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Methodological Review for Capacity and Punctuality Assessment Procedures

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A B S T R A C T

Climate change, congestion, safety, energy consumption and pollution are among the major issues that the European Union and the wider world are facing nowadays. The European Commission is working towards the creation of a Single European Railway Area, encouraging a modal shift towards rail (mainly from road) in order to achieve a more competitive and sustainable European transport system. In this context, the research sector is contributing to the competitiveness and attractiveness of rail transport by tackling issues such as reliability and quality of services. Many parts of existing railway infrastructure are operated almost at full capacity and are not always capable of offering adequate levels of service. There is thus the need to boost the productivity of infrastructure assets in order to improve the reliability and responsiveness to customer requirements, as well as the capacity and the whole efficiency of rail transportation. This article provides a review and a practical comparison of capacity and punctuality assessment methodologies. Most importantly, it also identifies and evaluates a manageable and streamlined approach to their estimation for preliminary or large scale analysis based on consolidated formulations for travel time, delay and utilized capacity. This becomes particularly relevant in the absence of detailed infrastructure and timetable data as we aim at evaluating some fundamental operational and performance indicators.

Keywords: capacity; punctuality; delay; analytic methods

1. Introduction

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, the 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 European transport system (European Commission, White Paper 2011).

In order to reinforce and enlarge the role of the rail sector in the global transport market, there is a strong need of addressing issues such as customer's satisfaction and efficiency of the system through targeted actions, i.e. rising reliability and quality of services. Improved competitiveness and attractiveness of services, combined with increased capacity, would lead to notable rises of the rail share in transport demand, thereby contributing to the reduction of traffic congestion and CO_2 emissions. On the other side many parts of existing railway infrastructures are reaching their maximum capacity thus shrinking their capability

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to provide users and customers a higher and/or adequate level of service.

In this context, scientific literature has recently devoted greater 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 capacity and the track access process.

Nowadays, according to the level of detail of the available data (infrastructure and timetable) based on the abundant and reliable scientific procedures (and/or simulation tools), different operational and performance analysis of a railway network can be carried out to support inter alia policy makers' decisions. However, one of the main difficulties faced by the authors in defining a broad analysis of capacity, punctuality and accessibility of the whole European railway system stems from the lack of available or usable data. Although time tables 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 global or European database (despite the fact that various attempts in this direction have been proposed or are currently on-going, especially for infrastructure data, i.e. the UIC's Erim Project and RailTopoModel, the RailML initiative, the ERA's Register of Infrastructure, etc.).

The main scope of this article is to offer a review and a practical comparison of capacity and punctuality assessment methodologies, as well as identifying and evaluating a manageable, streamlined approach to their estimation for preliminary or large scale analysis based on consolidated formulations for travel time, delay and utilized capacity.

It is worthy to notice that this simplified approach, due to its intrinsic assumptions and approximations, should not to be regarded as an innovative and/or a comprehensive procedure for the evaluation of bottlenecks or track access cost; it rather seeks to provide a straightforward evaluation of some fundamental operational and performance indicators in case of limited available infrastructure and timetable data. It should be seen as a useful tool for preliminary analysis or to depict large scenarios for policy makers; anyway its results, although relevant, should be handled and interpreted carefully, recurring to more detailed approaches if necessary according to the scope of the analysis or if more exhaustive data become available.

2. Capacity versus punctuality trade-off

By applying various models (e.g. based on the queuing theory) a direct interrelation between operating quality and capacity of a railway infrastructure can be assessed (fig. 1); the theoretical capacity n_{max} of a railway infrastructure is the number of trains, which can be processed with specification of a defined route and safety standards, but with an unlimited storage capacity in the infrastructure. The optimal capacity n_{opt} is the number of train paths reducing the average waiting times and the average delays to a value compatible with the market expectation ($ET_{W,zul}$ –level of service).

Starting from the analysis of railway capacity and its efficient exploitation, during last decades this topic has assumed an increasing importance and several authors have contributed to discuss this issue (see references from [1] to [20]).

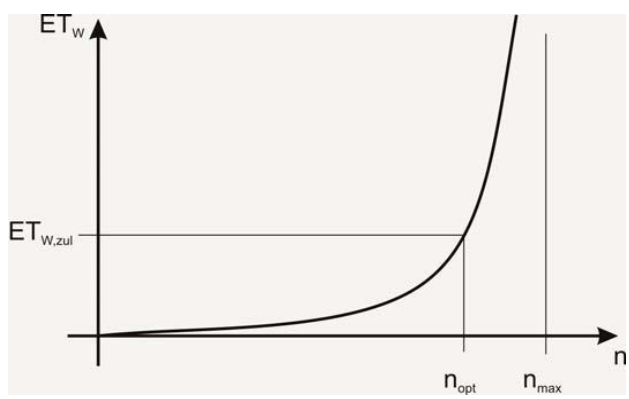

Figure 1. Trading-off between waiting time and capacity [21].

As stated in the UIC leaflet 406 – Capacity (2004) [11], '*capacity as such does not exist. 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' (fig.2).

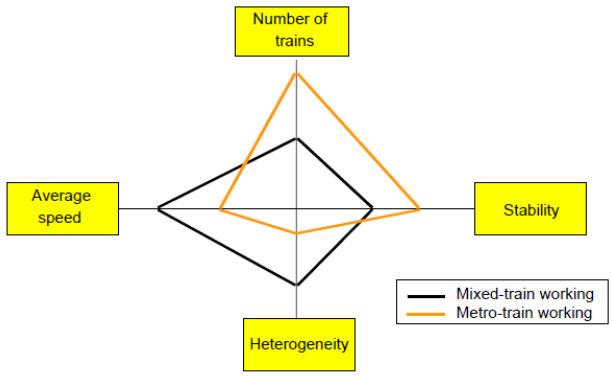

Figure 2. Capacity balance according to UIC Leaflet 406 [11]

In this section are presented different approaches to evaluate the capacity of a railway network (depending as always on the level of detail of the available data) and are proposed various methodologies (with different 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.

