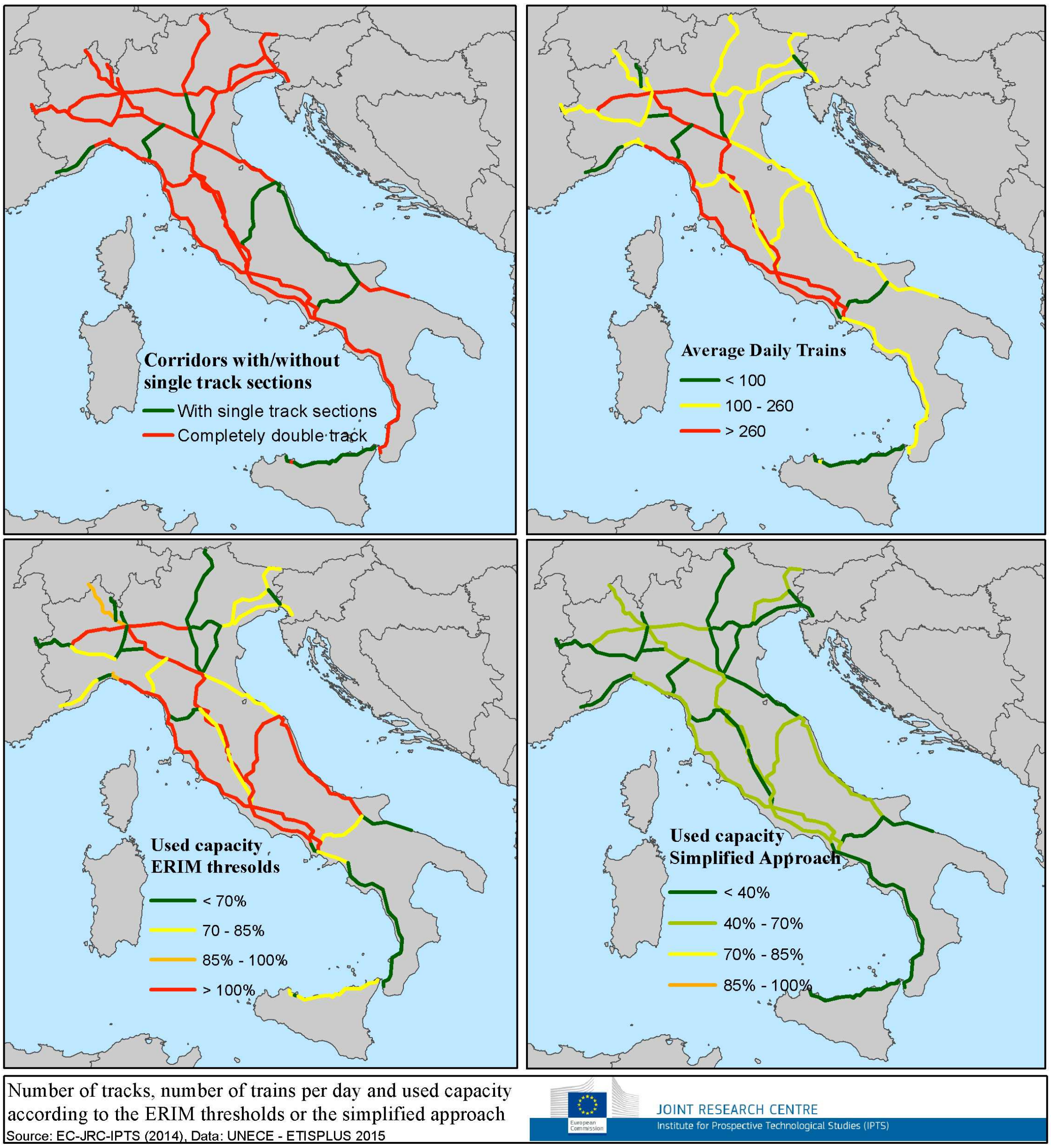


Figure 23: Italian railway network – 2005: Number of tracks, daily trains and used capacity according the ERIM capacity thresholds or the simplified approach.

To better explore the simplified approach and its added value compared to procedures considering only fixed capacity thresholds, which is the reference method for a majority of studies and strategic analysis where lack of detailed data hinders the application of many of the methods presented in the previous section, the previous maps (see Figure 23) illustrate for relevant links of the Italian network the level of capacity usage according to the UIC ERIM ATLAS project [90] recommendation (bottom left) or applying the proposed simplified approach (right). The UIC ERIM ATLAS approach considers fixed values for daily average traffic as capacity thresholds for single (i.e. 100 trains/day) and double track lines (i.e.. 260 trains/day); the used capacity (saturation level) per each link has been calculated as ratio of the average daily trains (volumes) and the mentioned limits of daily capacity. This procedure is fast, simple and widely spread but shows various limitations. In the present case, it leads to the identification of severe congestion (>100%) and saturation (85%-100%) on several lines as the thresholds do not take properly in account the characteristic of the line, in particular the speed and the signalling system (three aspects; i.e. importance of block length).

In practical terms, by assuming fixed limits for the capacity of a line based only on the number of tracks, we imply that such line can tolerate the same traffic load either if the maximum allowed speed is 100 km/h or 150 km/h or even 200 km/h; also the heterogeneity of the traffic is not taken in account unless proposing different ranks based on different or more detailed characteristic of the lines. The simplified approach instead, takes partially into account these factors, either adding actual detail when available or making reasonable assumptions on these data (see previous section). The results of this methodology show a striking difference regarding capacity usage assessment when compared to the *'fixed thresholds'* assessment approach, with capacity consumption actually below acceptable limits for all considered lines.

