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Capacity analysis in urban railway nodes with High Density ERTMS technology

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to Carmela, Michele, Saverio

[… the railway service, a vast and complex organism, in which are composed, with admirable harmony, the most modern discoveries of science, the wise and firm discipline, the active collaboration of a multitude of people operating in several sectors…]

Pope Pius XII

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1. Introduction

A railway node is a part of the railway network characterized by a variable configuration due to the presence of lines, halts, stations and junctions in a limited area. The railway nodes are generally considered the bottlenecks of the railway network due to the increase in the infrastructure utilization rate with respect to the inbound and outbound lines one. The concentration of different services, with high and constant frequency during specific time interval, in limited parts of the infrastructure shows different problems with respect to the circulation of the same amount of traffic on a line. The necessity to assign common paths to different services leads to a great interference among trains, with an increase in the probability of disturbance propagation on the part of the infrastructure interested by the disturbance itself. The mutual interference are a very strong limit to the increase in the supply the Infrastructure Manager (IM) can offer in relation to its quality targets, measured in terms of punctuality. In those cases, the principal problems are the identification of the critical infrastructural elements and of the measures to obtain the best nodal performances: the single element, or a small group of elements, are a determinant factor in the assessment of the potentiality if the whole railway node, so that an intervention on them could resolve the problems of a greater part of the network; on the other hand, even if only one element had a capacity that was lower than the operational requirements, or a utilization rate not able to guarantee the required quality, it would create a bottleneck that would have a negative impact on the overall potentiality.

The growing mobility demand, either systematic or not, towards large metropolitan nodes one side led to the planning of interventions on the main merging lines, on the other hand, the need to identify others that can guarantee circulation within nodes with a regularity like that guaranteed along the lines. Contextually, the design of suburban services along the so-called "belts" together with the rise of freight traffic, a specialty to which these were traditionally dedicated, introduced the need to foresee intense mixed traffic, different in both type of service as in the material with which it is carried out.

To the conflicts that can be generated in the conflicting point must be added those that can be generated on the stretches of line between two consecutive stations. Along these stretches of infrastructure, the circulation takes place following the same principles of the open line: the minimum spacing depends on the block technology that it is implemented and by the length of the respective sections. Depending on type and volumes of traffic that converge on a specific node line, it is possible that the minimum spacing is respected, or during the timetable design you are forced to program the trains spaced less than the minimum allowed by the technology in use.

As long as the utilization rate is compatible with the regularity that is to be guaranteed, the possible exogenous perturbations, such as those generated at the stations, could be reabsorbed with some ease, just as it is more difficult to generate endogenous perturbations that can propagate at the stations. In each case, in the process of circulation the interactions between contiguous elements are very strong and focusing only on interference resolution is not an effective strategy to improve the potentiality in the metropolitan railway nodes.

Among the interventions launched in the past few years, are cited, among others, the specialization of the lines, the technological renewal of the stations interlocking systems, the construction of flyovers for the independence of flows, the review of the preferential routes. These interventions are aimed at reducing conflicts and their effects; a complete independence of movements within the railway nodes is almost impossible, so the conflicts must be compatibilized. As traffic increases, compatibilization becomes more difficult and the margin between two successive trains reduces, while after a delay increases the probability of having a conflict at a conflicting point.

A question to be noted is the adoption of Block Systems (BS) with short sections, which allow a reduction of the minimum distance between two successive trains. This measure can be aimed at the need to increase the capacity of a node line, as to a need for regularity with the same traffic. By extension from the application in open line, the shorter the sections, the less the spacing obtainable but less also running speeds. This limit has made the block system with short sections (450 ÷ 900 meters) so far applicable only where a significant top speed is not required.

In this context the innovative technological block system "High Density ERTMS / ETCS" (HD ERTMS) has been designed, potentially capable to increase the potentiality of node lines by reducing the minimum distance between two successive trains, without any particularly restrictions to train running being established. With these premises, the new BS can be used as much to decongest critical points of the infrastructure as for an increase in the supply provided, without affecting the quality of the same.

It is clear that a capacity analysis is needed, a typical theme of highly used networks, crucial not only for the evaluation of investments but also for a better management of the existing infrastructure, to be done downstream of a functional study of the product, aimed at understanding qualitatively its potentiality.

The strong decongestion of the node lines represents a possible strategy, whose effectiveness must be carefully assessed in relation to complexity implementation and management of the intermediate phase, during the transition from the equipment with the national train protection system at the completion of the one with ERTMS/ETCS.

2. Objectives

This work was carried out as part of an internship for a Master Degree thesis at the Network Development Structure of the Sales and Network Management Department in Rete Ferroviaria Italiana S.p.a.

The development of the work is linked to the mission of the Structure of assessment of the line and station infrastructural coherence to the timetable and the scenarios of traffic (also using traffic simulations) by formulating proposals for upgrading or simplifying the infrastructure, with a view to achieving the best level of quality and efficiency of circulation. (1)

The object of the work is the Block System called "High Density ERTMS/ETCS", with strongly innovative characteristics compared to traditionally ones adopted by the IM on the lines in operation.

The goal is to estimate the benefits it can offer, where implemented, in relation to its functional characteristics, to verify its compatibility with the traffic scenarios defined through the appropriate Framework Agreements and to preliminarily evaluate the implementation strategy. The system represents one of the "RFI proposals for overcoming bottlenecks", included in the 2012-2016 Agreement - Investment (2), signed with the Ministry of Infrastructures and Transport.

Given the extent of the investment and the implementation and management complexities that will be discussed in the following, we also set ourselves the objective of investigating busier scenarios, in order to have more elements of evaluation of the effectiveness of the System within complex contexts, such as metropolitan railway nodes.

The study of a highly innovative Block System compared to those traditionally adopted by the National Infrastructure Manager is divided into several phases. In a first phase it analyses the functional specifications of the system, as well as presented by the Technical Department of the IM, that designed the BS. This analysis is aimed at understanding how the innovative features introduced can qualitatively influence the design of the supply and the management of railway traffic by the competent structures of the IM. In the second phase, a theoretical model is designed to analyse quantitatively the benefits provided by the aforementioned functions. The construction of the model was made by analysing the models already present in the literature and, based on the analysis carried out in the previous phase, by reinterpreting them in function of the specifications of the BS object of the job. The third phase consists in applying the methodology proposed to a case study. Finally, is proposed a simulation analysis of the same scenarios hypothesized previously that can support the analytical analysis in verifying that HD ERTMS can guarantee the benefits envisaged by respecting the quality objectives of the IM.

3. The urban railway nodes

The urban railway nodes are portions of the network characterized by the presence of the typical elements of the railway infrastructure, condensed in limited portions of the same: stretches of lines, halts, stations and junctions.

The term "stretches of line" refers to the sections of main lines that merge in a railway node. Similarly, they are those portions of infrastructure specifically identified or constructed within the nodes and that are dedicated to the circulation of more homogeneous possible types of traffic. Examples of this second type are the metropolitan tunnels and the belt lines, with mixed traffic and not. Each stretch of the line needs a different configuration, whose BS must be optimized according to the traffic that circulates there. In approaching the node and along these stretches there is an intensification of the expected traffic so much for the presence of proximity services, attested just outside the nodes, as for the confluence of multiple lines in a single stretch. Both cases can lead to congestion of the stretch as it is possible that being reached superior limits of utilization of the infrastructures, as calculated by the IM (4) and communicated to the Railway Undertakings (RU) (3).

In this chapter are introduced the principles of circulation within railway nodes and the problems are examined; will be reviewed current technological solutions that allow safe and regular circulation, the methodological approach by through the timetable is planned, as well as the solutions so far taken to resolve the critical issues within the nodes. The chapter is preparatory to the introduction of the object of the work and, by making a description of the context in which will be applied, it will allow a qualitative estimate of the benefits.

3.1 Railway Operation: principles and problems

The traffic operation in the stretches follows the same principles as the open line: the safety function is carried out by the BS, which, whatever the technology used, makes sure of the freedom of the track and of occupation and blockage of the track itself; the communication of the state of the track to the driver is via the signaling system, this too

can be declined according to several types and technologies. The very close link between the BS and signaling introduces the definition of Safety and Signaling Systems (IS), whose characteristics depend on the potential of the line in question. The main feature is the length of the block sections in which the portion of a line is divided between two stations. The travel time necessary to overcome a finite number of block sections such that the train does not perceive restrictive information on the status of the track defines the time in which the specific one portion of the infrastructure is prohibited for the movement of another train. Said that the number of block sections to be covered is defined by the set of conditions, defined in (11), (12), (13) and (14), according to the characteristics of rolling stock, infrastructure and equipment, the length of the sections becomes that synthetic parameter to which it is possible to associate a minimum headway that must be achieved so that there is not reciprocal conditioning in the running of two successive trains. At this headway is then linked the value of the theoretical capacity of (a stretch of) a railway line, as indicated in (4), (15) and (16).

Within the railway nodes, on a simply stretch or on a common stretch between more lines, it is possible to observe an increase in the number of programmed trains that, even if not should lead to the achievement of the theoretical capacity of the stretch, at least it would undermine regularity by reaching those values of practical capacity[1] that determine a lowering of the punctuality level, objective of the IM.

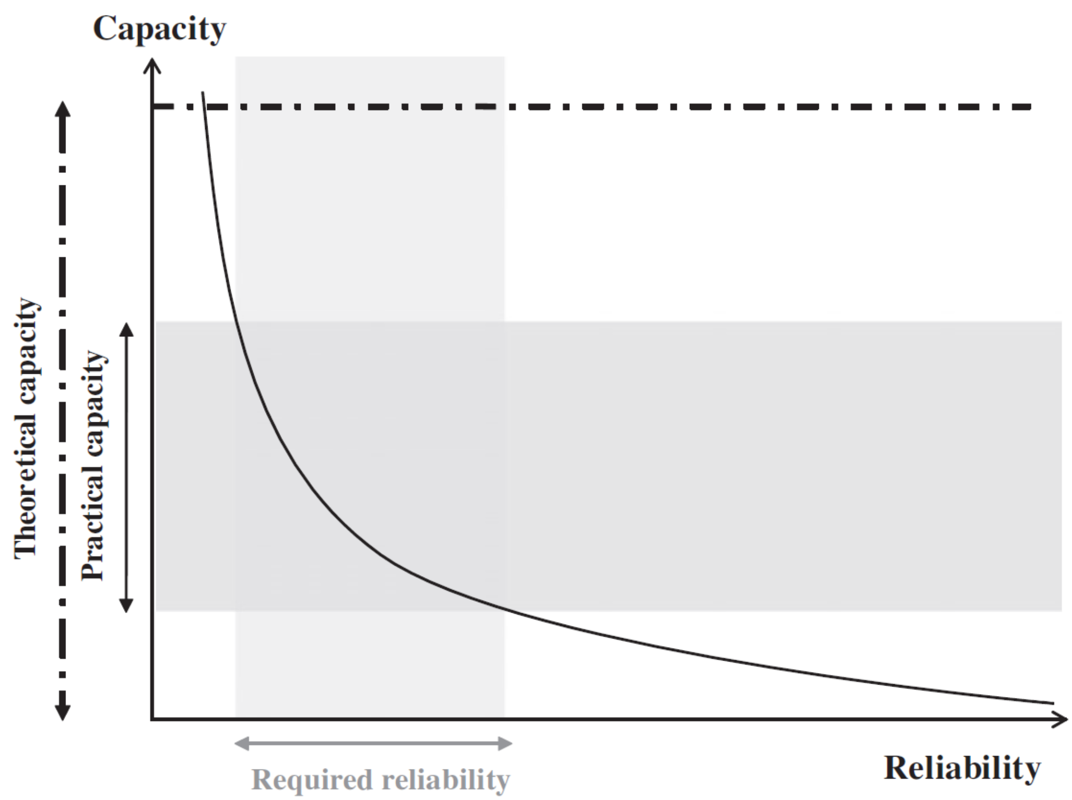

Figure 1: Link between capacity and regularity

To guarantee the safety of traffic in the stations and junctions, it is necessary to add all the necessary operations to form the desired itinerary -

[1] The definitions of theoretical capacity and practical capacity and their difference are explained in (4).

maneuvering, ensuring and controlling switches - and to ensure that incompatible movements are not possible with the formed itinerary. These operations are carried out by means of the interlocking system which allows the operator to arrange the signals only after it has correctly carried out all the operations of the entities, and obtained through the same system, all the necessary checks. The characteristics of the interlocking influence the potentiality of the station, to the extent that the need to predict a whole series of security checks can be the least impactful possible on the movement of trains within the locality.

In fact, the biggest problem within the stations is that the trains run along the incompatible routes it is strongly conditioned by the characteristics of the track, the interlocking and the type of services. The realization of the unperturbed run within the locality, like what was obtained in line through the minimum headway, places more restrictive conditions and, in many cases, needs a greater headway than in line, from which a greater utilization of the infrastructure with the same traffic. To act on the variables that influence the potentiality of stations is as important as improving operation along the stretches line; even more so because they are the places where it is possible to reach first the saturation, they are also those in which efforts have been concentrated over the years to improve the operational management.