Restricting our focus on the synthetic and analytical methodologies, they use deterministic and/or probabilistic expressions to evaluate the railway capacity indicators: examples of this kind of parameters are reported in [1], [2] and [3]. A detailed and comprehensive analysis of all the possible analytic and synthetic procedures is beyond the purpose of this paper; nevertheless, as stated in [3], the results among the different approaches could slightly vary, mainly depending on input data and variables.

2.1 UIC's analytical method-leaflet 405R [3]

This paragraph describes the analytical method proposed in its first edition by the International Union of Railway (UIC) in the leaflet 405R; despite this methodology was officially replaced in 2004 by the compression method (UIC's Leaflet 406) as a standard on 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:

$$P = \frac{T}{t_{fm} + t_r + t_{zu}} \tag{1}$$

- P is the capacity (daily, hourly etc.)
- T is the reference time (usually 24 hours for the daily capacity);
- t_{fm} is the average minimum headway;
- t_r is an expansion margin;
- t_{zu} 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_{zu}=0.25*a; 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:

$$t_{fm} = \sum \left(t_{h,ij} * f_{ij} \right) \tag{2}$$

Where $t_{h,ij}$ is the minimum line headway for the train j following the train i and f_{ij} is the relative frequency of combination: train j following train i; this parameter is calculated based on the absolute frequency F_{ij} derived by the timetable:

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

The expansion margin t_r is 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; it is calculated applying the queue theory considering the critical section as a service station (i.e. a M/M/1 queuing system). In particular the length of the queue for entering the section is equal to the number of trains encountering a disturbance (delay) and it depends on the intensity of traffic Ψ (utilisation rate of the system) given by the ratio between the average number of arriving trains ($\lambda=1/(t_{fm}+t_r)$, i.e. inverse of the expected inter-arrival time) and the maximum number of trains which could simultaneously utilize the section ($\mu=1/t_{fm}$, i.e. inverse of expected service time):

$$\Psi = \rho = \frac{\lambda}{\mu} = \frac{t_{fm}}{t_{fm} + t_r} \quad (4)$$

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 tr≥0.67tfm;
- 0.75 (corresponding to 3.1 users waiting in the queue) valid for a short period of time (peak hours), hence the condition tr≥0.33tfm;

By having assumed a M/M/1 system the mean queue length (average number of delayed trains) will be equal to:

$$L_q = \frac{\rho}{(1-\rho)} \quad (5)$$

while the average time spent waiting (average delay per train) can be evaluated as [5]:

$$w = \frac{\rho}{(\mu - \lambda)} = (t_{fm} + t_r)\frac{\rho^2}{(1-\rho)} \quad (6)$$

The presented approach is based on very simple formulas and does not require a big amount of data, besides easy-to-get values such as number of trains, reference period, etc. Anyway the length (or the travel time) of the relevant block section of the line should be measured or at least hypothesized. It is for these reasons that we propose a possible simplified approach of this procedure in case of limited available data.

2.2 A simplified approach

As above described, the UIC's leaflet 405R proposes an analytical method to be applied on the critical section of the line (based on blocking time sequences, see fig. 3). Anyway in case of large scale railway networks or for preliminary studies it is not always easy to find or collect information regarding the signalling system and in particular the length and the characteristics of all the sections along each line. Even if a simplified approach would be less detailed and representative than more rigorous ones, it could allow facing an ideal situation in which not all the data are available; by means only of the distance, scheduled travel time and number of trains between consecutive nodes, we try to apply a 'simplified' or 'ad hoc' version of the UIC 405 method to obtain an indicative value of utilised capacity and possible delay per train: 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 by a train per time, neglecting the missing infrastructure information related to the characteristics of the block sections; of course this kind of assumption, even if applied also in other consolidated procedures (e.g. Capacity Utilisation Index, see next paragraph), will lead to more restrictive and less representative values of capacity due to the hypothesized longer line sections and headways, but in absence of further details (as for example in case of the analysis of very large network) it could still provide a slight but valuable indication of capacity and related delay.

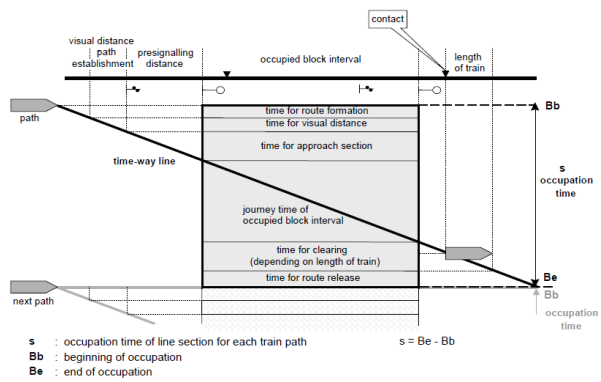

Figure 3. Scheme of blocking time occupation (source [11])

Trying to partially limit the above described effects, in case of long distances between consecutive stations (more than 3-4 km) we suggest to consider the section divided into blocks of fixed length (e.g. 2 km) and evaluate the occupation time of the resulting block intervals. The number of intermediate hypothesized block sections will enter also in the calculation of the extra time t_{zu}.

In order to better explain the described approach and to compare its results with the ones from other methodologies, in section III an application to the

Italian line Napoli Centrale – Salerno has been carried out.

2.3 Capacity utilization Index (CUI) method [8][9][10]

Whenever the scheduled timetables for analysed lines are available, it could be possible to follow the CUI approach for the calculation of capacity; 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'*.

The CUI method is used in the UK by Network Rail for capacity analysis based on the minimum headways and it requires less details 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 separation 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 fig. 4, CUI = 45/60 = 75%). Of course the method, even if worthy, provide an estimation of capacity sensitive to the way the timetable is compressed.