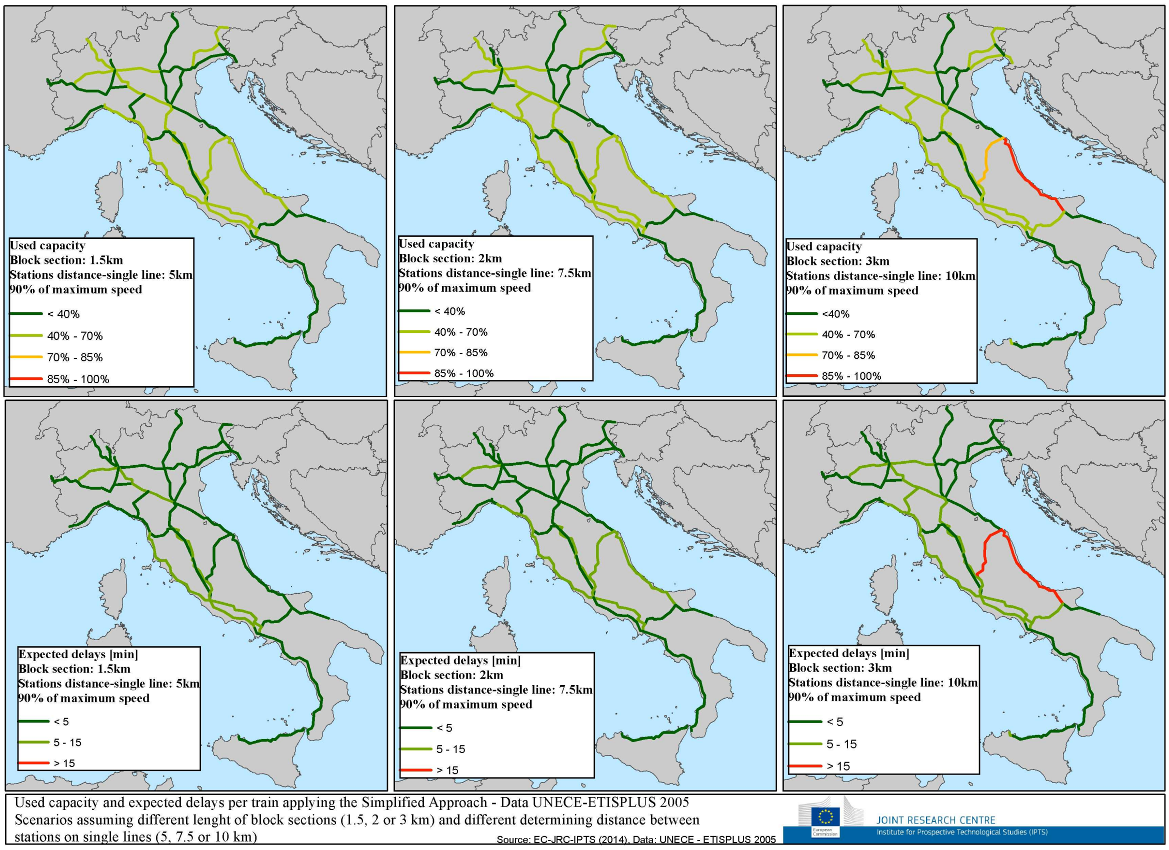


Figure 24: Used capacity and expected delay per train applying the Simplified Approach for three different scenarios (length of block sections of 1.5, 2 or 3 km and determining distance between stations on single lines of 5, 7.5 or 10 km).

The simplified approach also allows us to estimate values of expected delay per train (see Figure 24). This is a particularly useful insight as some lines might show high levels of used capacity without significant impacts on delay, due to homogeneous traffic or slower trains.

Figure 24 shows also the importance of the assumptions introduced in the Simplified Approach when considering different values of the block lengths and distance between nodes for single track lines.

As it is evident from the previous maps, assuming different average lengths of block sections (1.5, 2 or 3 km with a three aspects signalling system), results in varying used capacity and the expected delay values; however they remain rather stable for double track, falling under acceptable levels of congestion. The results for single lines show a higher sensitivity to these assumptions. The corridors with increasing congestion results evince mainly issues with available data versus actual, more detailed information on infrastructure. Ancona-Foggia on the Adriatic coast is a double track corridor (and corresponding high reported traffic volumes) with a single line segment (33 km out of 350 km) of unreported location, which must be considered in the analysis as a bottleneck impacting the overall performance of the whole line, thus the high level of congestion and delay. Ancona-Roma (East-West central corridor) is characterized by single track for more than half its length (132 km on 211 km between Ancona and Orte) and by an average maximum speed of 110 km/h, clearly too low. The presented results show the importance of the assumptions considered in the simplified methodology for single track corridors, where generally further detail is needed and specific analysis can reasonably carried out. All in all, this outcome should be considered with increasing confidence as the level of detail of input data improves; nevertheless, under limited data availability, this analysis still offers valid global indications.

In order to underline the potential and the relevance of the presented methodology, it should be pointed out that similar kind of analysis, based on actual timetables, has already been proposed at country level in different EU members. Landex (2009) [41] proposed similar maps of capacity consumption in Denmark and Sweden, while a slightly different analysis has been carried out by Department For Transport of London in [65]. This UK report evaluates load factors, defined as number of passengers divided by total capacity (focusing on crowding more than infrastructure capacity; i.e. see also the last paragraph of the report) during peak and peak-off hours both at national level and for the London area. Other analyses conducted by Cambridge Systematics Inc. in [16] and in [17] proposed a similar analysis to compare trains volumes (focusing particularly on freight) with current and future train capacity respectively in the United States or only in a given State (Minnesota).

The leading idea of this section is to propose a user-oriented evaluation of the railway travel time conceived both as an operational and performance index of the level of service and as an impedance indicator (for accessibility or cost-benefit analysis, etc.). To start with, the travel time between two stations along a line could be treated as sum of time on board, waiting time depending on the frequency of the services and waiting time for delays of trains (depending on the used capacity or 'congestion' of the line between i and j):

$$t_{ij} = t_{board} + t_{waiting\,(frequency)} + t_{waiting\,(delay)} \tag{17}$$

According to the available data and to the scope of the analysis, it is possible to use the previous formula with a different level of detail. A manageable way to evaluate the time on board is based on the actual timetable proposed by the Rail Undertakings, while most accurate calculations require more data or assumptions. According to the infrastructure and/or rolling stock characteristics it is possible to evaluate (or even better to simulate with software tools) the speed-diagrams along each section of a line for each train type.

For the evaluation of the waiting time related to service frequency (scheduled departures), it could be easy and straightforward to use a deterministic approach, as already proposed in many contributions (see Hesse et al. (2013) [67] or Douglas & Miller [68].