The command[2] and control[3] function of operation within the urban railway nodes is generally performed, within the so-called Control Room, by automatic traffic command and control systems under the responsibility of

[2] Activation and remote-control activities of line systems, directly influencing the safety of movements of trains.

[3] More general activities of supervision and of a provisional and decisional nature.

operators having jurisdiction over even larger parts of the network. The introduction of these systems has pursued the needs of benefits that in terms of safety and regularity of operation are introduced in terms of interface in the control and decision aid in the management phase.

The high infrastructural density on the one hand allows the formation of multiple routes for railway services that merge in the node, allowing differentiation of the commercial supply, on the other hand it causes mutual conditioning, generating potential causes of delay to trains entering and leaving the node. If you think that the run along the lines that merge in the node is itself subject to perturbations, the high density that has been discussed performs as an amplification factor and detrimental to the overall quality of the supply that the IM is able to offer.

Other constraints are of an infrastructural nature: even if the line stretches being part of a node had block sections of length optimized for obtaining reduced headway values, the presence of single-section junctions or long roots of stations, altering the succession of sections of optimized length, would infect the capability to withstand programmed trains according to the expected headway. In the same way that the "bottleneck" of the node can be a stretch of a line, for the reasons mentioned above, the same can be any station or junction inside the node, where the conflicts of circulation between interfering movements limit the use of the locality and, consequently, of the entire infrastructure.

Considering this, a joint assessment of the operation along the line stretches and within the localities. Different contributions on the subject were given, as in (7) and (8), and show quantitatively as the problem of railway circulation in urban nodes has two-side; qualitatively, any the "bottleneck", this in addition to being probable source of perturbations that could propagate at other points of the node, is a point in where any perturbations generated in other points would be propagated.

Not only are the volumes of traffic programmed to determine *tout-court* the saturation of a portion of infrastructure rather than another but also combinations of routes can affect operation within the node. It becomes not only fundamental to identify the "bottleneck" inside the node but above all to understand what are the possible interventions to decongest and how much they are sensible to variations in traffic, volume, typology and itineraries. The same intervention can be aimed at reducing the utilization rate of a portion of the infrastructure, with benefits on the regularity of the services that insist, or to lay the foundations for an increase of the commercial supply, otherwise not achievable. In the first case, benefiting from the "bottleneck" would also benefit the operation in the whole node; in the second case, the adjacent infrastructural elements would be loaded, and compatibility of traffic increase should be verified. Only the whole node analysis, or in any case, of the part of it which is believed to limit the influence of the intervention, can provide significant information on the effectiveness of the proposed intervention.

3.2 Station Interlocking Systems

The different station interlocking systems can be distinguished in:

- ACE/ACEI – In a central unit with electromechanical technology the operational functions (switch maneuvers, signals, track devices, etc.) are implemented by electromechanical devices while checking the safety conditions (logical functions) are carried out by relay electric circuits: the logic is based on a correspondence between current circulation and physical/logical state of the institutions (free track, recorded itinerary etc.). In the Individual Levers Electric Interlocking (ACE, in Italian) the formation of the route and the opening of the signals happen by means of special levers. These can be maneuvered only if certain safety conditions are verified through mechanical or electromechanical locks. The Route-Setting Electric Interlocking (ACEI, in Italian) allows the formation of the routes by simply pressing the appropriate buttons, one for each route envisaged by the tracks, which control the route formation process and the maneuvers of entities and signals. The verification of the security conditions takes place through relay logic circuits (wired logic).
- ACC – The Computerized Interlocking (ACC, in Italian) is characterized by a logic based programmed structure and allows control of the operation by displaying it on a monitor with safety features. The substantial difference compared to the wired logic of the ACEI is that the security conditions are verified by a software program installed on a computer that performs the analysis of the states of the

yard entities and, based on this, provides the result of the verification. To guarantee an adequately high security level the architecture is redundant. There are many advantages over ACEI:

  - Decreased hardware used and reduced dimensions
  - Increased operation flexibility, especially for devices that require remote control
  - Reconfiguration managed by software
  - Better management of degradation phases
  - Integrated diagnostics
  - Modularity and adaptability to several types of yard

- ACCM – A further evolution of the ACC is the Multistation architecture (ACCM) which provides for the management of a line or a series of stations through an ACC with the Multistation Central Post (PCM) installed in a locality and the Multistation Peripheral Post (PPM) installed along the line. The Central Operational Controller (DCO) from the PCM gives remote commands and detects the position checks of the entities. Between PCM and PPM (also located to hundreds of kilometers of distance) there is an optic fiber communication network that allows the remote controls in safety. Logics and stations configurations are concentrated in a PCM and is created an operator interface that safely checks the line and securely displays every single PPM. The latter consists only of actuators for yard entities. The ACCM is also used for the management of nodes and lines with "mixed" interlocking systems (over PPM also ACC and ACEI). In fact, the PPM can also be ACC stand-alone controlled by

PCM (PPACC) or ACEI (PPACEI) controlled by PCM through a specific interface called Interlocking Electronic Manager (GEA). When, as in these cases, the logic remains allocated in the peripheral entities, the PCM will integrate features for the sole purpose of displaying them correctly in the PCM Operator Room. The evolution towards ACCM involves:

- Merging on a single type of product
- Better and timely management of traffic in case of disruption
- Integration of line and station functions in a single interlocking
- The abandonment of electro-mechanics and wired logic
- Optimization of diagnostics and maintenance processes
- Predisposition to the connection with RBC
- Predisposition interfacing with systems of command/control/supervision/automation (SCC)

3.3 Block Systems

Different devices and different operating configurations characterize the realization of the spacing of trains on line. The several types of BS existing on the RFI network are shown below:

- BEM – The Manual Electric Block (BEM, in Italian) is a semi-automatic block system that requires the intervention of a Signalman or a block post keeper in each intermediate block post. The spacing is achieved through an exchange of requests, transmissions and receptions of block electromechanical consents between the operators for the free disposal of the signals. The communication between posts takes place in fact through the so-called Block Instruments, connected by telephone cable; normally there is only one section between neighboring stations. The interlocking carries out the checks of correctness on the sequence of imposed operations, but the verification of integrity is not carried out automatically and is therefore delegated to the operator.

- BAcf – With an automatic locking system there are considerable improvements in terms of safety, capacity and the disappearance of the cost of attendance. It is also possible to use of such types of BS for both directions on the same track and to have a two-way double-track operation of the line (the occupation of the section is detected when a train enters both from one extreme and the other). In a fixed current automatic block system (BAcf) the train spacing on line takes place automatically using electromechanical devices and track circuits that can detect the presence, and hence the occupation, of a train in one certain block section, or on the contrary ascertain its relative absence in order to free disposal of the signals.
- BAcc – In the Automatic Block with codified currents (BAcc) the spacing is made automatically by electromechanical equipment, electronic and track circuits (CdB), such as to add to the functions of the previous one BAcf, the so-called Continuous Repetition of Signals in the cab (RSC). Code is injected on the CdB by cyclically interrupting the current with a determined codification period, whose inverse represents the frequency (expressed as 1/min) with which the code is

identified. This code, taken from the rolling stock, it provides the board equipment (SSB) with the status of the track, and therefore of the signals that are still not visible, in advance and for a long distance in the direction of the route. This information allows the SSB to process and adapt continuously the braking curve allowing a better use of the speeds allowed by the line. Every code is shown to the driver, who can thus associate with one specific target speed. The above results in an increase in security and in the capacity of the line. For this reason, the BAcc is used on lines with traffic intense with CdB of a length normally equal to 1350 m and corresponding to block sections.

- BAcf with RSC Emulation – RSC emulation is a system that can only be used on a stretch of line managed by ACCM. When a section is free, on the track exists a traditional uncodified current. At the arrival of the train the ACCM, knowing the status of the line, calculates the right code and places it on the track. The code sequence is then managed directly from the PCM and no longer from the BAcc equipment on line. The advantage lies in the great simplification of the equipment installed on the line.
- BCA – In the Automated Axle-Counter Block system (BcA) the verification of the freedom of a section is based on the check of parity of count between entered axes and exited ones in the section itself during train passage. This is possible by means of differential counters of type electromechanical or electronic controlled by electromagnetic axes at the entry and exit of the line section. The latter can be long until 20 or more kilometers and contain multiple block sections. Normally it

uses double pedals to obtain two wheel passages each time successive pulses in time that allow to identify the direction of travel. Compared to the use of CdB, there are advantages in terms of economy and simplicity in technical equipment (for example, there are no sections of the rails, etc.), although there is no possibility of repetition of signals in the cab. For these reasons the BcA is generally used on low-traffic lines.

3.4 Design process according to Headway Norm technique

The translation of infrastructural, regulatory, technological and rolling stock constraints into a minimum value of which the trains must be spaced so that they can run regularly without disturbances, both on line and at a station, makes possible planning of the service timetable. In order to give this a certain stability with respect to punctuality, it is necessary to provide a buffer time, the so-called 'regularity margin', in order to not propagate the disturbances to which the circulation is subject to other trains. At the Italian Infrastructure Manager, it is in use to complete the minimum spacing (infrastructure blocking time[4]) juxtaposing the regularity margin regularity to form the so-called Headway Norm. The choice of proceed following this setting, rather than placing the margin at the end of a sequence of trains just spaced according to the blocking time, has orders two advantages: on the one

[4] It is the time during which it is forbidden a portion of infrastructure protected by a main signal.

hand it is possible to proceed to a more immediate timetable design, assessing later the timetable stability, on the other hand it is also possible to proceed immediately to the calculation of the infrastructure utilization and of its remaining capacity. It introduces, however, the topic of the quantification of regularity margin. The headway norms are divided into:

- Line spacing
- Crossing and overtaking station
- Spacing for conflicting movements in station
- Arrival, departure and passing movements on conflicting routes
- Arrival and departure from/to the same line
- Junction spacing

A thorough theoretical treatment of headway norms on lines equipped with automatic block with codified currents was made by Vaghi in (16). Between the greatest achievements it is possible to understands that the headway values historically used by Italian Infrastructure Manager are obtained by doubling the blocking time, therefore contain a regularity margin at least equal to it. In this way it is achieved the simple stability: no deviation within the punctuality interval can carry out the same interval the interfered trains and if the next train presented with an own delay, after the interaction, the final delay would be the greater of its initial deviation and that propagated by the first train. It would be also possible to accommodate, within a sequence, an external train, spaced of only the blocking time from both trains of succession.

Ciuffini et al. (18) dealt with the construction of arrival and departure norms from/towards the same direction in the case of terminal stations, supporting the theoretical construction with the software simulation of operation and concluded that the margins of regularities can be quantified by finding the right balance with the timetable robustness.

Referring to (16) the deepening of the construction of the headway norm on line, we do own the results and introduce a construction method for the norms that have not been treated. Since there is no scientific treatment on headway norms in conflicting points, outside of what has been described in (18) only for the terminal stations, it was necessary to make assumptions based on experience feedbacks. The regularity margin has been assumed constant for all the considered interference.

So that between two trains there are no reciprocal conditioning, the passage of the heads of the two trains at *Punti Orario*[5] (PO) must be programmed according to its norm, which can be constructed by bringing back at a temporal spacing problem, starting from a distance spacing one. The distance spacing must be achieved between the rear-end of the first train at the point in which it releases the infrastructure and the head of second train, which must be in a point where it does not perceive restrictive aspects by signaling[6]. The transformation in a temporal spacing problem is made by means of the equations of motion, taking into account the characteristics of the infrastructure and rolling stock adapted to circulate.

The blocking time consists of the following contributions:

- Infrastructure occupation by the first train[7]
- Release of IS equipment and formation of the second route
- Infrastructure occupation by the second train[8]

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[5] Specific points of railway infrastructure in which it is referenced in timetable the train path.

[6] It is included the visibility distance in the case of light signaling without RSC.

[7] From the passage under the main signal which protects the conflicting point until the rear-end release of the occupied entity.

The POs are generally referred to the main signals of junctions on line and to the platform in station, then do not coincide with the points where materializes the interference between two movements; also could be that the conflicting point is not protected by main signal which is reported the PO. In both cases must displace spatially or temporally, the norms, referring them to the PO. From this point of view, it is preferable that the conflicting points are put as close as possible to the signals that protect them.
The use of the headway norm may appear rough compared to the use of the blocking time, which represents with greater accuracy the actual use of the infrastructure, simply relying on a microscopic model of the same. However, with a norm built as described, they benefit both the timetable design process and infrastructure capacity assessment process: for each movement to be programmed is quantified the temporal distance that must be respected with respect to any other conflicting movement, in both cases of capacity analysis in the absence or presence of timetable.