It has been shown [8] that there is a relationship between CUI and the Congestion Related Reactionary Delay (CRRD) per train mile; this subset of delay is the portion that would be expected to increase more-than-linearly with an increase in traffic.

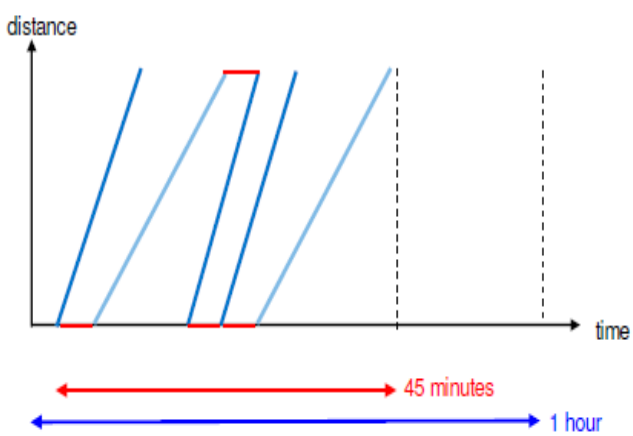

Figure 4. Capacity utilization calculation according to CUI method [9]

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

$$D_{it} = A_i * \exp(\beta * C_{it}) \tag{7}$$

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 A_i and β have been calculated and are regularly updated for the UK network [8] and they could be generalised to other networks only on the basis of a specific investigation; for the purpose of the present analysis a hypothetic shape of the function has been depicted based on a range of coherent values for A_i and β (see section III).

As already noticed in the previous paragraph, the capacity utilization 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.

2.4 UIC's compression method-leaflet 406 [11]

As the Leaflet 406 [11] 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 bottlenecks for a line, the capacity consumption of 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 capacity consumption. The block sections are occupied, depending on signalling systems, as long as the point behind them (which has to be cleared for safety reasons) is passed by the end of the train and the route is released (fig. 5).

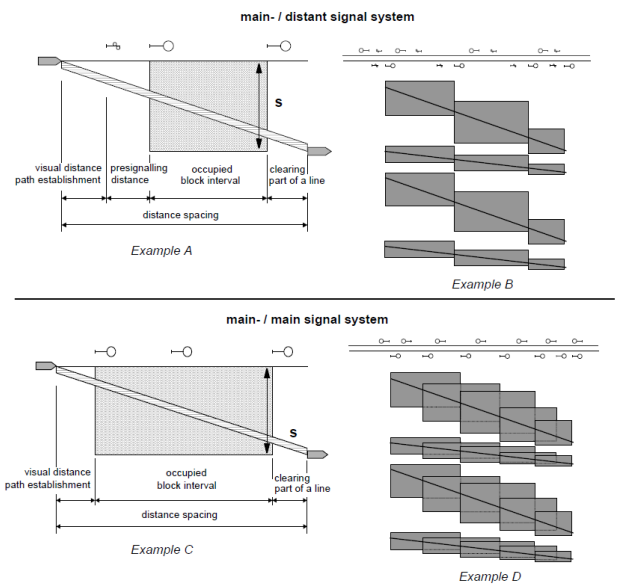

Figure 5. Example of occupation times in different signaling system [11]

The capacity consumption calculation method suggested in UIC Code 406 is based on blocking time sequences: for each block section the occupation time is evaluated as a sum of times for (see fig. 3 and fig. 5):

- route formation;
- visual distance/driver reaction;
- approach the section;
- journey itself;
- clearing time;

all depending on infrastructure and vehicle characteristics. Reference [21] reports some samples of practical values of operational times to be applied for various signaling systems.

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

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

Part of the remaining time slots cannot be used due to market requirements while a second share of the unused capacity represents still available capacity (see fig. 6).

Given a reference time t_u the capacity consumption K [%] is defined as:

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

UIC specifies a guideline for standard values of infrastructure occupation in order to achieve a satisfying operating quality. These values are indicated as a function of the type of line and the infrastructure use (tab.1).

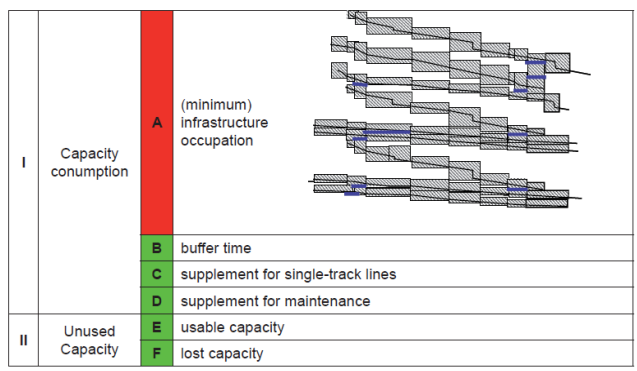

Figure 6. Determination of capacity consumption (UIS's 406)

TABLE 1. UIC'S R RECOMMENDED VALUES FOR INFRASTRUCTURE OCCUPATION (SOURCE [11]).

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 railway infrastructure's performance.

2.5 Strele formula (method of Schwanhäußer) [21]

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

$$\underline{t} = \frac{\underline{z} * (1-\rho)}{\rho} = \frac{A * (1-\rho)}{N * \rho} \qquad (10)$$

where is:

- ρ recommended value for the infrastructure occupation by UIC 406 (tab.1);
- $\underline{z}$ 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 [21]:

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

with:

- $\underline{t}_p$ avarage buffer time;
- $\underline{z}$ avarage determinaive minimum headway time;
- $\underline{z}_g$ avarage determinaive minimum headway time of equal-ranking successions of trains;
- $\underline{z}_v$ avarage determinaive minimum headway time of different-ranking successions of trains;
- $\underline{t}_{ve}$ avarage delay at entry;
- $\underline{p}_{ve}$ probability of delay at entry;
- $\underline{p}_g$ probability of an occurrence of an 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 worthy to notice that (11) requires the definition (by measurements or hypotheses) of the average delay t_{ve} and of the probability of delay p_{ve} at entry.