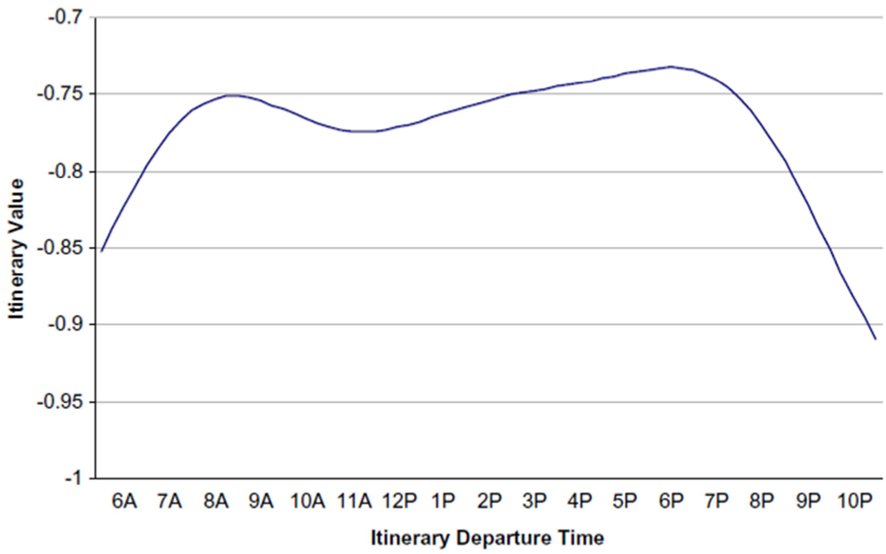


Figure 25: Passenger departure time preferences by logit deviation sin–cos schedule delay model (source Koppelman et al. (2008) [70])

It is possible to obtain a better representation of this parameter or a more detailed analysis for peak or off-peak hours, by extending this approach including the actual (continuous or discrete) distribution of departures (scheduled timetable) and passengers' preferred time of departure. They can be based either on a model (e.g. the logit deviation sin–cos schedule delay, see Koppelman et al. (2008) [70] and Figure 25) or on estimations by mean of revealed preferences (RP) / stated preferences (SP) surveys (see Cascetta & Coppola (2012) [71] and Figure 26).

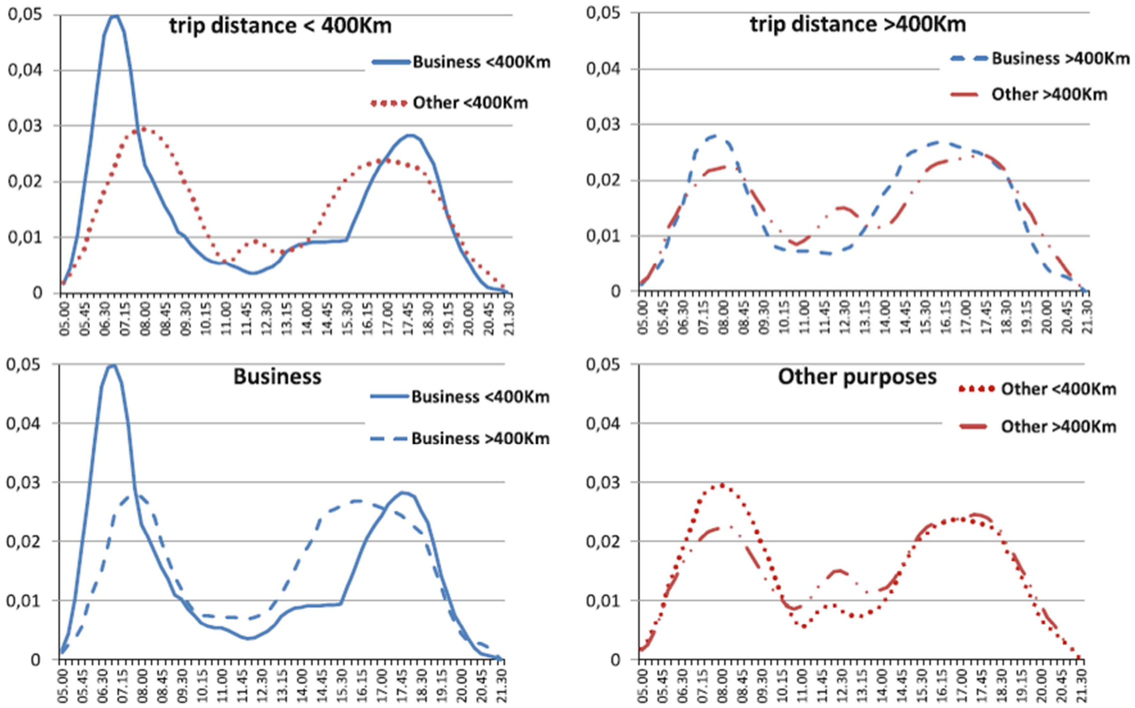


Figure 26: Passenger desired departure time estimated by a RP-SP survey on Naples-Rome HS line Cascetta & Coppola (2012) [71]

The described capacity and punctuality assessment methodologies could allow evaluating the unscheduled waiting time and the infrastructure utilisation rate.

To offer a more comprehensive picture, we have further deepened the Italian case study to embed the already described capacity/punctuality results in a wider geographical accessibility analysis. The topic of accessibility and related indicators have been widely treated in the scientific literature of the last years (see for example Hesse et. al. (2013) [67], Geurs & Ritsema (2001) [73], Wegener et al, (2002) [74], Rotoli et al. (2014) [75]) and in several European and international research projects or studies (e.g. Spiekermann & Wegener (2007) [72]). Although the definition of accessibility may slightly differ among the various authors, it is possible to define it negatively as *"the amount of effort to reach a destination"* or positively as *"the number of activities which can be reached from a certain location"* (Geurs & Ritsema (2001) [73]). Indicators of accessibility measure the benefits households and firms in an area enjoy from existence and use of the transport infrastructure relevant for their area (Wegener et al, (2002) [74]).

As highlighted in Wegener et al, (2002) [74], accessibility indicators could differ in complexity and they may be sensitive to several dimensions: origin, destination, spatial impedance, type and mode of transport, etc.

Due to the limited level of detail of the considered UN rail network (i.e. only main lines) the analysis has assumed as origins and destinations the Italian NUTS2 zones (i.e. mostly regions), considering that each trip will start or end in the most important station on the main lines. More detailed infrastructure and timetable data could allow a much better representation of the network and an accessibility analysis at NUTS3 level (i.e. provinces) or even per cities/stations.

The spatial impedance between two regions can be defined as the travel time over the rail network calculated by means of Eq. (17). The travel time on board has been set equal to the ratio of the length of the section on the 80% of the maximum speed allowed by infrastructure's characteristics; the adopted reduction in speed takes partially into account the different speed profile along a line, the acceleration and deceleration phases, the different behaviour of the drivers, etc.

When two or more lines connect two regions/capitals (e.g. the Florence-Rome-Naples section) the time on board is the average time, weighted on the daily number of services for each line. Finally, for peripheral cities of regional interest, an additional extra time of 30 minutes to represent the access or egress time to the station (e.g. by regional railway lines) is included.