3.5 European Railway Traffic Management System (ERTMS)

The automation developments that have been achieved for the IS equipment allowed to obtain benefits in the movement of trains as well as employees in operation. The realization of the RSC and, in general, of the Class B[9] train run protection systems has allowed to increase performance and security both in

[8] Up to the achievement of the PO with the train front-end.
[9] Pre-existing train protection system with respect to ERTMS/ETCS and whose requirements are the responsibility of the Member State and not a EU one.

speed signaling as in the short spacing contexts. The trend of railway progress is particularly favored by specific innovation strategies at European level, in relation to research and development projects sponsored by the European Union, in the ERTMS project. ERTMS is the European Railway Traffic Management System and consists of two main components:

- ETCS – European Traffic Control System for the control-command, run protection, spacing and signaling
- The telecommunications network GSM-R (Global System for Mobile communications – Railway)

The requirements and general specifications for ERTMS are regulated by Technical Specification for Interoperability relating to the "Control-Command and Signaling" subsystems of the rail system in the European Union (TSI CCS), of which one *Baseline* represents a specific version referred to a fixed documental set that discipline:

- The control and command System (ETCS)
- The radio communications (GSM-R network)
- The train detection system

With the ERTMS project the European Union has created a common platform for national railways, authorities and industries producing signaling systems, allowing communication between the rolling stock, made by different manufacturers for different railway companies, and track equipment specifications of the various countries. They have been standardized information, language and transmission techniques of on-board and trackside components, thus creating an important prerequisite for interoperability and a market of products and applications by a single recognized standard.

To answer to different functional requirements related to the need to overlap, even before than substitute, to national systems, three functional levels have been identified, which differ as follows:

- Level 1: train integrity and track occupation are recorded on the track via different systems by the ERTMS; the transmission of information takes place in discontinuous or semi-continuous way through to ERTMS standard systems and/or pre-existing systems; the spacing is secured by the existing systems and line signals are not eliminated
- Level 2: train integrity and track occupation are recorded on the track via different systems by the ERTMS; the transmission of information takes place in continuous form by radio with ERTMS standards; the spacing is managed as a fixed block from the Radio Block Center (RBC) according to the state of block sections and line signals may or may not be eliminated
- Level 3: the integrity of the train is detected by the ERTMS on-board via different systems, the track occupation is communicated to the RBC thanks to safe knowledge on-board of its own position (EUROCAB device); the transmission of information is in continuous way by radio to ERTMS standards; the spacing is managed as mobile radio block from RBC and the line signals are deleted.

Beyond the EU obligations and the need for interoperability, it has consolidated the idea that the potential of ERTMS may become an important opportunity for rail transport also and especially in special situations such as operation at high speed, in case of high density traffic in nodes.

In the following paragraph it will refer to the ETCS component which constitutes, among other things, the trains spacing system of ERTMS.

3.5.1 ETCS Level 2

ETCS Level 2 is a BS based on a land-train radio digital data transmission. In the cab information about the state of line and the authority to run are directly displayed, obtained by means of appropriate interface with the signaling system of the line, usually run by ACC-M. This enables a safe traffic management by automatically adjusting the run in a centralized system called Radio Block Center (RBC) connected with each train (within its jurisdiction) via a radio transmission system (Euroradio) on GSM-R network, implemented by Radio Base Stations (BTS) along the line.

The track occupation system and the integrity check can be realized by means of Axle-Counters or CdB, as for conventional systems. The Management System of the track (GdV) provide to RBC the status of the yard entities, train routes and track occupation. The RBC transmits the permissions to move the train (Movement Authority, MA), consistently and together with all the relevant information about the line (occupation, slopes, details and characteristic points). Are transmitted also the Static Speed Profile (SSP) that indicate to the SSB the permitted speed of the train at every instant, calculated based on the above information. The movement of trains is thus continuously monitored by the SST and the GdV system and is realized the so-called Automatic Radio Block (BAR).

The on-board computer (EVC, Euro Vital Computer) provides to continuously process acquired data as well as monitor the maximum permitted speed, depending on the characteristics of the line and of the train. Based on these data, the computer processes the better braking curve of the Dynamic Speed Profile (DSP), commanding the automatic braking in case of non-compliance of the running constraints.

In addition to the continuous transmission of data between train and RBC also exists a discontinuous communication between SSB and SST realized through Eurobalises. They are used as positioning detectors, also for the purpose of control and calibration of the odometric board system. Generally, Eurobalises are not switchable and can be positioned on the tracks in correspondence of the complexities of the line to transmit both the position and the presence significant entities.

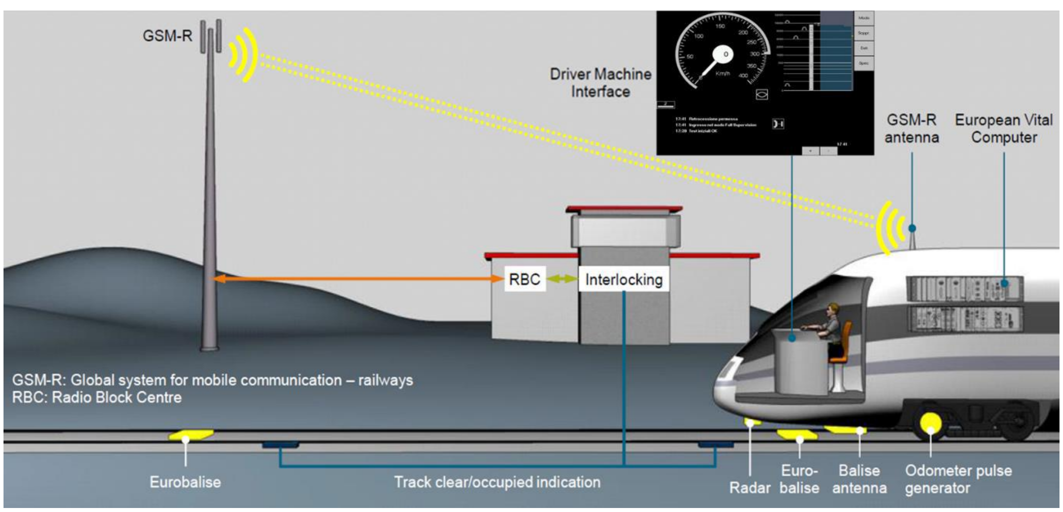

Figure 2: Operational principles of ERTMS/ETCS

The Information Points (PI) are constituted by at least two Eurobalises; most of them is located approximately 200 meters before the end of each section, in both running directions. The two balises in succession also allow the identification of the running direction. The SSB notes the succession of balises the train meets along its route as well as the distance between a PI and the next one. Based on the last PI met (Last Relevant Balise Group, LRBG), the onboard computer sends to the RBC so-called Position Report (PR), a radio message containing among other things the position, the operating mode, the speed and direction of the train, the request of MA.

The ETCS Level 2 realizes an Automatic Train Control (ATC) whose operating mode operating in normal conditions is defined Full Supervision. All information, indications, warnings, authorizations to movement which allow the movement and the spacing in safety are displayed in the cab (Cab Signaling) on the DMI (Driver-Machine Interface), standardized in such a way as to ensure the operational interoperability on ETCS L2 lines.

From the point of view of technological equipment of the ground system, the need of having fixed light signals disappears. On the other hand, it is required the presence of several BTS to ensure a smooth data flow between the ground and train, a certain level of communication quality and an adequate signal-to-noise ratio. There should be no grey areas in the long line radio coverage but rather must be provided that, in case of BTS out of service, is the next and previous stations compensate for this lack.

3.6 The resolving bottlenecks process in urban railway nodes

The growing and joint requests for new tracks and railway timetable stability make the need to provide increasingly urgent interventions aimed at decongesting metropolitan railway nodes. Among the most effective interventions, some concern the design of timetable and require no investment, but a verification of the compatibility of the proposed solution and estimating the benefits, and they are immediate applicable; others, needing more or less expensive investments, require a long-term planning and their realization, also delayed in time, could result a constraint to the railway operation, which is why the evaluation of the proposed solution must be so general, in virtue of independence from current conditions of the infrastructure, operation, services and rolling stock, however accurate because of the extent of the investment.

Among the first there are several management interventions:

- Revisiting the structure of services, including: transformation of services, paths modification or displacement
- Modification of the itineraries within the node aimed at lightening specific stretches of line or conflicting points that the operational management has shown to be critical

Among the latter, there are interventions infrastructural or technological renewals of IS systems:

- Installation and/or replacement of switches that, allowing for greater running speed, permit the reduction of the infrastructure occupation times.

• Creation of new tracks within the node

• Changes to the track layout

• Realization of bypasses between lines that allow the independence of the routes

• Renewal of the Interlocking system in station

• Change the BS that equips the stretches of line

Each of those tasks not only pursues a specific operational requirement but is inserted within a broader contexts concerning, among other things, the transport supply planning by RUs and competent agencies or the need for renewal in technological and maintenance purposes: aspects related not only to the skills of the Infrastructure Manager but also to those external subjects. .

The Infrastructure Manager must consider several variables in prioritizing investment in the nodes, such as: the cost of the intervention, the benefits, the operational constraints, technological conditions, traffic scenarios, agreements with external parts.

Given that the nature of management interventions, they are frequently operated, and also in the course of timetable, to improve operating activities in railway, it is possible to detect that the priority has traditionally been given to renewal of the station interlocking and tracks layout, with simultaneous switches speeding up. Long-term projects concerned especially the creation of new pairs of tracks inside the nodes, allowing the specialization of traffic, and the realization of bypasses.

Over time was tried to make as less impact as possible the merging of different lines within nodes, where the presence of low potentiality stations would affect the service regularity. The spacing systems implemented in the case of construction of new lines have been the traditional block technologies, albeit with some improvements where it has been possible to fit. The decrease in the length of the block sections up to the length "normally reduced" of 900 meters or "abnormally reduced" of 450 meters made possible to reduce the headway norm up to 4'00”[10], with the constraint of a limited maximum speed on line. In the "Milan suburban railway tunnel" the headway norm is between 3’30” and 4’00” in presence of block sections length between 450 and 900 meters but limiting the maximum speed to 60 km/h. The presence of close-up stops, served by suburban services and dedicated rolling stock allows not to perceive the infrastructural aspect as a limit. On the contrary, it is a case in which the IM internal and external commercial needs and technological and regulations developments have resulted in an optimum situation. However, it is not possible to think of extending this solution to stretches of line not specialized for two reasons:

- It may be required higher speeds
- The presence of junctions or stations with long roots would require the presence
- of non-optimized block sections length, compromising the running of trains spaced according to a norm rather low as 4'00”

Should there be that a stretch of line reaches utilization rates next to maximum capacity, that is a possible "bottleneck" of the node, a possible solution would be the revision of the headway norm, as told in (16), reducing the regularity margin to the detriment of timetable robustness. This solution in addition to going in the opposite direction with respect to the greater

[10] The headway norm traditionally adopted with BAcc and section length up to 1350 meters is 5’00; otherwise, 6’00”.

stability requests, it falls within the list of those managerial interventions capable to face with a contingent exigency, which may be the presence of some isolated paths in rush hour, or the establishment of a new relationship. It cannot be seen as a definitive solution to the congestion that has been created on the stretch of line, even more so if operators on the one hand ask for more and more services and on the other pushing for a commercial supply systematization throughout the day. The competent local authorities, through the Framework Agreements, reserves a part of the residual capacity of a line well in advance; the passenger RUs operating in a competitive market try to reserve the paths commercially more attractive, whose position in the timetable structure is detached from that of the public transport services and therefore may be quite close if they had to be respected "clock" constraints; the freight RUs make pressure to have systematic paths within nodes, especially in the early morning and late afternoon, opening and closing times of intermodal terminals. These different requests result in the need to reduce the utilization rate of the stretches of line within the metropolitan railway nodes, without putting other restrictive conditions such as the limitation in the maximum speed or the presence of conflicting points in stations and junctions.

4. High Density ERTMS/ETCS (HD ERTMS)

4.1 Operating principles

Based on what was discussed in Chapter 3 it was studied the innovative BS High Density ERTMS/ETCS (HD ERTMS), arranged for specific rolling stock, in order to maximize the densification of trains along the line and in station within the node. The goal of the development of this technology is the decongestion of the more loaded stretches of line within the urban railway nodes, in order to achieve the expected traffic volumes without affecting the operation regularity. Furthermore, the main goal can be joined with the creation of the conditions for an increase in commercial supply, which possibility should be verified through an evaluation of the impact on other infrastructure nodal elements.

The new specifications ERTMS Baseline 3 optimize the use of the line due to a better parameterization of braking curves (through the sending of parameters from ground) for trains having particularly good braking performance. Also, as part of the evolution of Baseline 3 it may be added to the ETCS specifications the possibility to use GPRS communication packet based on IP and the interface with ATO functionality (Automatic Train Operation). The main feature to be used in high density combination with ERTMS consists in providing driver a recommended running speed to optimize densification. At now, this feature is not yet available, therefore refer to future developments in the functional and commercial study of this innovation, leaving this work to analyse in the same way the pure HD ERTMS.

In order to overlap HD ERTMS and an Automated Block system is needed that the station and junction interlocking are computerized. The intervention inserts in a wide context of renewal and improvement of the nodal infrastructure, in which the electric interlockings will be progressively substituted with computerized ones and, contemporarily, will be improved the line operation.