2.6 Further methods for the evaluatin of trains' 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.

References [19] and [20], for example, report different queuing models for this scope.

Hertel (see [1], [6], [17] or [18]), instead, presented an analytical approach for the waiting time as a function of traffic flow, related waiting time sensitivity (partial derivative of mean waiting time to track occupancy) and maximal traffic energy, defined as product of train intensity and speed:

$$E_{traffic\ energy} = \frac{n}{s} v^2 = \frac{n}{t} v \qquad (11)$$

with:

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

According to Hertel (fig. 7) 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.

Finally Landex in [15] proposed another approach following an idea by Kaas: the total amount of delay

Σt_d can be calculated based on the initial delay $t_{d,1,i}$ and a delay propagation factor $y(t_{d,1,i})$:

$$\sum t_d = t_{d,l,i} * y \qquad (12)$$

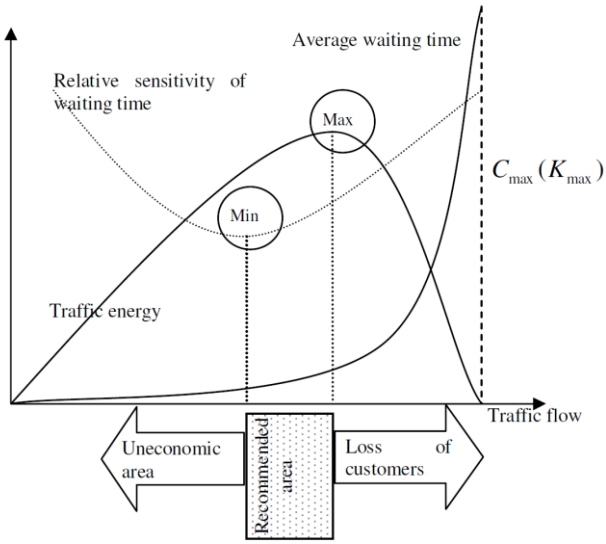

Figure 7. Hertel's approach

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

$$t_{d,l,i} = n * t_{h,\min} \qquad (13)$$

as also reported in fig. 8, 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):

$$y = \left| \frac{n}{\left(\frac{1}{K}-1\right)} \right| + 1 - \frac{\left(\frac{1}{K}-1\right)}{2n} \left| \frac{n}{\left(\frac{1}{K}-1\right)} \right| \left(\left| \frac{n}{\left(\frac{1}{K}-1\right)} \right| + 1 \right) \qquad (14)$$

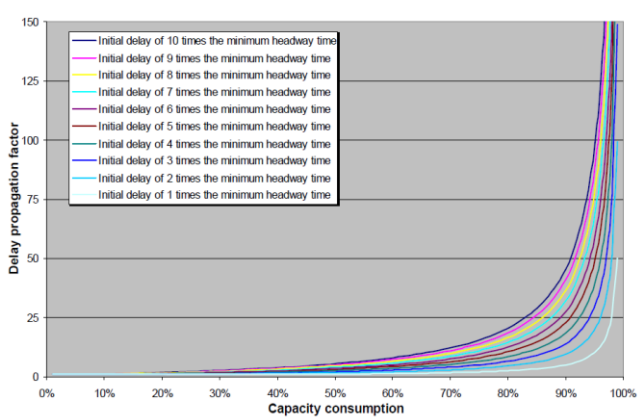

Figure 8. Delay propagation factor as a function of capacity consumption and initial delays [15]

As evident from the previous image, the delay will increase as the capacity consumption increases and the propagation starts growing dramatically when the capacity consumption is over 80%.

3. Application: Napoli centrale –salerno line

In order to test the applicability of the described methods (and particularly, the simplified approach) and to estimate the difference in the data needs and in the results applying the various capacity and punctuality assessment procedures, an application to the Italian line Napoli Centrale – Salerno (fig. 9) has been developed.

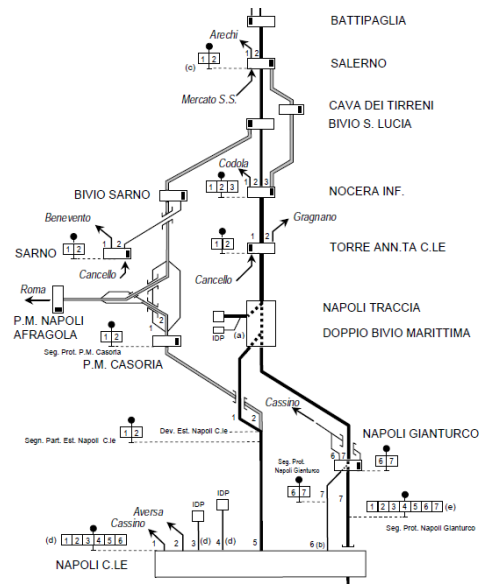

Figure 9. Schematic layout of the Napoli centrale-salerno line by RFI

The line is comprised of several parallel sections with different characteristics and traveled by all the types of passenger trains (High Speed, Intercity and Regional):

- the traditional line from Napoli Centrale to Salerno passing by Torre Annunziata is mainly used by regional trains and it is further divided in two (double track and electrified) lines between Nocera Inferiore and Salerno; in detail 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; it is utilized by Intercity and High Speed trains.

Since the High Capacity line is still travelled by a limited number of trains we have concentrated our attention on the more congested and critical traditional line. Detailed data related both to the infrastructure and to the timetable of the line are available and free-downloadable from the RFI (Rete Ferroviaria Italiana) website (e.g. see fig. 10 and 11).