Regarding the average waiting times related to service frequency (*'frequency delay'*), for simplicity (and unavailability of more detailed data, e.g. timetable), we have followed the approach already proposed by Hesse et al. (2013) [67] and based on previous analysis developed by Douglas & Miller (1974) [68]:

$$t_{waiting\,,\,frequency} == \frac{T}{4 \times F} \tag{18}$$

where T denotes the reference (window) time and F the number of services along the line within T.

Hesse et al. (2013) [67] defined the schedule delay or *"frequency delay"* as the difference between the favourite and the real time of departure. It describes the mean of minimum (i.e. zero) and maximum waiting time. In practice, the passengers' preferred time of departure is assumed to be distributed uniformly over a circular period of time, so that each individual passenger takes the average schedule delay into account.

The waiting time due to service's frequencies between two NUTS2 regions is the maximum waiting time along the lines connecting the two zones (corresponding to the section with lowest frequency).

When a direct connection between two zones is not scheduled, an extra interval of 10 minutes takes into account the waiting time spent at the interconnection to change train.

Of course, a detailed timetable (see for example Vannacci et al. (2015) [76]) would allow a more precise identification of direct and indirect connections and related frequencies for each line/corridor and among different destinations, but it is not in the scope of this exercise.

Lastly, for the calculation of the unscheduled waiting time due to the delay of trains, we have applied the previously described Simplified Approach (see Section 5.1.1), assuming as reference values for infrastructure parameters presented in Section 6.1 for the double track lines and a distance between nodes of 7.5 km for single tracks (see Figure 24); for each couple origin-destination the expected delay due to the capacity utilisation has been assumed equal to the maximum delay generated on the sections of lines connecting the two zones (i.e. neglecting propagation effects).

The described procedure allows us to calculate the travel time t_{ij} between each couple of NUTS2 regions. On this basis, it is possible to proceed with the accessibility analysis. In particular we have considered two different accessibility indicators, the location index (L) and the potential accessibility (PA).

The location index represents the average travel time between each couple OD weighted on the population of the destination regions:

$$L_i = \frac{\sum_j t_{ij} \times W_j}{\sum_j W_j} \tag{19}$$

where:

- L_i represents the location index of origin i;
- t_{ij} represents the travel time between i and j;
- W_j represents the population of destination j (activities in j).

Figure 27 reports in ArcGis Maps for each NUTS2:

- The values of the location index considering the travel time as described in Eq. (17)
- The variations and the percentages of variation of the location index assuming the travel time expressed by Eq. (17) or considering only the time on board to define it (neglecting the waiting times due to frequencies and delays).

Figure 27 indicates not only which regions are connected with others by means of higher travel times, but also how including the waiting times as proposed above will induce an impact on average travel times within 3% and 8% (depending on the region). Moreover, as expected, the maps show high values of location index not only in southern peripheral zones (Calabria, Puglia or Basilicata) but also in central regions as Umbria, or in northern regions as Liguria, Friuli Venezia Giulia and Trentino Alto Adige.

The potential accessibility, instead, is a combination of two functions: the activities function (representing the activities or opportunities to be reached) and the impedance function (representing time, distance or cost needed to reach them):

$$A_{im} = \sum_j W_j \times F(c_{ij}) \tag{20}$$

where:

- A_{im} represents the accessibility of origin i by mode m (i.e. rail in our analysis);
- W_j represents the population of destination j (activities to reach in j).

- $F(c_{ij})$ represents the impedance function depending on the generalized cost to reach destination j from origin i;