The HD ERTMS is a ERTMS/ETCS L2 system with some typical features of Level 3 and involves the use of a RBC, called "Nodal RBC". The realization of high density provides for the reshaping of traditional sections. In particular, in order to concentrate more trains within a traditional block section, the same must be divided into several partial sections (Radio Block Sections, SBR) both on line and in station, to allow the management of partial routes (emi-routes) within a traditional one, as well as the assignment of MA on those partial routes. The installation of ETCS line equipment (SST) is designed, at the time, and as an overlay and integration to SCMT[11], in order to ensure the entry also at not HD ERTMS trains. This is expected to allow for the gradual adjustment to HD ERTMS technology of the RUs rolling stock. It appears clear, as described next, the advantages offered by the ground implementation of HD ERTMS/ETCS are fully achieved only if all the trains running on the node enabled the ERTMS SSB and all of them have the same performance characteristics. On-board, in fact, the system is usable only by

[11] The Train Run Control System (SCMT) is a national Class B system of running protection, with discontinuous information that, in a transparent way with respect to operations of driver, except in some cases as an indication of the reduced speed, maintains a continuous control over a series of parameters which determine the permissible speed for the train and, if necessary, controls the braking intervention. (20)

very performing trains in braking and deceleration and with the Train Integrity functionality included on board.

The introduction of HD partial sections does not require the installation of new light signals (which generally are not required by the ERTMS/ETCS L2, or displacing existing track circuits, except in exceptional cases[12]. The realization of SBRs occurs through the positioning of ERTMS PI and signals within the existing sections (without use electromechanical joints). The end of each HD ERTMS section or emi-route that does not coincide with light signals is identified, in particular, through appropriate signals posed on tables (ERTMS signal "Stop marker"). This solution allows a more proper management of the run even in cases of disruption (identification of the exact point of end HD section or route).

An “HD partial section” is a section configured on part a station section, corresponding to one or more contiguous CdBs, which allow to determine occupation status. In fact, in the stations, the CdBs have a length lower than that of the line CdBs and comparable with that of the sections for the high density. The operation on "HD partial sections" on station CdBs is illustrated in Figure 3.

[12] If the division into virtual sections of optimized length require the displacement of a signal, and then the variation in length of the traditional block section, then it would be necessary to modify also the relative CdB.

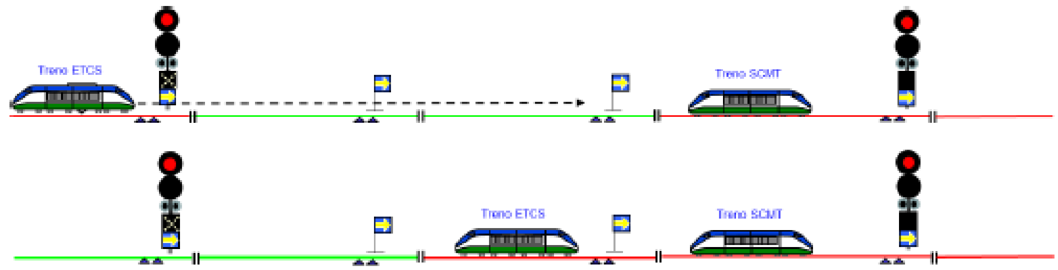

Figure 3: Track management in station; each SBR has own CdB; the ETCS train is able to approach the SCMT train

The interlocking logic provides that the command of a traditional route includes the formation of HD ERTMS emi-routes of which it is composed, after verification of the incompatibility as with the traditional routes. In order to achieve the high density, it is possible to command a still occupied route, as well as a rout with a different Final Point (PF). In these cases, the high density is possible only if the first HD ERTMS emi-route downstream of the light protection signal has returned to free disposal and the command of successive HD emi-route automatically happens with the progressive liberation of the upstream emi-routes.

An "HD virtual section" is a section configured as part of a line section, with an extension lower than that of the CdB section; more than one virtual sections are thus including in a single block section and do not have dedicated CdB. Consequently, the HD line sections do not match the existing track circuits, and their state of occupation cannot be determined only on the basis of the information provided by Interlocking or from the automatic block control equipment, but it is determined by RBC on the basis of data provided by the specialized rolling stock that implements the Train Integrity function. The freedom of the virtual line sections line is therefore governed by RBC through the acquisition of the Position Report with train qualifier

"Q_LENGTH" appropriately valued based on actual train integrity and certifying the rear-end overpass (Minimum Safe Rear End) of virtual section end-point. This functionality is ensured by the operation of the rear SSB in "sleeping"[13] operating mode.

Figure 4 shows the operation of the HD ERTMS system on line with trains having Train Integrity functionality. The ETCS Train 1 engages the SBR signal and communicates downstream his new position so that the RBC transmits to interlocking, which provides the danger disposal of light signal for ETCS Train 2. The ETCS Train 1, crossed the virtual section, communicates to RBC that his rear-end has safety released the SBR previously engaged. The RBC transmits to interlocking the information. When ETCS Train 2 is in proximity of the light signal, the interlocking establishes the lighting of X to allow the run of the train until the HD virtual section signal (released by the previous ETCS Train 1).

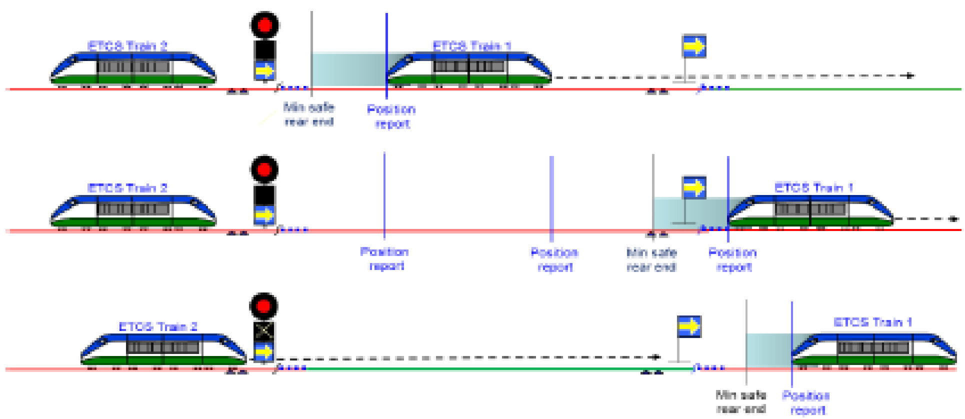

Figure 4: Release of a SBR through the Train Integrity function

In the case of the line section occupied by a train without Train Integrity function, the main light signal of the occupied section remains at danger and

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13 See (20).

the subsidiary information remains off. The extent of the MA for a successive train will be limited to such light signal.

As seen from the previous case, it is expected the presence of a subsidiary information on the light signal, provided by the introduction of a new signal aspect: Red + “X". When the appearance is of type Red + "X" turned on, the train has been recognized as HD ERTMS on and thus can receive the MA to advance in downstream emi-sections depending on their freedom or occupation. If the train is not HD ERTMS one, this will continue to travel according to the previous signalling system and with traditional CdB length.

Below some functional scenarios that may occur on line, in the simultaneous presence of HD ERTMS and SCMT trains.

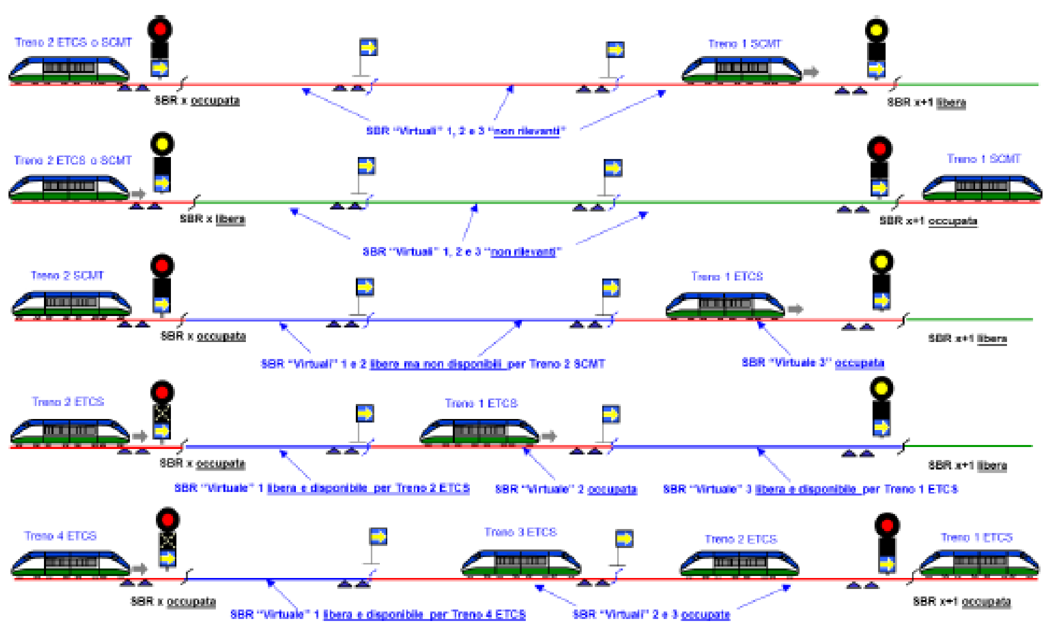

Figure 5: Functional scenarios in line operation

Another innovation introduced, acknowledging the ERTMS Baseline 3, regards the speeding up of the arrival routes in station. Traditionally the change of speed takes place in correspondence of the main signal; thanks to the cab signalling and an appropriate RBC Node configuration it becomes possible to have the speed change point at the tip of the switch in order to optimize the speed profiles for crossing routes (Figure 6), promoting the high density of the trains.

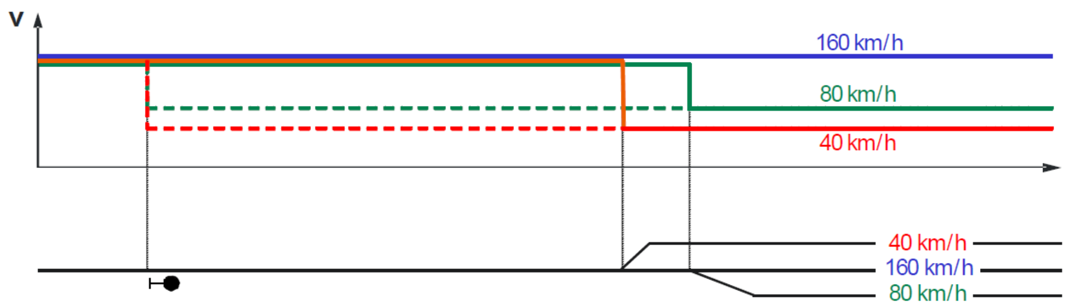

Figure 6: Static Speed Profile in correspondence of the root of a station

4.2 Potentiality

The potentiality of the BS HD ERTMS need to be assessed to the extent that this can improve the design parameters of timetable, i.e. the Headway Norms, without affecting the regularity because of traffic increase, of which the implementation of HD ERTMS constitutes a purpose. The high density on lines is functional to the reduction of the spacing norm, while high density in station to the reduction of conflicts between specific incompatible movements. In order that this reduction will effectively occur is necessary that the trains can be spatially brought without affecting the running speed, in security and regularity. The improvements made by the ERTMS Baseline 3 in terms of braking allow trains equipped with ERTMS HD SSB, and with the necessary requirements, to occupy a SBR at a given speed, depending on the extension of the MA that can be communicated. The assumed requirements are:

- Mass Braking Percentage (PMF) not less than 115%

- Release speed calculated on board
- Disabling of the service brake in the target speed control
- "Mobile Terminal" with appropriate filters for radio interference
- "Rolling Stock Correction Factor" equal to 0.9

In Table 1 are shown the nominal speeds at which the entrance in a SBR is allowed in function of the licensable MA and the virtual overlap length at the end of section.

Movement Authority	**Minimum distance EoA – SvL**	**Nominal speed**
350 meters	≥ 20 meters	50 km/h
	≥ 50 meters	50 km/h
	≥ 100 meters	55 km/h
700 meters	≥ 20 meters	80 km/h
	≥ 50 meters	80 km/h
	≥ 100 meters	85 km/h
1050 meters	≥ 20 meters	100 km/h
	≥ 50 meters	105 km/h
	≥ 100 meters	105 km/h

Table 1: Possible nominal speeds depending on the MA that can be granted and the length of virtual overlaps

The obligation for the driver to run ever at full speed and the need to have a regular run without disruptions introduces a very strong link between the MA which is must be ensured between two successive trains and the line speed. So that the HD ERTMS implementation is as transparent as possible towards the actual existing paths[14] the process of calculating the spacing norm must necessarily impose the line speed as invariant, at which value must be approached the nominal input speed in SBR, which corresponds to a

[14] This choice derives from the purpose of this work of comparison with respect to technologies implemented in the railway nodes.

specific extent of MA and i.e. the minimum spatial distance that must be guaranteed to obtain a smooth and unperturbed run.