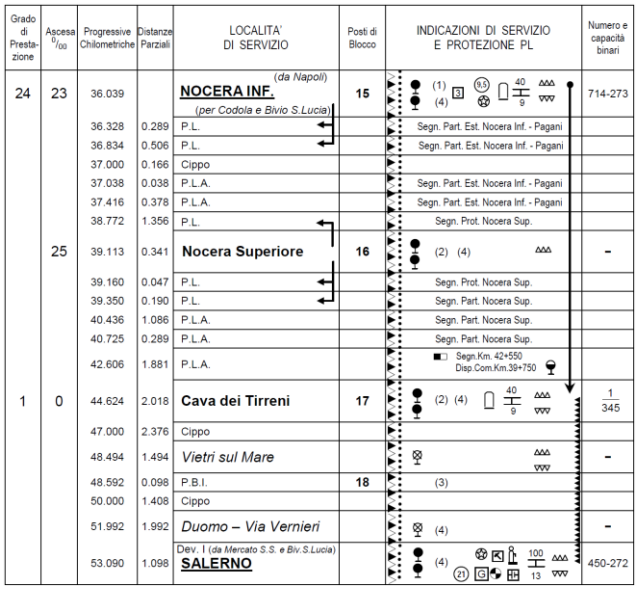

Figure 10. Infrastructure data of the Salerno-Nocera inferiore line (via Cava dei Tirreni) by RFI

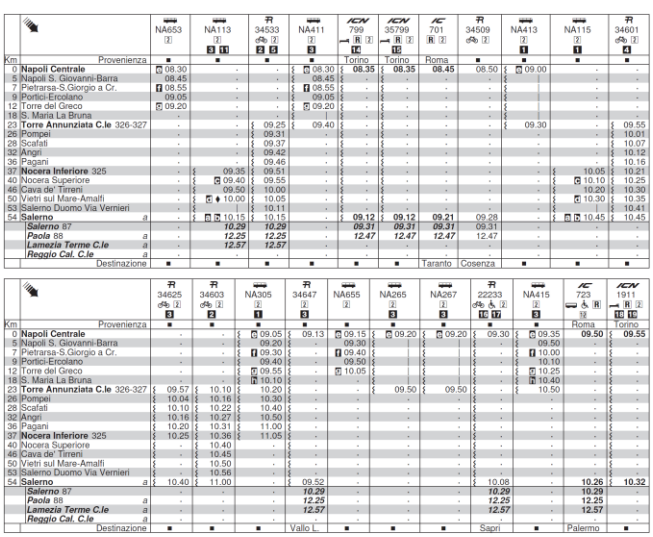

Figure 11. Extract of timetable of the Napoli central-Salerno line by RFI

An initial capacity and punctuality analysis has been carried out by means of the UIC's analytical method (leaflet 405), considering an operational time T of about 18 hours (as deducted by the timetable); in particular table 2 reports the values obtained applying the methodology to the block sections, while table 3 reports the results of the simplified approach. In the first case, the block interval depends on the signaling system; considering a main signal system with 3 possible aspects, the block interval along the line will be constituted by 2 consecutive blocks (fig. 12), with exemption for block intervals entering stations with more dwelling 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, i.e. null approach time).

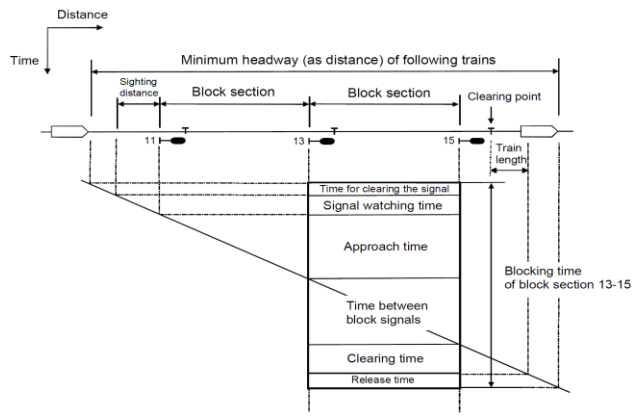

Figure 12. Blocking time by [13]

Regarding the simplified application, as already described above, in case of long distance between two consecutive stations we have hypothesized the section divided in more intermediate blocks of length equal to 2 km; we have applied this approximation to the section Napoli – Torre Annunziata (since 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) and to the line from Nocera Inferiore to Salerno via Bivio Santa Lucia.

In both table 2 and 3 we have reported not only the actual used capacity (utilization rate) and the related results for queue's length and delays but also the 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.

TABLE 2. Application of the UIC's method (Leaflet 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 scenario			t_i	$\rho = \Psi = 0.6$, $L_q = 1.5$		
N	From	To			All	Reg	IC	HS			ρ	L_q	w [mm:ss]		t_r [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

As it becomes evident, all the results in the two tables (ρ, P, w, t_r) are on average quite similar even if of course not identical; the major differences, as expected, are related to the longest sections. For the section between Napoli Centrale and Torre Annunziata we have presented 3 different types of analysis in table 3: 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), and finally a last one hypothesizing this part of the line divided in blocks of a fixed length of 2 kilometers (row 19); the results of the first and of the last assumption are quite comparable between them and with the results from table 2. Anyway applying the last two described assumptions even to the line from Nocera Inferiore to Salerno via

Bivio Santa Lucia (rows 12 and 20 in tab. 3), 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 tab. 2).

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

this calculation for the application of the UIC' methods (around 9 minutes, see row 22 in tab. 2), to generalize our investigation to the case of missing/limited infrastructure data, we have assumed and analyzed several scenarios and for each one of them we have hypothesized a different value of minimum headway along the whole line (respectively of 3, 5, 7 or 9 minutes).

The next two figures report the actual timetable and the compressed timetable in the hypothesis of minimum headway of 7 minutes, while tab. 4 reports the calculated values for the capacity utilization index and the reactionary delay.