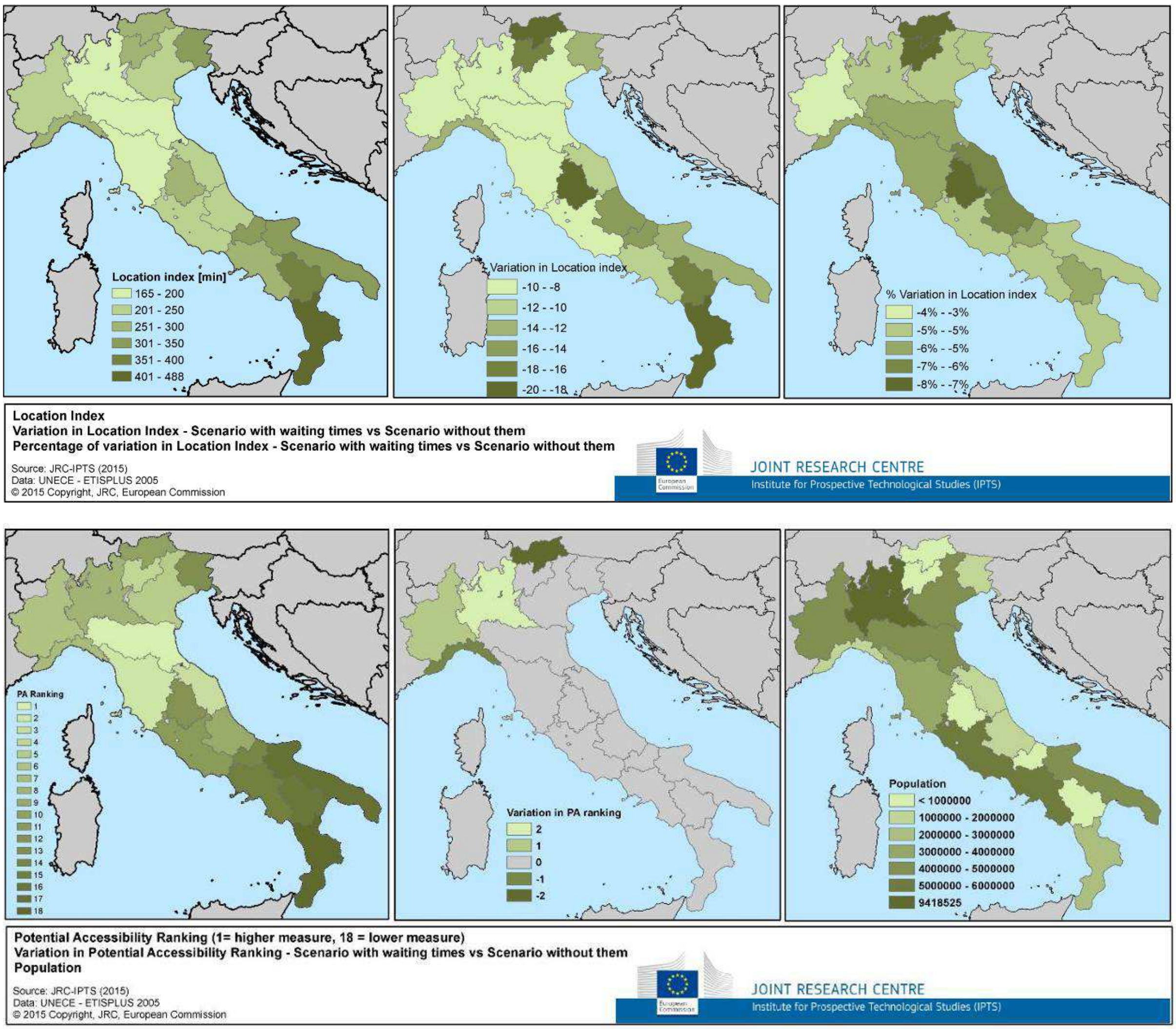


Figure 27: Location Index (top) and Potential Accessibility (bottom), by using the Simplified Approach.

In practice Eq. (20) calculates the total of activities reachable in j weighted by the ease of getting from i to j. As described by the impedance function, the interaction between locations declines with the increasing disutility (distance, time, and/or costs) between them. Several forms of distance decay function have been already widely investigated; here we have assumed a negative exponential function:

$$F(t_{ij}) = e^{-\beta t} \tag{21}$$

With the parameter β set to 0.005.

This means that:

- For a travel time between two regions of zero minutes (which does not occur in reality), the population of the destination region would be included with its full value in the potential accessibility of the origin region;
- For a travel time of little more than two hours the weight is 0.5, and for a travel time of little more than five hours the weight goes down to 0.2.

Figure 27 reports:

- the ranking of potential accessibility across Italian regions (using Eq. (17) for travel time);
- the variation in ranking neglecting the proposed waiting times;
- the population of each region.

We have reported also the population for each region, since as evident from Eq. (20) and Eq. (21) the proximity of highly populated areas would influence the accessibility. Despite this, zones as Basilicata, Umbria, Friuli Venezia Giulia, or the provinces of Bolzano and Trento are at the bottom of the ranking, showing clearly a lower level of service by rail (and a high average travel time, Eq. (19)).

Moreover, Figure 27 shows also how the effects of frequency and delay (waiting time in Eq. (17)) influence the ranking in potential accessibility of some regions. In particular, Liguria and Alto Adige areas loose ranking positions while Lombardia and Piemonte districts gain ground.

The final aim of the authors is to notice how maps as the ones reported in Figure 23 and Figure 24, together with accessibility maps by rail (Figure 27) could offer a highly valuable tool for decision makers. They allow them to identify not only areas more or less accessible from/to other zones but also to evaluate how and where improvements in infrastructure and/or levels of service could benefit users.

7. Modelling railway transport with capacity constraints

Network-based transport modelling at EU-level is a challenging task, albeit a necessary one in order to provide policy makers with a quantitative assessment of the European transport system. In this respect, the ability to capture modal shifts and multimodality aspects of the transport systems, calculate external costs or carry out any type of corridor analysis, among others, are hindered by the lack of proper capacity constrains representation of the railway system. Modelling rail capacity constraints is not straightforward, as evidenced throughout this report, and the level of complexity depends upon the availability of input data and its level of detail as well as the expected accuracy of the outcome; in this section we summarise existing different approaches to model railway systems at a large scale and in particular, infrastructure-related capacity constraints.

As mentioned previously in the report, the main issue in creating (and eventually maintaining) an adequate rail infrastructure dataset, especially at European level, arises from quality and availability of data. It is worth to underline that there are several public (openly available even if not fully comprehensive) sources of information, such as OpenStreetMap, the GTFS-based dataset provided by Rail Undertakings (e.g. UK, Netherlands, France, etc.) or the Register of Infrastructure (RINF) of the European Railway Agency; particularly interesting is the attempt by the RailML initiative to develop an interchangeable format for infrastructure data.

Possible raw data sources for the infrastructure are in general (see Hansen & Pachl (2014)[45]): track layouts plans, signalling plans, illustrative schematics and data on various electronic devices/format (Mysql or Oracle databases, RailML files, Excel-sheets, OpenStreetMap and GIS-based information, public internet websites, etc.). Once the data are collected and stored, the easiest, straightforward and more flexible way to model railway infrastructures is represented by the graph theory; it allows depicting even the more complex railway system in an efficient mathematical model. These kinds of models can be extended and modified without huge issues. The infrastructure elements (tracks, block sections, signalling systems, gradients/radius/overlap sections, etc.,) are represented by links bounded by nodes.

The level of infrastructure detail can be defined as follow (see chapter 3 of Hansen & Pachl (2014) [45] and also next figure):

- Microscopic node-link models contain the highest possible level of details on links and nodes, depending on the purpose (and of course on the availability of data).
- Macroscopic node-link models contain aggregate information on nodes and links (with less accuracy/detail of outcomes)
- Mesoscopic node-link models are synthesis of microscopic and macroscopic infrastructure models.

Using a graph model it is possible to represent not only the concrete characteristics of the system, but also abstract dependencies and rules, in order to process different railway issues/analysis by means of (computer) algorithms; indeed several really efficient mathematical algorithms and heuristics already exist for optimisation problems, such as (beyond the well-known shortest path problem and the Dijkstra algorithm) the calculation of maximum or minimum flows in graphs-network taking in account capacity functions to the links or nodes. As well stated in Hansen & Pachl (2014) [45], *'it is proven by a large number of applications that graph theory can model very complex and large railway infrastructure in a mathematical model. Furthermore, efficient algorithms and concepts to store the data and to solve railway operational problems have been developed'*.