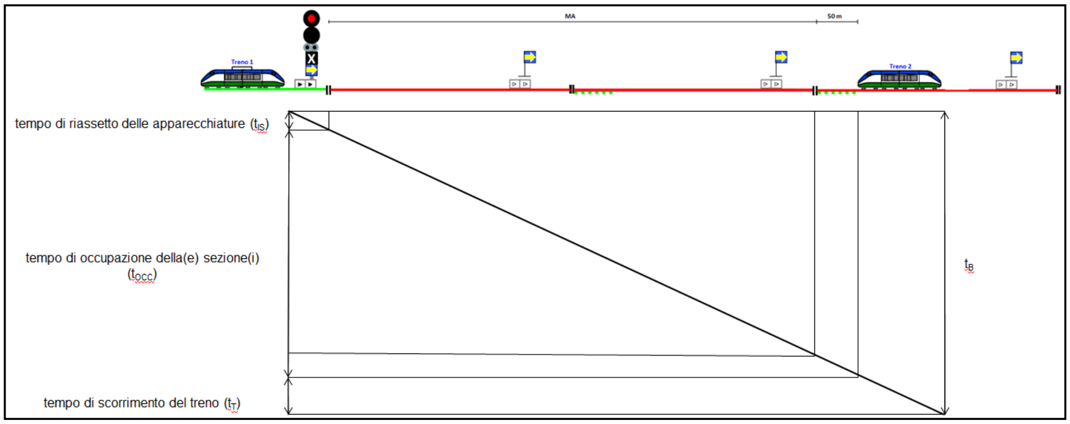

Figure 7: Blocking time construction

Figure 7 shows the space-time diagram which allows to pass from spatial to temporal spacing, according to what has been described in (16). The following tables show the blocking time and headway norm values obtained for the virtual overlap length equal to 50 meters, reset time of IS equipment equal to 30 seconds[15] and train length of 250 and 350 meters.

MA	L_{RIC}	V_{NOM}	t_{OCC}	t_{IS}	L_T	t_T	t_B
350 m	50 m	50 km/h	29 s	30 s	350 m	25 s	84 s
700 m	50 m	80 km/h	34 s	30 s	350 m	16 s	80 s
1050 m	50 m	105 km/h	38 s	30 s	350 m	12 s	80 s

Table 2: Blocking time in case of maximum train length equal to 350 meters

[15] The value of t_{IS} that has been adopted is a first hypothesis one and allows us to consider the various infrastructure configurations that may be encountered within the nodes. In fact, it tends to zero in open line while it may reach up to 60 seconds in complex installations (operated by ACC). The value chosen is conservative with respect to the movement in open line and it seems to be realistic if, in one or more line sections there are stations or junctions (rather simple, for example a crossing) operated by ACC. More restrictive values of t_{IS} will be considered in the calculation of norms in station.

MA	V_{NOM}	Headway norm	Rounded norm	
350 m	50 km/h	168 s	180 s	3’00”
700 m	80 km/h	160 s	180 s	3’00”
1050 m	105 km/h	160 s	180 s	3’00”

Table 3: Headway norm in case of maximum train length equal to 350 meters

MA	L_{RIC}	V_{NOM}	t_{OCC}	t_{IS}	L_T	t_T	t_B
350 m	50 m	50 km/h	29 s	30 s	250 m	18 s	77 s
700 m	50 m	80 km/h	34 s	30 s	250 m	12 s	75 s
1050 m	50 m	105 km/h	38 s	30 s	250 m	9 s	77 s

Table 4: Blocking time in case of maximum train lenght equal to 250 meters

MA	V_{NOM}	Headway norm	Rounded norm	
350 m	50 km/h	154 s	150 s	2’30”
700 m	80 km/h	150 s	150 s	2’30”
1050 m	105 km/h	154 s	150 s	2’30”

Table 5: Headway norm in case of maximum train length equal to 250 meters

The most important result is that, for each of the train length values considered, the value of the headway norm is the same whatever the nominal input speed, i.e. the line speed. These values refer to the ideal case in which, after the old sections division, it is able to ensure an extent of MA exactly equal to that required by the line speed, through the interposition of more SBRs between successive trains. In real applications some SBRs can have a not optimized length[16], such as to ensure a greater extent of MA than the minimum allowed by the technology.

Therefore, the line headway norm design process must consider, on the basis of what has been done with traditional BS, the extent of MA, obtained by means of a succession of an integer number of SBRs, with the greatest travel time.

[16] The first hypothesis optimized value is 350 meters.

Another important advantage of the split in the SBRs is junctions placed in a corridor equipped with HD ERTMS. In traditional BSs with short sections, a complex junction or a rather long root station are generally included within a section longer than those of line. In the nodes, where the succession of trains is strong, this constitutes a problem for the operation regularity because these sections have a greater occupation time than the others, perturbing the running of successive trains and not guarantying the expected spacing. The construction of the norms for conflicting movements (interference norms) suffers this problem, having to design a considerable spatial spacing between the movements so that there are no reciprocal conditioning. In addition, at the roots of the stations, the conflicting points between incompatible movements can be significantly far from the respective main signals, impacting negatively on the norms and operation in general.

The introduction of "HD virtual sections" and "HD partial sections" in stations and junctions, on one side allows not to interrupt the sequence of optimized length sections, ensuring the headway provided on line, on the other it allows to bring the signals, although virtual, near the conflicting points, reducing infrastructure temporal interdiction and setting the stage for a revision of the interference norms.

Similarly, it results better also the circulation on lines with all-stop services. In these cases, as indicated in (16), the line headway norm can be conditioned by the presence of halts within section significantly longer than platform. In particular, so that the movement does not result perturbed, needs to be two conditions:

- A train stopped at the halt must not interfere with the run of the next approaching train at the same halt, according to the normal braking curve which leads him to stop at expected point of stop (PNF)
- A train started from the stop must not interfere with the running of the next train during its restarting phase, i.e. must be at a distance such that at the second train can be granted a MA which corresponds the line speed

The presence of short SBRs makes less binding these two conditions. Qualitatively, the infrastructure occupation is limited at SBR containing the platform, while the other SBRs of the traditional section can be considered as line sections, so useful for outdistance the trains in the approach and in the restart from the halt.

Finally, the optimization of the speed profiles at switch tips contributes, according to the extent of the switches zone, to the reduction infrastructure interdiction times, allowing for both a review of the norms as for a greater flexibility in operational management. For example, Figure 8 shows how in correspondence of a junction in open line equipped with BS HD ERTMS, a train can be programmed spatially, i.e. temporally, closer to the PO, allowing the revision of the norm.

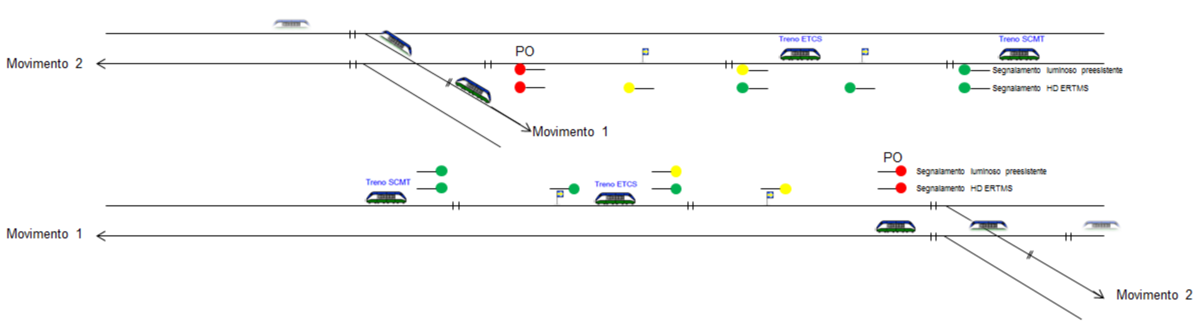

Figure 8: Train programming at junctions

The major benefit provided by HD ERTMS consists in bringing the successive train, identified as "Movement 2" at the junction PO, normally the main signal of the same. In this way, the time interval which must elapse between the transit of the two heads of the trains at PO is reduced.
Moreover, because the train that engages the junction in reverse position is able to reach the top speed in correspondence of the PS, the occupation time of the SBR containing the conflicting point will also be lower.
This results in the decrease of the interference norm. Similarly, they could be reviewed the interference norms in station.

4.3 Limits

The highly innovative character of the new BS involves some limitations to the perfect overlap with current technologies. The obtained norms can only be maintained if all trains enter the SBRs at a speed equal to the nominal one. In the absence of a system which allows to provide driver a recommended speed, the entrance with lower or higher speed does not allow the high-density optimization. As result, the run a train faster than others would be disturbed by the battery of trains that precedes it; and the run of a train slower than the others affects that of the battery that follows it. To obtain top performance in high density is therefore necessary that trains run at the same speed. Conversely, if it were implemented the functionality of ATO in overlap with HD ERTMS, it would be possible to adjust the running of one or more fast trains approaching to one or more slow trains, making the speed homogeneous and allowing high density without perturbations.

In urban railway nodes there are small speed differences between trains. For the purposes of the study of HD ERTMS, for simplicity, the operation will be considered homogeneous, while in the implementation phase heterogeneity should be assessed locally. A possible solution may lie in reviewing the top speed on HD corridors, so that the SSP is the same for all trains. The optimization of HD ERTMS functionality is possible when are satisfied all the requirements referred in the previous paragraph. The trains that are not equipped[17] or with SSB HD ERTMS not working cannot obtain the MA for SBRs. The freedom of the track and Train Integrity are detected by CdBs of traditional sections, and therefore those trains must be spaced from the adjacent by a time interval equal to the headway norm of the pre-existing block. Similarly, any train following another one without SSB HD ERTMS or with SSB not working, for which cannot be realized the Train Integrity functionality, not allowing the release of SBRs, must be spaced from the previous by a time interval equal to the headway norm of the pre-existing block. Finally, the presence of a train longer than the shortest SBR involves the occupation of more than one SBR, with the consequent need of increase in the spacing between this and the next one.

The need to provide not equipped /be not equipped with HD ERTMS or of considerable length and to ensure a transitional phase of progressive implementation on rolling stock is a very strong limit to obtain the benefits that the BS is potentially able to provide. The elaboration of functional scenarios shown in Figure 5 explains how two trains can be programmed according to the reduced headway norm if and only if they are both

[17] Including those equipped with SSB ERTMS L2 without its functionality HD ERTMS; or because the requirements are not respected.

equipped, with the necessary requirements, and lesser than the shortest SBR; vice versa they must be programmed according to typical existing block norm. The problem is twofold: on the one hand concerns the planning of services to be performed with equipped material, which must be consecutive in scheduled serviced to be spaced in accordance with the HD norm, the other concerns the impact on the operation of a fault to the SSB of one or more trains programmed as equipped.

Even if all the conditions set before are met, the full benefits achievement would be possible in homogeneous traffic conditions. The presence of trains with different commercial speed would result in substantially the same capacity consumption that would be in the case of line equipped with automatic block. The possibility to program the departing and arriving trains at a reduced value represents the only introduced advantage. Moreover, the structures of typical periodic rail services provide that trains with the same commercial speed are programmed at regular intervals and that they are not interrupted by the presence of trains with different commercial speed. At the most, these services can be inserted into a periodic timetable without distorting it.

Conversely hardly sequences of trains in the same category are grouped; certainly, the infrastructure was being better exploited but would be affected the capacity to sell the commercial supply. For this reason, the study will focus mainly on the application of BS in homogeneous contexts.

5. Methodology and potentiality analysis

The study of HD ERTMS is divided into two phases. The first is the general assessment
of the new BS, to be conducted on the functional analysis carried out in the previous Chapter and aimed to highlight potential and absolute limits, regardless the implementation context.

The main benefit of HD ERTMS is the decrease in the line headway norm value with respect to the actual automatic block systems, therefore its potential will be studied by comparing the current values of infrastructure capacity with those reached after the implementation. Particular attention must be given to the transition phase, wherein the rolling stock will be progressively equipped for high density. In fact, the major limitation is constituted by the impact of the not equipped trains on the planning and operational management and needs to be studied quantitatively.

The second phase consists in the capacity analysis of an urban railway node, comparing the current and future infrastructures, after the implementation of HD ERTMS, in various traffic scenarios. The goal is twofold: on one side, to estimate the benefits that the system could give to the actual situation; on the other, to study its behavior with progressive increases in traffic.

This phase will be devoted the next chapter, while this will also describe the methods by which will be carried out the analysis, in which each of the formulations introduced will depend on variables that allow to appreciate the benefits introduced by HD ERTMS.

The analysis has carried out considering as reference time window the rush hour.

5.1 General analysis

The objective of this first part is to compare the two block technologies in terms of capacity, that one traditionally adopted in urban railway nodes and the innovative one, as well as highlight the peculiarities of the latter.
The quantification of the capacity values obtainable with HD ERTMS was carried out by the application of " Norma Interna – Determinazione della capacità dell'infrastruttura ferroviaria: linee" elaborated by Italian Railway Network S.p.A. (4). The used formula is:

$$C = \frac{T}{S_{dist} \cdot k} \qquad \text{(I)}$$

where C is the theoretical capacity, maximum amount of programmable trains in the reference time period with an ideal supply;
S_{dist} is the headway for line spacing expressed in minutes;
k is the level of trains heterogeneity;
T is the amplitude of the reference period expressed in minutes.
The same document also defines the Utilization Rate (Ut):

$$Ut = \frac{X}{T} \cdot 100 \quad \text{(II)}$$

where X is the amplitude of the temporal window, expressed in minutes, required to plot the paths provided in the reference period using the compaction method, described in (15).