Regarding the CRRD's parameters, NetworkRail

TABLE 3. APPLICATION OF THE SIMPLIED APPROACH TO THE NAPOLI –SALERNO LINE

Section			Number of trains				Inter-arrival time [mm:ss]	Blocking time [mm:ss]	Actual scenario			Distance [km]	Intermediate blocks		t_i [mm:ss]	$\rho = \Psi = 0.6$, $L_q = 1.5$		
N	From	To	All	Reg	IC	HS			□	L_q	w [mm:ss]		Hp.	Real		t_r [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

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

Referring to the CUI evaluation, since both 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, in order to evaluate the minimum headway we could not refer to the dwelling time in the intermediate stations (as suggested in [9]) but we should calculate the occupation time corresponding to the different block intervals. Although we have already proceeded to

have evaluated the values of A_i and β on the whole railway network in Great Britain; even if they could be generalized to other networks only on the basis of a specific investigation, for the scope of this analysis we have just hypothesized various significant values for them (see fig. 15); for example the assumptions A_i=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 worthy 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.

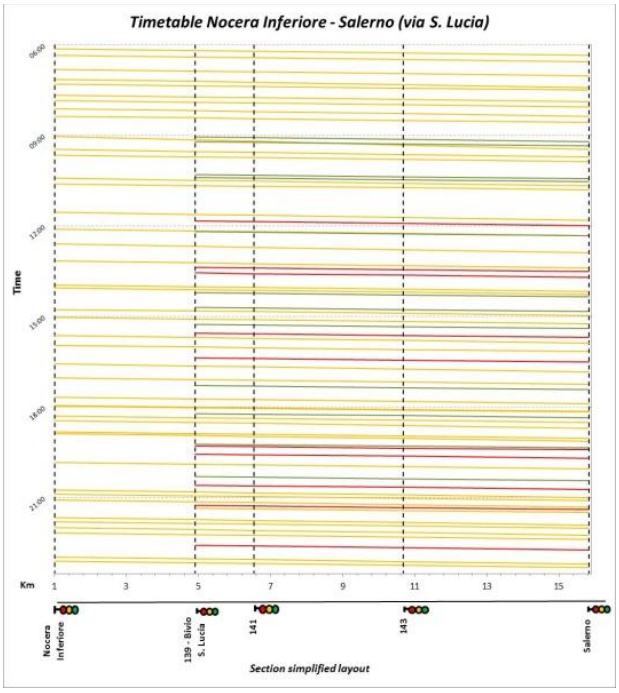

Figure 13. Nocera Inferiore – Salerno (Via S. Lucia): Actual timetable

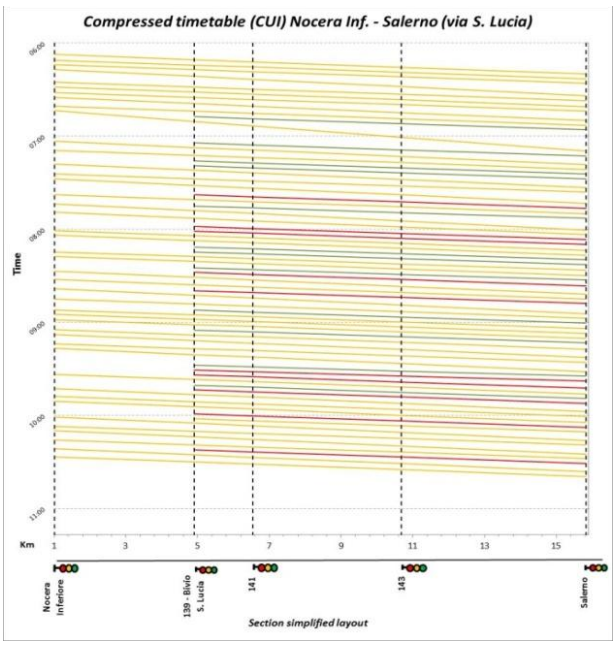

Figure 14. Nocera Inferiore – Salerno (Via S. Lucia): Compressed timetable with minimum headway of 7 minutes

From table 4 it is easy to observe that if we consider in the CUI application an headway of 9 minutes (in accordance with the block occupation time of section 22 in table 2), the average CRRD along the line will be 10.15 minutes assuming A=0.1 and β=3 or 9.65 minutes with A=0.05 and β=4 (the authors prefer this last assumption, since they believe that lower initial delays in case of low values of CUI are more significant/likely); these values are quite similar to the delay w calculated for the section 22 with the UIC 405 method (10,5 minutes) even if the resulting values of used capacity are slightly different (as expected the CUI approach, considering the distances between stations and not the block sections, provides more restrictive values, i.e. the capacity utilized index is higher).

TABLE 4. CUI APPROACH RESULTS FOR THE SECTION NOCERA INFERIORE – SALERNO (VIA BIVIO SANTA LUCIA).

Headways [minutes]	CUI	A_i	β	CRRD per train mile[min]	CRDD [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

Finally in order to apply the UIC's compression procedure, more detailed data regarding infrastructure and timetable need to be considered. According to the leaflet-406's indication, we have considered (since critical) only the line section between Bivio Santa Lucia and Salerno (even if there are not intermediate stops between Nocera and Salerno) since in Bivio the number of trains increases (High Speed and Intercity trains from the high speed line).

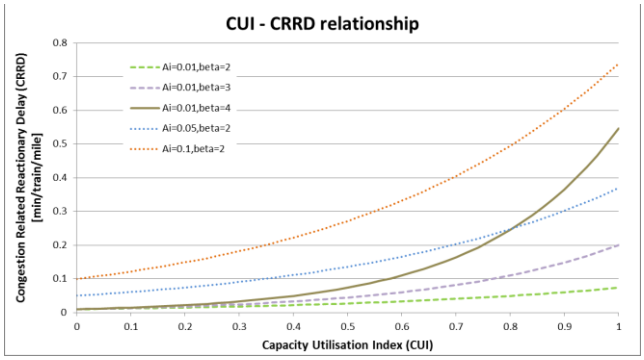

Figure 15. CUI-CRRD Relationship for various values of A_i and β

The next figure reports the compressed timetable with the buffer time for the considered line section.