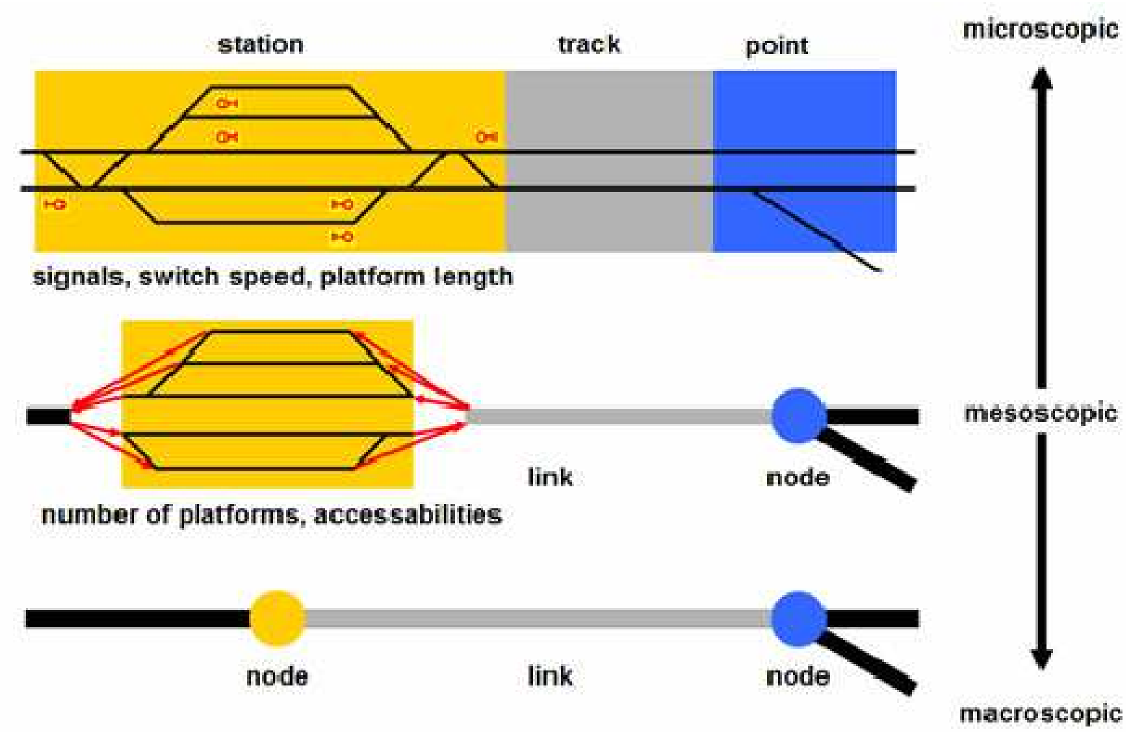


Figure 28: Transforming detail level of railway infrastructure models, Gille et al. (2008) [84]

Trying to better describe and analyse the detail level of the infrastructure model, unlike the microscopic graphs, the macroscopic approach considers far fewer links and nodes (see next figure); a node represents a station or a junction in the network, while the links represent the line sections between two consecutive nodes usually holding the following aggregate information:

- length
- type of line
- number of tracks
- train availability (electrification, axle load, loading gauge)
- average running time
- average capacity (e.g. according to UIC 406)

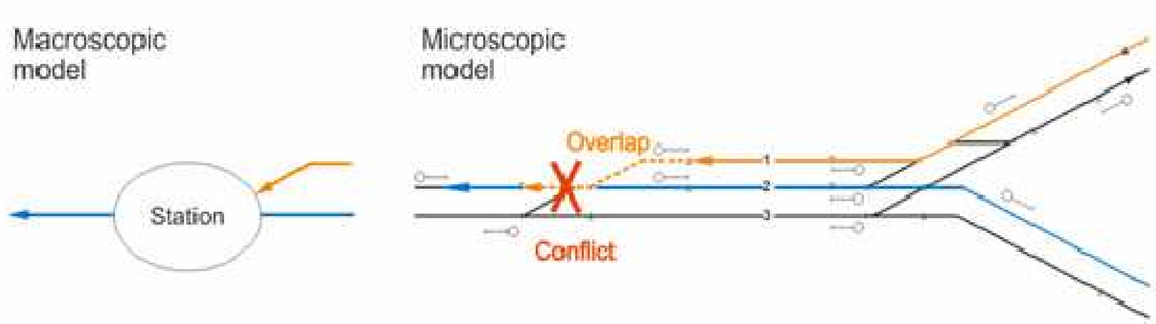


Figure 29: Difference in detail in infrastructure modelling (micro vs macro approaches), Gille et al. (2008) [84]

Macroscopic data can be entered manually or downloaded/derived from different sources: public websites (IM or RU websites, OpenStreetMap, etc.) but also transport databases used for European transport models (e.g. EtisPlus database, UNECE rail census database, DG REGIO/GISCO Database, partially EUROSTAT database, etc.).

Of course, if microscopic infrastructure databases or models are available, a direct migration of data could allow a more detailed transformation of information (e.g., better evaluation of average running time and average capacity which represent the weakest/less accurate factors of macroscopic approaches). The level of required detail is very high including not only infrastructure data (among others, length of the link, gradient, permitted speed per train type, radius, electrification, signalling systems (M/P, ATC, LZB, ETCS 1-3, multi-aspect signalling), release contact and clearance location, block and routes, interlocking techniques, etc.) but also operating information (exclusion of routes, maintenance and repair works, etc.).

In general, macroscopic models are preferred for long term capacity planning (and evaluation), traffic generation and assignment problem, vehicle scheduling etc.; in particular one of the main applications for long term planning and traffic assignment purposes is represented by the individuation of feasible train paths in the network without time restrictions (e.g. in order to introduce new services during assignment, to allocate slots for and/or rerouting freight/passenger trains, or to evaluate the effects of policy actions on traffic assignment/flows).

In this context, the simplified approach proposed in the previous sections provides a simple and straightforward methodology to estimate the average capacity and running time of a macroscopic model based on aggregated open and available data (UNECE rail census and EtisPlus) in order to evaluate the capacity/scarcity constraints of wide (possibly European) rail networks.

The mesoscopic model is an intermediate stage between micro and macro models. It reduces the data need/complexity compared to a microscopic model and is often used when microscopic data is not available. A typical approach could be to transform the approximate information of a macroscopic network into data with a higher level of accuracy, by means of established knowledge of the rationalities and habits in railway construction and operation (assumptions). This is the approach we partially tried to follow in our evaluation of rail capacity, by inserting in a more general/aggregate macro method average information related to the rail line (namely average length of the block section). Clearly the proposed approach is quite simple and *'basic'*, but of course it could be modified/complicated according to the level of detail of available data and the purpose of the analysis; here we want to point out once again how the proposed methodology and mesoscopic models in general can provide just average, indicative capacity measures, while to obtain more accurate and/or completely reliable figures it is strongly recommended the application of microscopic models (Hansen & Pachl (2014) [45]).