BS	S_{dist} [min]	T [min]	k	Theoretical capacity [trains/hour/dir]
Automatic Block[18]	6′00″	60′	1	10
	5′00″			12
	4′00″			15
HD ERTMS	3′00″			20
	2′30″			24

Table 6: Theoretical capacity of differet Block Systems

Table 6 shows the theoretical capacity achievable after the implementation of HD ERTMS on a homogeneous corridor and in case of rolling stock completely equipped. Adopting a 3'00" norm there is a significant increase in capacity compared to blocks that allow 5'00" and 6'00" norms and marginal compared to blocks that allow 4'00" norm. By adopting, however, the reduced norm by 2'30" the capacity increase can be considered significant any existing BSs. Recalling that the 2'30" value was obtained eroding the margin regularity, it is proposed to consider as the standard headway for HD ERTMS the value of 3'00", while reserving the possibility of adopting the headway of 2'30" (or 2'00 ") in case of punctual need to recover capacity.

The context in which the verification of the validity of the choice made is more reliable is the case of corridor with stops in succession. In this way it is possible to verify both the running between two stops and the influence of a stop on the movement of a battery of successive trains, compared with the approach and the re-start from the halt. The lack, at now, of the design documents (schematic plans and table of conditions) relative to the corridor identified for equipping with HD ERTMS (Roma Tiburtina – Trastevere) does not allow for the application to simulator of an infrastructure stress tests for

[18] Included BAcc and BAcf+eRSC.

the aforementioned verification. About that, some simulations have been conducted in the past on the same corridor equipped with the BS called "High Density Traffic System" (HDTS). The detailed description of HDTS is contained in (23), while here we have just highlighted the main differences with HD ERTMS. Both are BSs with very short sections (the first up to 350 meters, the second up to 400 meters) whose purpose is to reduce the spacing between two trains, allowing high density. HDTS is based on SCMT and the second on ERTMS, allowing better performance of the system thanks to the improvements made in the parameterization of braking curves and in the management of the SSP in correspondence of switches, which is translating respectively in a higher input speed in the line section of and a lower interdiction time in the station.

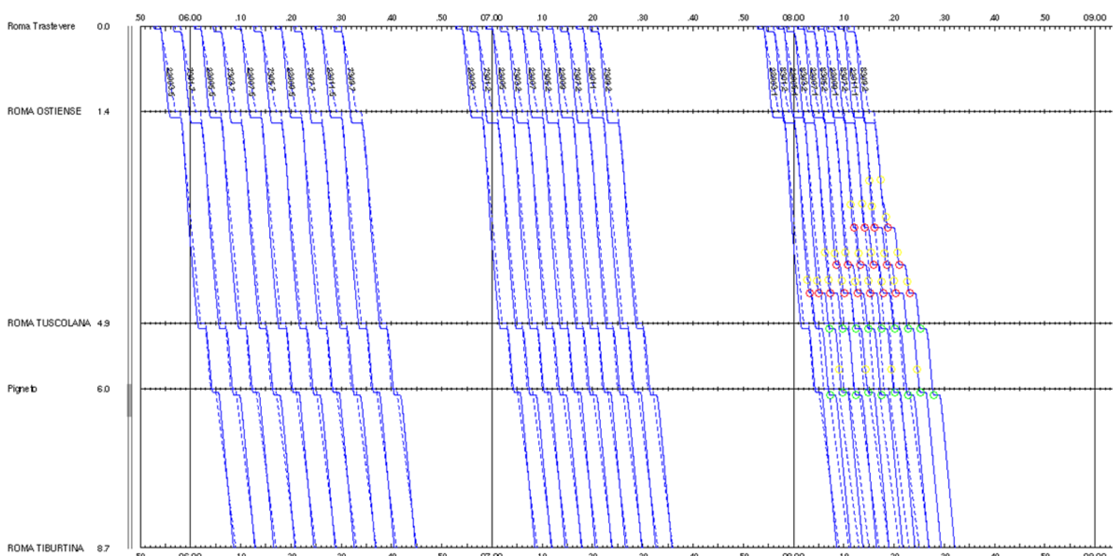

Figure 9: Train Graph with programmed pahts. from left to right, every 4'00", 3'00" and 2'00"

Figure 9 shows the trains running on an infrastructure equipped with HDTS in case of three headway values: 4'00", 3'00" and 2'00". The infrastructure is saturated with the headway of 2'00" and under these conditions is known as two following trains run with a minimum spacing, equal to the blocking time, less than 2'00", up to reach 1'30" value. Therefore, considering the expected benefits from HD ERTMS compared to HDTS, it is estimated that, having to double the blocking time, the general line headway norm can be set equal to 3'00". Observing instead the spacing on arrival and departure from the stops are highlighted values next to 2'00", therefore two following trains should be spaced of 4'00". This value is consistent with the technique used to provides for the addition of the dwell time to the typical headway of the adopted BS.

Additional considerations about the choice of the HD ERTMS norm has been made in Chapter 7 after the traffic simulation in Milan railway node.

The implementation of a BS which requires the installation of a dedicated SSB on rolling stock introduces the problem of the transitional phase of progressive installation and, more in general, the effect of a non-equipped train (or failure to SBB ERTMS) inside an equipped battery of trains.

From the qualitative point of view, the presence of a non-equipped train involves two orders the consequences. During paths design process, it needs to be spaced according to the headway of the pre-existing BS, so the train which precedes as from the one that follows it, resulting in a greater capacity consumption. During operations, the unequipped train can run far from previous and next trains by a time equal to that of blocking.

BS	S_{dist} [min]	t_{block} [min]
Automatic Block	6'	3'00"
	5'	2'30"
	4'	2'00"
HD ERTMS	3'	1'30"

Table 7: Blocking times and headways of different Block Systems

Analysing the data of Table 7 can be highlighted the following conclusions: if a train programmed as equipped, i.e. with specific 3'00", suffers a breakdown such that it is not possible to densify it inside the battery, even with blocks which provide a 6'00" norm, this could run at limit of blocking time.

However, it appears clear that any perturbation to the running of the not equipped train, or to the previous one, has an impact on the battery of trains that follows it; if a train scheduled as not equipped circulates with a delay that will take him to the limit of his zone, it would disturb the subsequent trains, because it is not able to run at a distance equal to the blocking time because, also in case of 4'00" norm, this (2'00") would be greater than that of HD ERTMS (1'30").

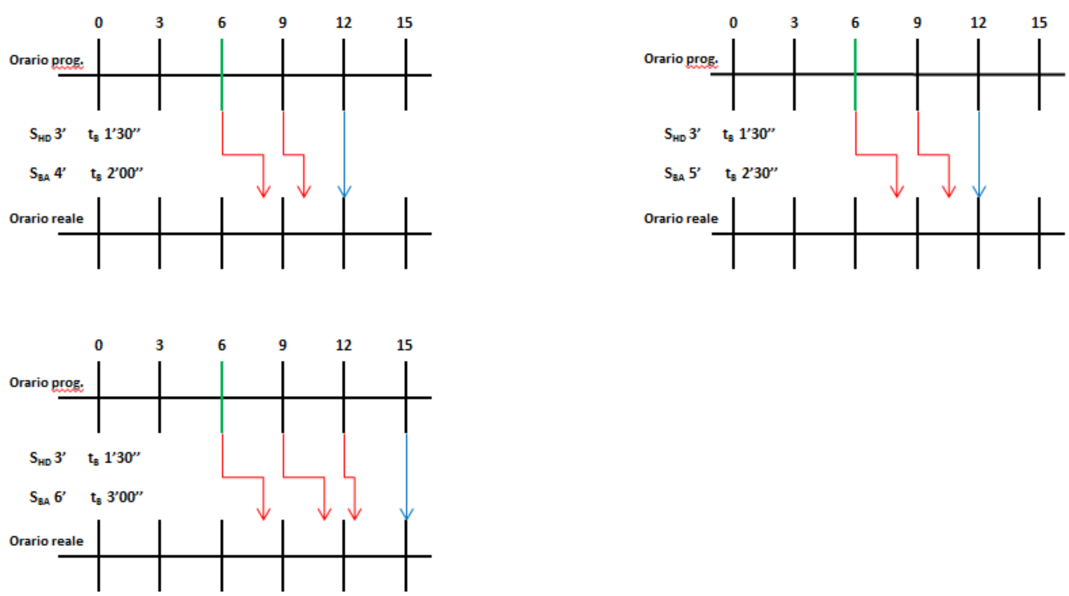

Figure 10: In green the delayed equipped train with a failure to SSB ERTMS; in red the deviations of the interferred trains; in blue the first train on time

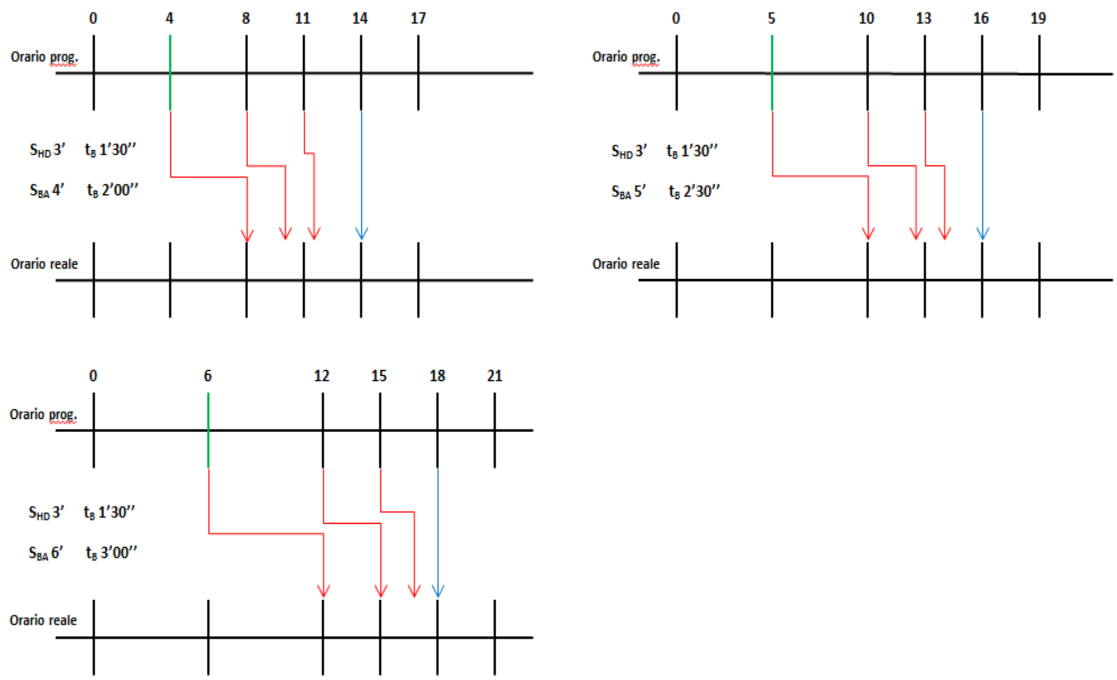

Figure 11: In green the delayed not equipped train, programmed according to the Automatic Block headway; in red the deviations of the interfered trains; in blue the first train on time

Figures 10 and 11 show how the possibility to densify trains immediately after the first interfered train reduces the impact of non-equipped train deviation on the following, allowing the absorption of the disturbance within a limited number of trains. The infinite variety of possible deviations does not make analytically difficult to deal with the problem from a quantitative point of view. In lack of a software capable of simulating the interactions between trains on infrastructure equipped with automatic block and HD ERTMS, there have been drawn some qualitative considerations and then proceed to the introduction of a model for estimating the capacity in function of train equipment, from which it is possible to make some conclusions on transition phase.

The main effect of a programming into the timetable of a not equipped train is decrease in line capacity, with respect to a timetable in which all trains have the SSB HD ERTMS. The influenced trains are: itself and the first of the sequent battery; the others can bring near the first, allowing a rapid depletion of the perturbation. The difference compared to an equipped programmed train, at the same time and that undergoes the same deviation, is the erosion of a greater regularity margin, quantifiable in 30'', 1'00'' and 1'30'' (differences between blocking times with HD ERTMS) respectively in the cases of pre-existing block with 4'00'', 5'00'' or 6'00'' norm. The same regularity margin, however, is added by means of the spacing according to a greater headway norm and, for the purposes of the disturbance propagation, because this takes place is need a greater deviation, respectively, of 30'', 1'00'' and 1'30''. It is possible to conclude that the presence of non-equipped trains does not entail any significant differences for the purposes of the regularity of the movement, compared with the margins included in the headway norms. However, the need to program trains with a greater headway leads to a higher line utilization rate and consequently the decrease in unused time interval, exploitable as regularity margin[19].

[19] The term "regularity margin" has been reported to two different time intervals: the buffer time within headway norm is mainly used to absorb the deviations within the next programmed path or in any case within punctuality interval; the unused time interval can be used to absorb deviations due to closely spaced batteries of trains or for interference management and timetable constraints.