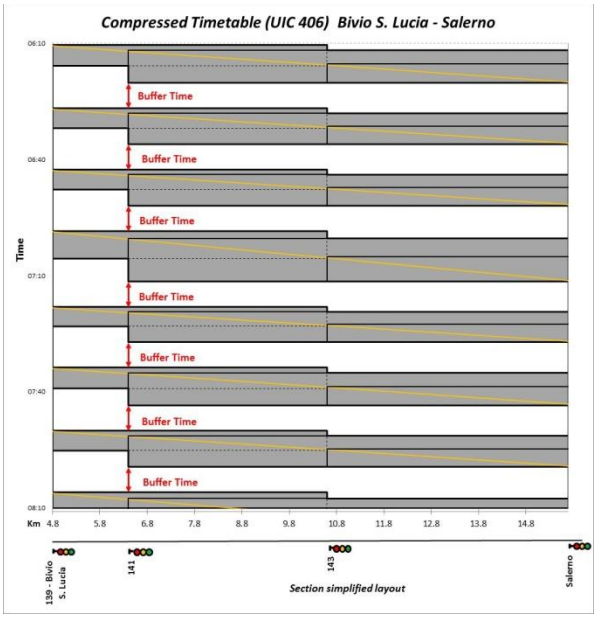

Figure 16. Extract of the compressed timetable with buffer time for the line section Bivio Santa Lucia – Salerno (UIC's 406 procedure)

The total occupation time *A* (8) results equal to about 10 hours and 50 minutes, corresponding to an infrastructure occupation (*A/T)* referred to the whole day of 45% and so 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 β=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 evaluated as 75% and the optimal number of trains will be:

$$N = \frac{T}{\bar{z} + \bar{t}} = 87.8 \qquad (15)$$

Comparing these results with the outcomes of the UIC 405 (row 22 tab. 2) and of the CUI (tab.4), they are quite similar; moreover they are also of the same order of magnitude of the results obtained with the proposed simplified method.

4. Simplified analysis of the Italian railway network

To better clarify and explore the possible scope of a simplified approach, an application to the Italian railway network is presented below. The analysis is based on the UNECE's rail census data for 2005 [22]; they provide information regarding length, traffic (annual and daily), number of tracks, etc. for the European main network at corridor level. For simplicity we focus only on Italy and since the database does not contain any figure regarding travel time, it has been integrated with the speed values for each link from the ETISPLUS dataset for 2005 [23].

As already described in paragraphs II and III, to calculate the block time we assume each line divided into sections of around 2 kilometers; for each of them a restrictive travel time is calculated based on the length, on the maximum allowed speed and hypothesizing a time of 30 seconds for the sighting, clearing and release of the signaling system. To be noted that the UNECE database provides for each corridor only information 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 (see fig. 17) and that in our analysis the capacity of the whole corridor is conditioned by the capacity of the eventual single track

section (which can be occupied only by one train per time).

The following map reports for each link of the considered Italian network the number of tracks and the number of daily trains per track for 2005, while figure 18 shows the values of utilized capacity and expected delay per train calculated by means of the simplified approach.

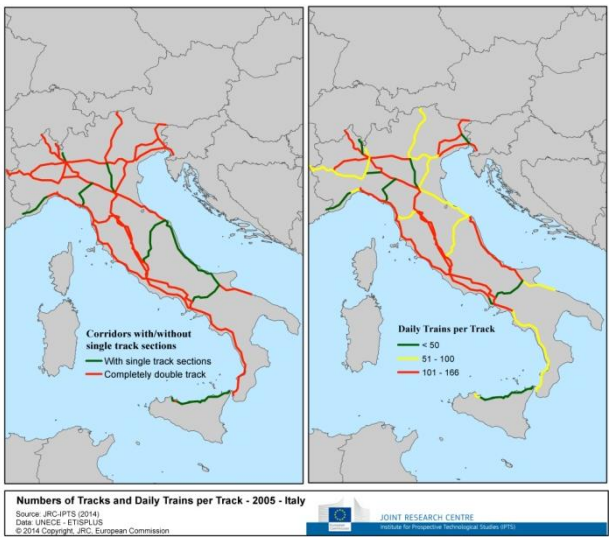

Figure 17. Italian railway network – 2005: Number of tracks and daily trains per track

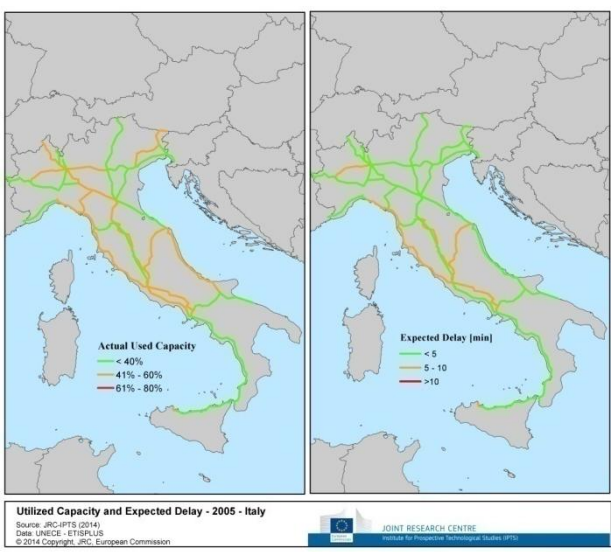

Figure 18. Italian railway network – 2005: Utilized capacity and expected dlay per train

For the whole network the traffic intensity is below the threshold of 60% recommended by UIC and the expected delays per train result less than 10 minutes. As already pointed out above, these outcomes should be treated with increasing confidence as the level of detail of the data improves; nevertheless even in case of large, less detailed databases, as for example the one proposed in our analysis, they could still offer valid indications.