Of course the methodologies presented in the previous sections of the report and the models just described here allow facing the issue of capacity scarcity and related delay from an infrastructure point of view; that means they evaluate the number of vehicles running on the network compared to the links capacity. Anyway, since the majority of the models for assigning passengers to transport network and considering capacity constraints refer to vehicle or platform capacity (crowding) here we want to present also a brief summary of this methodologies. A good overview of the issue is provided by Nuzzolo & Crisalli (2009) [77], Nuzzolo & al. (2012) [78] and Fu et al. (2012) [79]; the transit assignment models can be distinct in 2 different classes: frequency-based (also called headway or line based) and scheduled based (also known as timetable or run based). In general the first category is more used for high frequencies, requiring less detailed information but not always taking in account capacity constraints.

''However, when modelling highly congested networks a static frequency-based approach is not sufficient as it does not reveal the peaked nature of the capacity problem. The central idea for dealing with the line capacity constraints is the introduction of a ''fail-to-board" probability as in some circumstances passengers are not able to board the first service arriving due to overcrowding.'' (Schmöcker et al. (2008) [80]). The scheduled based models, instead, are often adopted for low frequencies and they allow considering

dynamic effects. Nuzzolo & Crisalli (2009) [77] and Nuzzolo & al. (2012) [78] describe in detail this category, differentiating between disaggregate and aggregate approaches; while the first ones consider the performance of each vehicle and take in account each individual user, the aggregate models consider groups of vehicles and users with common characteristics. In particular in Nuzzolo & al. (2012) [78] passengers flows are assigned according to user´s choices (waiting for next vehicle, changing stop or departure on time) and capacity constraints (crowdedness) in a dynamic approach.

In general schedule-based models specified at disaggregate level for both supply and demand can be classified as schedule-based microsimulation models; they are *''usually structured as discrete time simulation, in which individual user behaviour is considered accounting for interactions with other users boarding the same vehicle, and vehicle arrivals depend on the interactions with other vehicles on the same link. If vehicle capacity is reached, additional users are not allowed to board (fail-to-board event) and have to wait for following vehicles''* (Nuzzolo & al. (2012) [78]). It is important to notice that the schedule-based transit assignment has been implemented in both non-commercial and commercial software, such as Transcad by Esri.

Beside the mentioned *'transit-related'* articles, various authors concentrate in particular on the railway mode. Among others, Cascetta & Coppola (2012) [71] proposed an elastic demand schedule-based multimodal assignment model for the simulation of the Italian high speed rail systems, Shi et al. (2012) [81] presented a path-based traffic assignment algorithm accounting for transfer reliability while Han et al. (2015) [82] suggested a stochastic user equilibrium model for solving the assignment problem in a schedule-based rail transit network with capacity constraints (overload delay factor for in-vehicle crowding).

Last but not least, we would like to cite two interesting contributions dealing with the modelling issue of rail demand and capacity. In particular the first article, Blainey et al. (2012) [83], describes a capacity and demand assessment model for the UK transport system in which for the rail mode the capacity constraints are described simply by a Capacity Utilisation parameter, given by the number of trains (number of train kilometres) divided by the number of tracks (number of route kilometres) between two zones; this application clearly show how simple measures of capacity constraints (such as the capacity thresholds and the analytical methods described in the previous paragraphs) can be easily and profitably integrated in transport models.

Finally the Network Modelling Framework (NMF) and Appraisal for High Level Output Specification (HLOS) by Department of Transport (London) [65], [66] represents a very good example of how infrastructure and vehicle capacities can be integrated in the same model. The following figure describes the structure of the model; the train services (timetable) and the CUI (Capacity Utilisation Index) together with the demand are the input factors of the assignment model, while the crowding is the output. Of course service changes will influence both performance and demand while the impact of crowding on demand (to generate constrained demand) is estimated by using time crowding penalties.

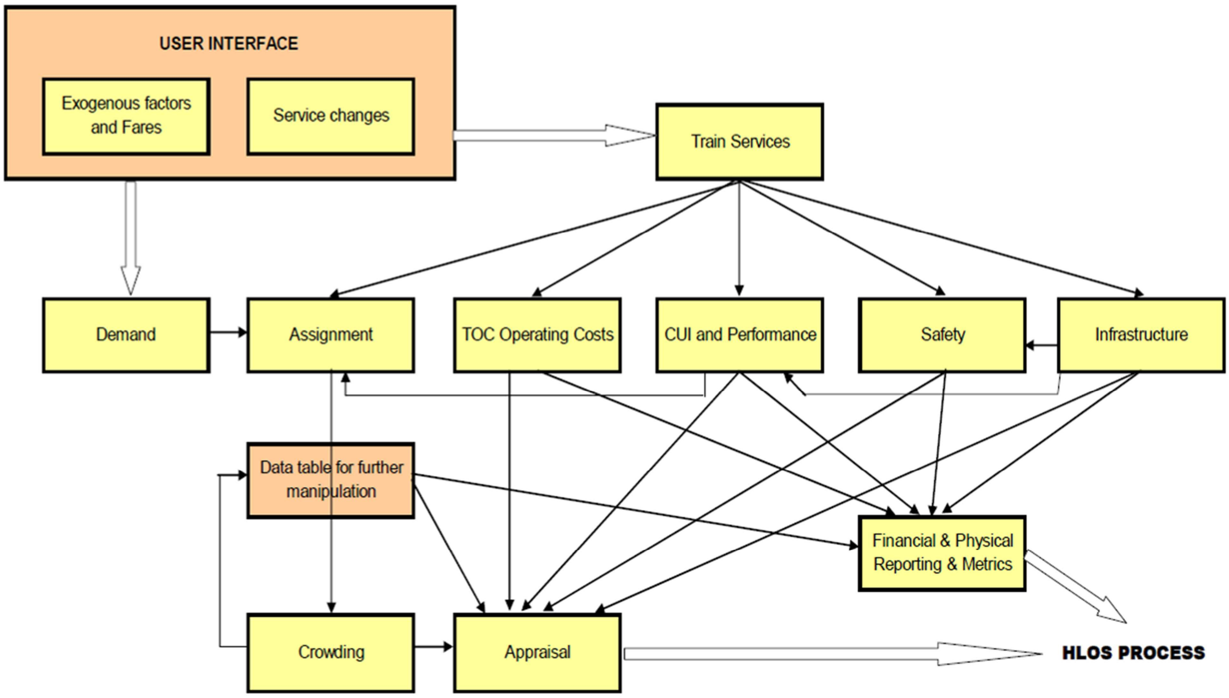


Figure 30: Network Modelling Framework - High Level Model Structure; source UK Department of Transport (2007) [65]

8. Conclusions

Railway capacity is a complex issue depending not only on infrastructure characteristics but also on imposed traffic and operating conditions; in general terms it can be defined as a measure of the capability to move a specific amount of traffic over a defined rail line with a given set of resources under a specific service plan (i.e. fixed level of service). Highly technical considerations and detailed input data hinder the formulation of a working definition of capacity and the estimation of congestion indicators. However, the ability of the railway system to accommodate future demand at a desired service level while ensuring an efficient use of existing assets depends on a robust assessment of capacity. Set against such background, this report aims at tackling the issue of capacity and congestion of railway networks, presenting several well-established procedures and even proposing a manageable and streamlined approach for large-scale analysis.