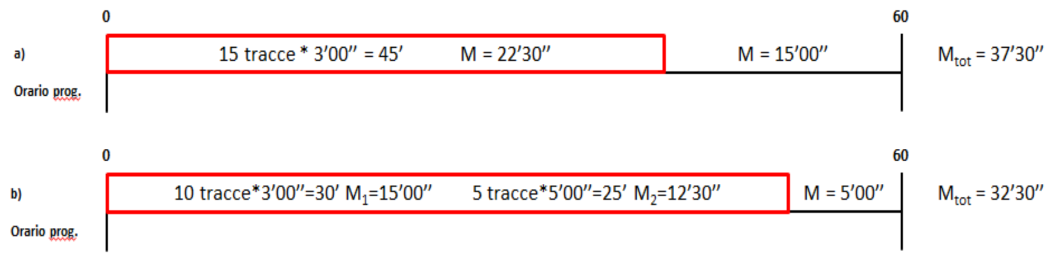

Figure 12: Capacity consumption by 15 programmed trains; above in case of all trains equipped; below in case of partial installation

Figure 12 shows the different use of the time interval by 15 programmed trains. In a) they are spaced according to the HD ERTMS norm: the "internal" margin is 22'30"and the "external" to 15'00" for a total of 37'30". In b) it is assumed that it is possible to densify 10 trains according to the ERTMS HD norm, while the remaining 5 will be spaced at 5'00": the "internal" margin is 27'30"and the “external” 5'00" for a total of 32'30". The presence of 5 over 15 not equipped trains (33%), leads to an increase in internal margins for the absorption of deviations especially of non-equipped trains, on the other side cancels the external edge.

In case of failure, however, also a minimum deviation can disrupt the run of the following trains. This is because the train with a failure to SSB would run at the limit of blocking time with respect to both the previous train and the next. Notwithstanding that must be guaranteed by RUs a failure rate close to zero, in order to deal with these eventualities, it can reserve a regularity margin by imposing to not reach the upper capacity limit of an ERTMS HD corridor, equal to 20 trains/hour/direction.

Before analysing the effects of the presence of non-equipped trains on the operation regularity, it is introduced a model capable to estimate the increase in capacity after the implementation of HD ERTMS. The need for such a model lies in the non-knowledge, in the planning stage, of some fundamental variables for the high-density realization: the timetable structure, the rolling stock equipment plan and the RUs rolling stock turnover. While it can be stated as it is possible to immediately obtain an increase in capacity by programming two equipped trains in succession, on the other this would require strong coordination between the IM and RU. It is also true that, in the strategic investments assessment, it is required a dialogue with RUs and competent agencies in the territorial planning of rail transport services. However, the specificity of the proposed realization is inserted in a broader context characterized by:

- Interest of competent Ministries in identifying and funding measures for improve rail services in metropolitan nodes
- European Union boost to migration from national train run protection systems to ERTMS/ETCS

Therefore, while maintaining the possibility to realize punctual successions of equipped trains in cases where is strictly necessary to reduce the line spacing, it is believed that the system should be studied without reference to this possibility and that the results of this analysis should be the based on the optimization process that gradually leads to full potentiality.

The goal of the proposed model is to correlate the amount of equipped rolling stock with the capacity values obtained based on functional characteristics of HD ERTMS overlap on existing Automatic Block. By using the *Norma Interna RFI* to estimate the capacity, the starting point is the quantification of the headway norm to be included in (I). Below the possible norms of which a train must be spaced:

- Equipped - Equipped → HD ERTMS norm
- Equipped - Not equipped → BA norm
- Not Equipped - Equipped → BA norm
- Not Equipped - Not Equipped → BA norm

There are two possibilities:

1. Modelling the case in which timetable and rolling stock turnover not allow for realization of successions of equipped trains. The trains are perfectly intercalated each other and it is not possible to use the HD ERTMS norm (deterministic formulation)
2. Modelling the case in which the presence of a specific sequence of trains depends probabilistically by the amount of equipped and non-equipped trains (probabilistic formulation)

5.2 Deterministic formulation

Since the only way to densify the trains is to have a succession of equipped trains, within the temporal reference period T, it is intended the portion $T_{A/N}$ to sequences that involve the existing norm and the portion T', complementary of $T_{A/N}$ to T, to the successions of equipped trains. Assuming to have the two train types completely intercalated, for each non-equipped train there must be an equipped one, spaced according to the Automatic Block norm. The capacity consumption in terms of time is:

$$T_{A/N} = 2 \cdot n_N \cdot S_{BA} \quad \text{(III)}$$

While the portion T′ is:

$$T' = T - T_{A/N} \quad \text{(IV)}$$

where n_N is the number not-equipped trains, n_A the number of equipped trains, S_{BA} the value of preexisting Automatic Block norm and S_{HD} the value of HD ERTMS norm.

Inside T' the maximum number of equipped successions s_A that can circulate is:

$$s_A = \frac{T\prime}{S_{HD}} \quad \text{(V)}$$

These sequences are added to the equipped trains interspersed with those who are not equipped for a total of:

$$n_A = s_A + n_N \quad \text{(VI)}$$

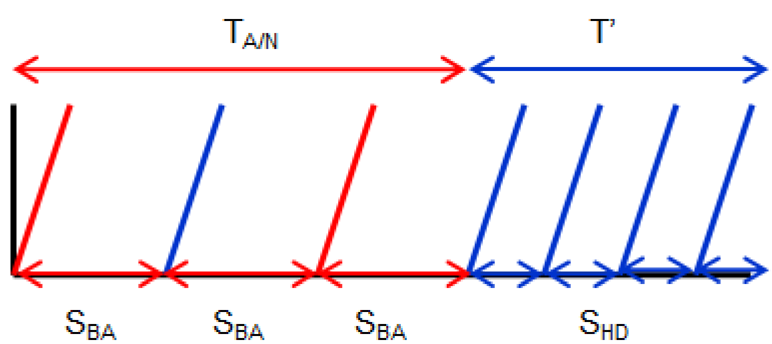

Figure 13: Capacity consumption by mixed trains

Line capacity will be equal to:

$$C = n_N + n_A \quad \text{(VII)}$$

It is evident that with the hypothesis made is possible to realize capacity increases only with a number of equipped trains greater than half of those programmed during T. At the limit, if n_N=n_A, we obtain the value of the maximum preexisting Automatic Block capacity. To calculate the utilization rate of the infrastructure, the term X in (II) will be given by sum of the times consumed by successions programmed at S_{BA} and those programmed at S_{HD}.

$$Ut = \frac{2 \cdot n_N \cdot S_{BA} + (n_A - n_N) \cdot S_{HD}}{T} \cdot 100 \quad \text{(VIII)}$$

5.3 Probabilistic formulation

This formulation aims at finding a mean value of the S_{dist} to be included in (I), weighted by the probability of having a specific sequence, in function of the number of equipped and not equipped trains. The probability of having a determined succession is given by the product of the probabilities[20] presentation of a specific train, supposed uniform within T. The probability of presenting a single train has been calculated by the classic definition of probability:

$$P_i = \frac{n_i}{n_i + n_j} \quad \text{(IX)}$$

The probability of the product is equal to:

$$P_{ii} = \frac{n_i}{n_i + n_j} \cdot \frac{n_i - 1}{n_i + n_j - 1} \quad \text{(X)}$$

$$P_{ij} = \frac{n_i}{n_i + n_j} \cdot \frac{n_j}{n_i + n_j - 1} \quad \text{(XI)}$$

The average norm was weighed with the probability of having a specific sequence:

$$S_{dist} = P_{AA} \cdot S_{HD} + (P_{AN} + P_{NA} + P_{NN}) \cdot S_{BA} \quad \text{(XII)}$$

[20] It has made the hypothesis of independence of the events "presentation of the train" by using the product of the probabilities.

5.4 General analysis results

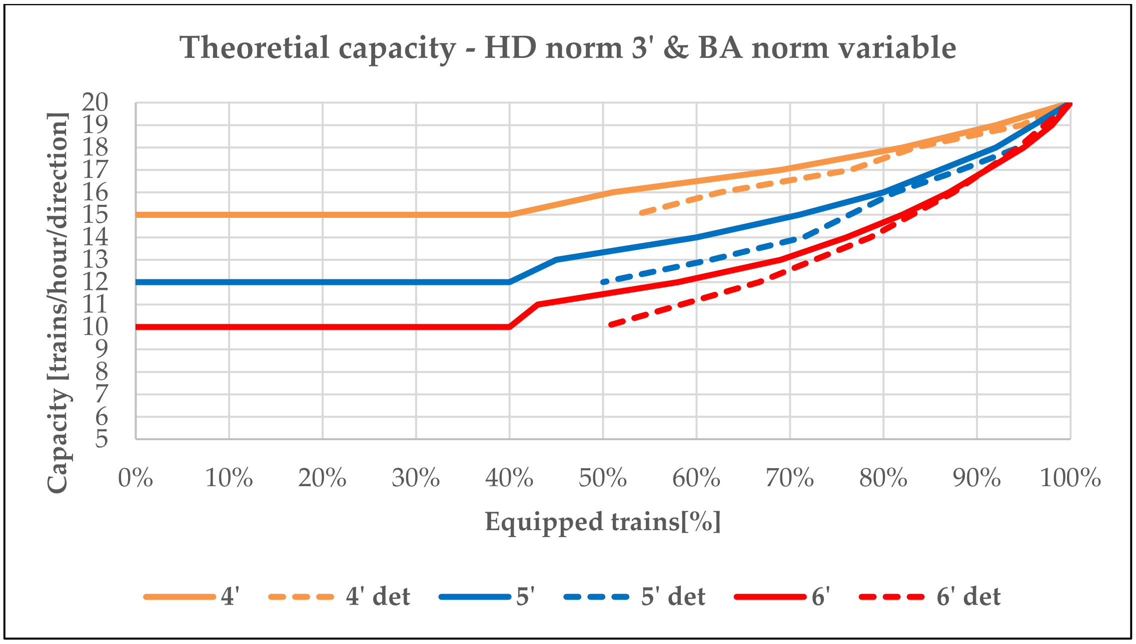

Figure 14: Theoretical capacity in function of the equipped trains percentage: the continuous line refers to probabilitic formulation, the dotted one to deterministic formulation

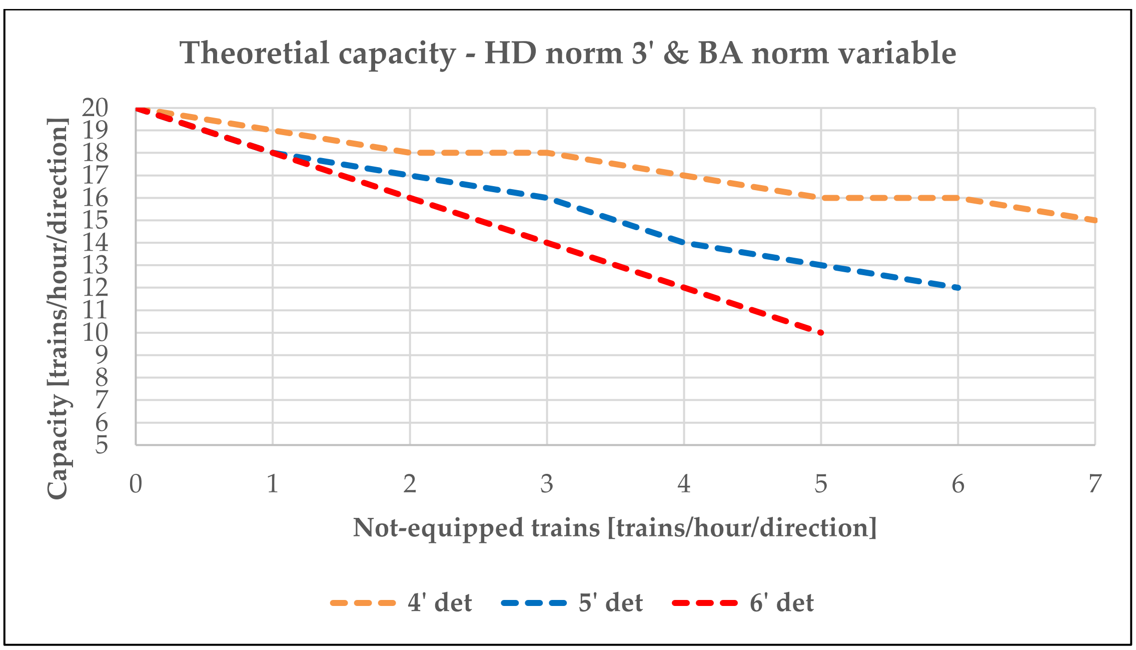

Figure 15: Deterministic influence on theoretical capacity of the presence of a not-equipped train

From Figure 14 it is possible to derive quantitative information on the increase in capacity offered by HD ERTMS with respect to the existing Automatic Blocks. It premises that the use of the percentage indicator is due to the generality of the analysis, so it was preferred at indicator "number of equipped trains". It is confirmed that, deterministically, the first benefits are obtained over 60%, while probabilistically starting from 40%. The increase in capacity, however, is little significant up next to 75%, where the benefits are beginning to be substantial and is also known a generalized increase in the slope of the curves of capacity, so that the more the increase in benefits the more the transition phase is moving towards conclusion. In addition, for high percentages both models offer similar results, as demonstration that the presence, compared to the total, of some not-equipped trains determines a deterministic lowering of capacity, interrupting, at most, batteries of equipped trains but not preventing their implementation. That is for slightly lower percentages that the distribution of not-equipped trains within the reference time interval has a greater effect on the capacity value that HD ERTMS can guarantee. This indication is very important as it suggests estimating,

deterministically, the influence of a single non-equipped train on the capacity consumption. Figure 15 shows the results obtained by reversing the relations of the deterministic formulation, whose estimation is realistic for those values of capacity in which the two formulations are overlapped in Figure 14. In each case, the difference between the two curves does not exceed the value of two trains per hour, for which the results are generalizable without committing errors.