4.1 Broader context

It is worthy to highlight that the driving idea behind this work is to propose an user-oriented evaluation of the travel time by railway, seen both as a significant impedance indicator (e.g. see accessibility analysis in [24], [25] or [26]) and as an operational and performance index of the service. 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 utilized capacity, i.e. congestion, of the rail line between i and j):

$$t_{ij} = t_{board} + t_{waiting,frequency} + t_{waiting,delay} \qquad (16)$$

According to the available data and to the scope of the analysis, each term of the previous formula can be calculated with a different level of detail. A manageable way to evaluate the *time on board* could be based on the actual timetable proposed by the Rail Undertakings, while most accurate calculations require more detailed data or assumptions. Based on 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 scientific contributions (see [27], [28] and [29]). However to better represent this parameter or to propose different and more detailed analysis for peak or off-peak hours, it could be useful to extend this approach including the actual (continuous or discrete) distribution of the departures (scheduled timetable) and the distribution of passengers' preferred time of departure based on a model (e.g. the logit deviation sin–cos schedule delay

[30]) or on estimations by mean of Revealed Preference (RP) – Stated Preference (SP) surveys [31].

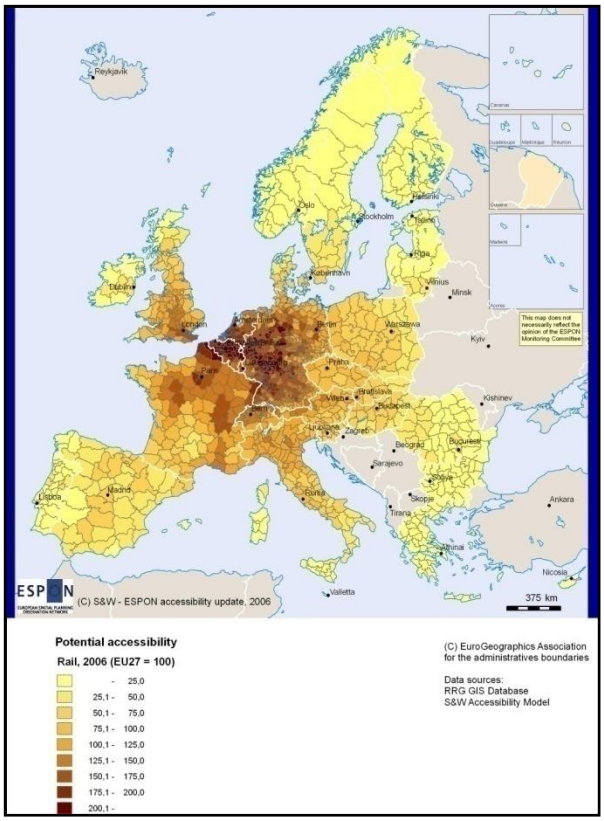

Figure 19. Accessibility by rail, Europe – 2006, source [24]

Finally the already described capacity and punctuality assessment methodologies could allow evaluating the *unscheduled waiting time* and the infrastructure utilization rate.

A further valuable step would encompass the calculation of accessibility indicators at a broad scale; it would be really interesting to propose analysis of accessibility by rail for the whole Europe (as presented for example in [24]) based on actual travel times and considering all the mentioned factors (service frequency, time on board and unscheduled delays).

The final aim of the authors is to notice how maps as the ones reported in figure 17 and 18 (already proposed also in [7] or [32]), together with accessibility maps by rail (see fig. 19) could offer a highly valuable tool for decision makers, allowing them to identify not only areas less or more accessible from/to other zones but also to identify how and where improvements in infrastructure and/or levels of service could benefit users.

5. Conclusions

The main scope of this article is to offer a review and a practical comparison of capacity and punctuality assessment methodologies, but it tries even to identify and evaluate a manageable and streamlined approach to their estimation for preliminary or large scale analysis based on consolidated formulations for travel time, delay and utilized capacity.

It is worthy noticing that this simplified approach, due to its intrinsic assumptions and approximations, could not and would not pretend to be regarded as an innovative and/or a comprehensive procedure for the evaluation of bottlenecks or track access cost; rather it seeks to detect a straightforward evaluation of some fundamental operational and performance indicators in case of limited available infrastructure and timetable data.

Indeed the outcomes of an application to the Italian line Napoli Centrale - Salerno confirm what is described above: the results obtained applying the UIC's analytical method, the CUI approach or the UIC's compression procedure are quite similar with slight differences due to their intrinsic assumptions, but they lead to the identification of the same critical sections; moreover the application of a simplified approach (based on more limited data) provides on average comparable values for capacity and delay, even if they could not be used for example for detecting bottlenecks. The outcomes of such simplified analysis should be treated with a confidence increasing with the level of detail of the data; in the authors' opinion they are relevant for preliminary studies or even better to depict large scenarios for policy makers, but they should be handle and interpreted carefully, recurring to more comprehensive methodologies if necessary according to the scope of the analysis or if more exhaustive data become available.

In order to better clarify and explore a possible scope of simplified approaches, the article reports an application to the Italian railway network based on the UNECE's rail census data for 2005 [22]. The outcomes

show how for the whole network the traffic intensity is below the threshold of 60% recommended by UIC and the expected delays per train result less than 10 minutes. These figures together with an appropriate analysis of accessibility by rail could offer a highly valuable tool for decision makers.

Finally the presented research could be further developed to analyse the procedures for the investigation of complex rail networks taking into account the effects of the layout of the station on the capacity of the line [33], e.g. by applying the proposed approaches also to the stations (see [10] and [14]) or by integrating them with synthetic approaches for the evaluation of capacity of nodes [34].

Disclaimer- The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

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