This report provides an extensive review of available capacity assessment methodologies, focusing on data requirements as this is a limiting factor in their application at European scale. Building on widely accepted definitions, we have proposed a simplified methodology of the UIC analytical method that yields consistent estimations of travel time, delay and utilized capacity; such approach is particularly relevant in order to evaluate fundamental operational and performance parameters in the absence of detailed infrastructure and timetable data. In particular the proposed simplified procedure aims to fill the gap between static and simple capacity assessment procedures based on fixed threshold figures and more complex and complete methodologies requiring more and more detailed data (not always available for strategic or feasibility analysis).

We have carried out a critical comparison of this simplified procedure and standard methods, analysing their respective results in terms of capacity assessment and estimated delay in the case of an Italian line (based on actual and detailed infrastructure and timetable data). Moreover, we have applied the simplified methodology to the Italian railway network (where, instead, only more aggregated data was available), allowing us to showcase the importance of this methodology in the context of a broader scope and in comparison with *'fixed threshold'* approaches.

Figure 31 summarizes the results of the analysis, as particularised on the line Napoli – Salerno in Italy by reporting the variability along the analysed Italian line of the actual utilisation rate (i.e. actual used capacity) and the practical capacity imposing a fixed level of service (as recommended by UIC) both applying the UIC 405R to each block section along the line and the proposed simplified approach; the results underline the validity of the intrinsic assumptions of the second procedure, namely the lengths of the block sections.

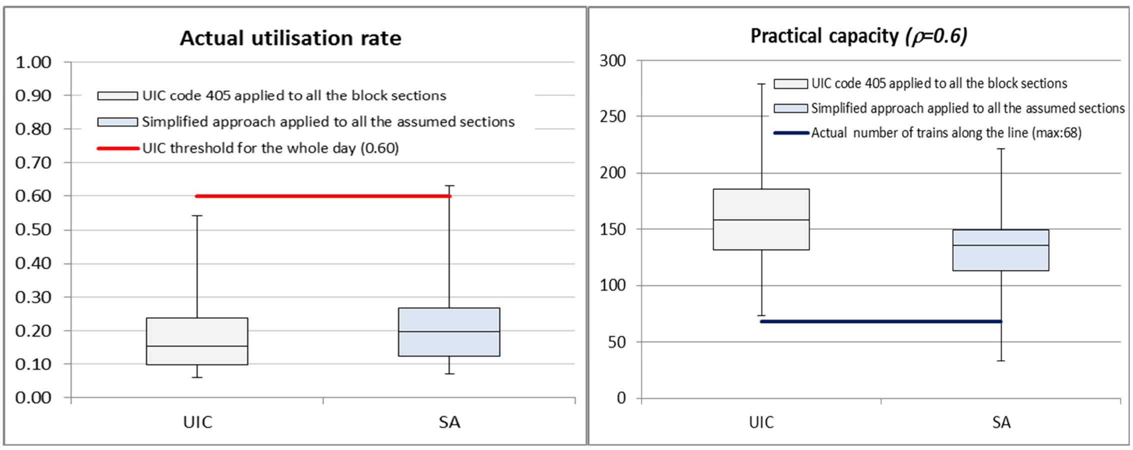


Figure 31: Variability across sections (Napoli – Salerno line) of actual utilisation rate and practical capacity applying the UIC Method (Code 405) and the Simplified Approach.

The obtained results show that the methodology presented in this report may represent a useful way to estimate capacity constraints on a railway network. The outcome of the simplified methodology (SA) is comparable with the results from other established methodologies which impose higher demands on input data; in the same time it allows to take in account more characteristic of a line (speed, eventual heterogeneity of the services, etc.) in comparison with practical 'fixed capacity thresholds'. The relevance of this report and of such approach is evident in the light of the continued efforts at EU level to set up network-based, quantitative tools able to analyse transport policies and particularly, identify infrastructure bottlenecks. We have presented the results of such application to the Italian railway network showing estimated capacity usage and expected delay at corridor level.

Ongoing efforts to broad the scope of competition on the railway systems will put pressure on infrastructure usage, efficiency of the system and fair established criteria for the allocation of rail infrastructure capacity as underpinned by the recent EU Directive 2012/34/EU establishing a single European railway area. The extension of our analysis at European level would provide valuable insight into the current levels of capacity usage on TEN-T Core and Comprehensive railway networks as well as enable a harmonised analysis of existing congestion.

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List of abbreviations and definitions

CRRD - Congestion Related Reactionary Delay

CUI - Capacity Utilisation Index

EC DG CLIMA - European Commission, Directorate General for Climate Action

EC DG ENER - European Commission, Directorate General for Energy

EC DG MOVE – European Commission, Directorate General for Mobility and Transport

EC DG REGIO - European Commission, Directorate General for Regional and Urban Policy

ERA - European Railway Agency

ERTMS - European Rail Traffic Management System

ETCS - European Train Control System

EU – European Union

FIFO – First In, First Out

GIS - Geographical Information System

GISCO - Geographical Information System of the Commission

GTFS - General Transit Feed Specification

HS – High Speed

IC – InterCity

IM - Infrastructure Manager

NUTS - Nomenclature of Territorial Units for Statistics

OD – Origin/Destination

OECD – Organisation for Economic Cooperation and Development

PA - Potential Accessibility

Reg – Regional (trains)

RFI - Rete Ferroviaria Italiana

RINF - Register of Infrastructure

RP - Revealed Preferences

RU - Railway Undertakings

SA - Simplified Approach

SP - Stated Preferences

TCRP - Transit Cooperative Research Program

TEN-T - Trans-European Transport Networks

TRB - Transportation Research Board

UIC - International Union of Railway

UK – United Kingdom

UN - United Nations (UN)

UNECE - United Nation, Economic Commission for Europe

UNIFE – Association of the European Rail Industry

USA – United States of America

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