From this conclusion, by using the results of the deterministic formulation it was quantified the regularity margin present in T in function of the used capacity and non-equipped trains. Recalling that the overall regularity margin contains an "internal" component, equal to half headway norm, and an "external" one, complementary to T of the utilization time, it follows that the margin M is equal to:

$$M = 0.5 \cdot X + (T - X) \quad \text{(XIII)}$$

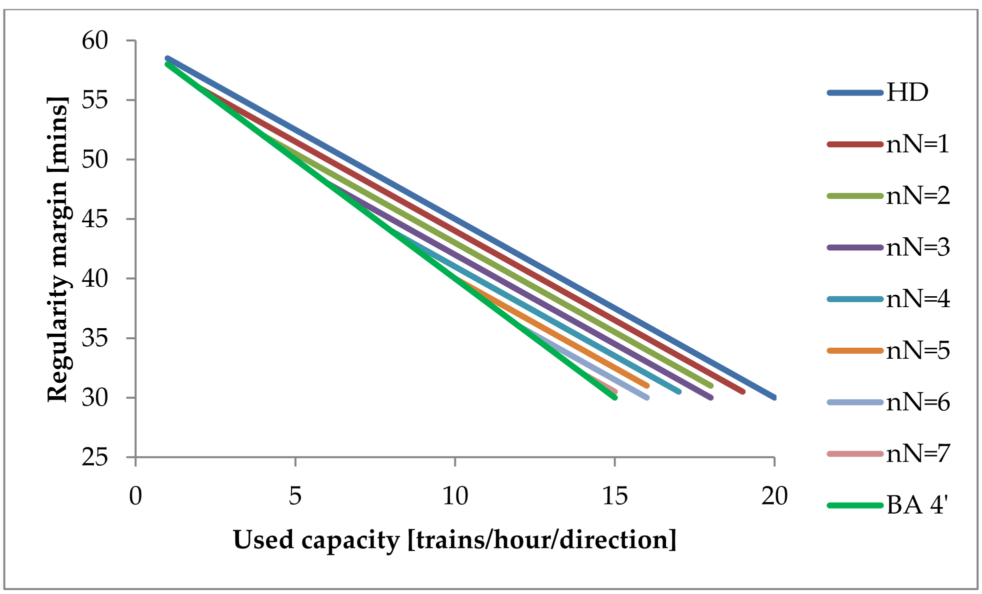

Figure 16: Incidence of used capacity on regularity margin in function of number of not-equipped trains in case of Automatic Block 4'00'' norm

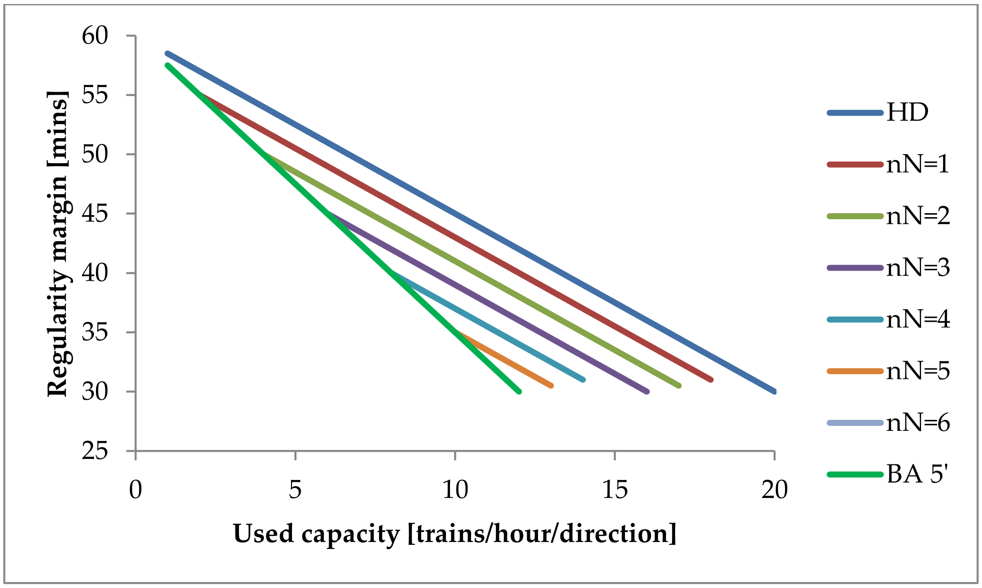

Figure 17: Incidence of used capacity on regularity margin in function of number of not-equipped trains in case of Automatic Block 5'00'' norm

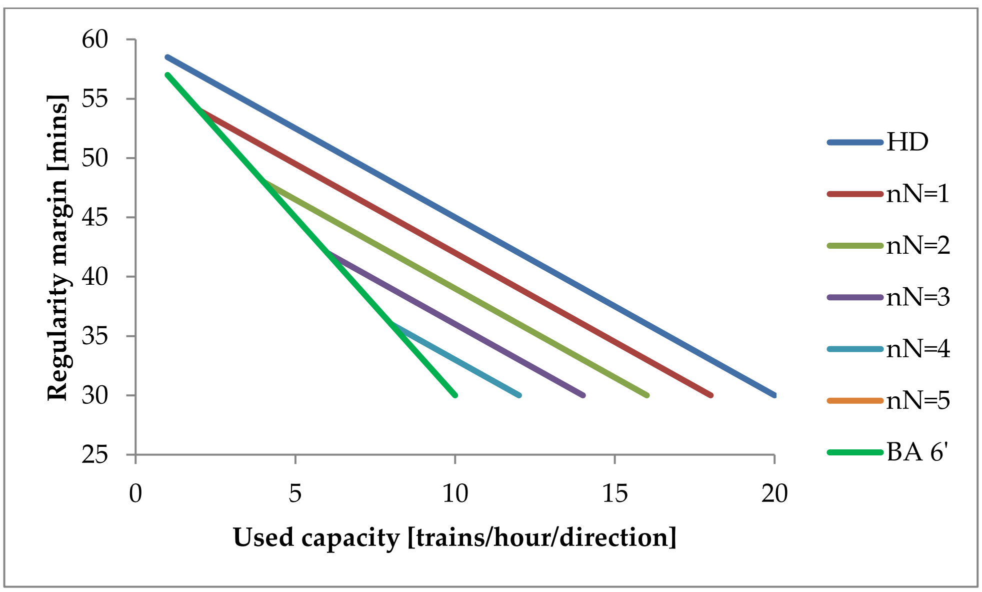

Figure 18: Incidence of used capacity on regularity margin in function of number of not-equipped trains in case of Automatic Block 6'00'' norm

Block System	Headway norm	Theoretical capacity	Used capacity	M	Δ
	[mins]	[trains/h/d]	[trains/h/d]	[mins]	
HD	3	20	10	45	-
BA	4	15	10	40	13%
	5	12	10	35	29%
	6	10	10	30	50%

Table 8: Regularity margin in case of 10 programmed trains

The graphs in Figures 16, 17 and 18 show the net effect, on overall regularity margin, of the introduction of a not-equipped train. The regularity curves which relate to the overlapping BA - HD ERTMS have a lower slope than that of the BA, so that an increase in traffic achieved by means of high density erodes less regularity margin than the same increase obtained without HD ERTMS, with a higher incidence the more the S BA is narrow. The programming of not-equipped train, in contrast, has greater influence more the S BA is wide. After this analysis, it is possible to make some considerations about the HD ERTMS effectiveness and the transitional phase management.

According to the curves of Figures 14, 15, 16, 17 and 18 it can be stated that the system shows the highest benefits only for percentages close to 100%, in each context of application. For BSs that already have a close norm, obtaining benefits in capacity and regularity happens with low minimum percentages of equipped trains because of the small difference between the headway norms, while they become noticeable all trains are equipped. For blocks that have wider norm, on one hand it becomes easier to appreciate the increases in capacity with low percentages, on the other hand the influence on the regularity of not-equipped train is greater. Therefore, while achieving punctual successions to recover capacity, this would reduce the flexibility of the system with respect to the management timetable constraint, especially interference and periodical timing.

Based on these general considerations, it is concluded that it is not suggestible to make increases in the amount of trains sold as long as the not-equipped trains are estimated at between 40 and 50 percentage points and up to values close to 75%. For example, considering a corridor with these characteristics:

- Automatic Block headway norm: 5'00"
- Used Capacity: 10 trains/hour/direction

The corridor is at the limit of saturation, having a utilization rate next to 85%. Probably it is possible to realize an increase of 2 trains/hour/direction, bringing the total to 12, for example spaced apart by 30 minutes, or one following the other, densifying respectively, two batteries of three trains or one of six trains, with a percentage of 50%. This could be a typical situation of incoming (starting) in (from) large urban nodes in rush hour. Looking to the continuous blue line in Figure 14, the theoretical capacity at the value of 50% is 13 trains/hour/direction, therefore the utilization rate would stand at 92%, higher than the actual one. The system regularity, however, would not be increased: the corresponding point in Figure 17 is in fact would find between the green and orange curves. To achieve the same increase keeping constant the regularity, it should be necessary exceed 60%, or 9 trains over 14, knowing that a possible failure to SSB ERTMS is able to compromise the stability of the timetable.

It is only when more or less all trains are equipped that it is possible to increase the commercial supply without affecting regularity margins present on timetable, up to reach the levels of traffic set by agreements with the relevant authorities.

5.5 Capacity analysis: junction and station roots

The capacity analysis methodology based on headway norms tries to combine the theoretical aspect of railway traffic, based on distances, times and conditions, with the practical aspect of timetable design. In this way, it will obtain the twofold objective of simplification of methodologies adopted and approach to the real operating conditions. The shared points between conflicting routes are different in nature and, for the purposes of their capacity assessment, they should be treated differently.

In junctions, the running on the common branch, for each direction, is carried out according to the headway norm: the analysis of diversion and merging points is therefore superfluous if the assessment methodology presupposes a planning through the headway norm technique. The only point to be analyzed for the junction utilization rate is that in which occurs the crossing movement between the conflicting routes. In this point the flows that insist are, in principle, independent. Really, who design the timetable can adopt some techniques to solve conflicts at that point, possibly moving them adjacent junctions or stations. It seems clear that an analysis which aims to be as general as possible cannot be based on those specifically details, therefore the methodology proposed reproduce the situation where all scheduled trains are here conflicting. In other cases, not the subject of this work, it must be evaluated the utilization of the junction in presence of timetable, in which conflicts are just resolved: it is possible to apply the compaction (15) and check the compatibility of some additional trains.

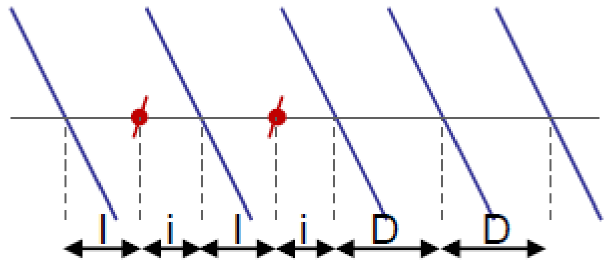

Figure 19: Scheduled trains at junctions; il blue the main flow and in red the secondary flow

The methodology for evaluating the utilization rate of the line junctions, proposed by Vaghi in (24), expresses the idea that the best trains compaction is when those of the prevailing flow continues to be spaced according to the headway norm and such spacing is enlarged as many times as between two of them must be programmed a secondary flow train, which is located at its own norm both ahead and behind itself.

$$Ut = \frac{S_{taglio} \cdot 2\varphi + S_{dist} \cdot (\Phi - \varphi)}{T} \quad \text{(XIV)}$$

The use successive nodes on the same route is understood as the complementary probability of alignment of the unused capacity of successive points.

$$Ut_{A-B} = 1 - [(1 - U_A) \cdot (1 - U_B)] \quad \text{(XV)}$$

5.6 Capacity analysis: stations

In more complex stations there is the merging of more than two lines and there are many conflicting points. The division of Automatic Block sections in SBRs within stations brings the points within different SBRs, and then the occurrence of a conflict at a point does not make unavailable the part of station from main signal but only from the virtual ERTMS signal at protection of the SBR in which falls the point itself.

Similarly, for outbound trains from the station, forwarding on the same SBR also towards different lines can happen as soon as the same SBR is released. To be able to appreciate this HD ERTMS peculiarity was selected the "Potthoff method", based on interdiction time of conflicting routes. In this way it was possible to evaluate both the corresponding benefits provided by reaching the route speed at switches tip and the possibility to bring the following train until the virtual signal of the SBR that contains the conflicting point between the two routes.

The verification of a node starts with an analysis of a simple node. Consider a simple intersection marked with the letter X in correspondence of which it can have only one train a time. The time T available for operation will be suitably distributed among the transit if “line 1” and “line 2” train.

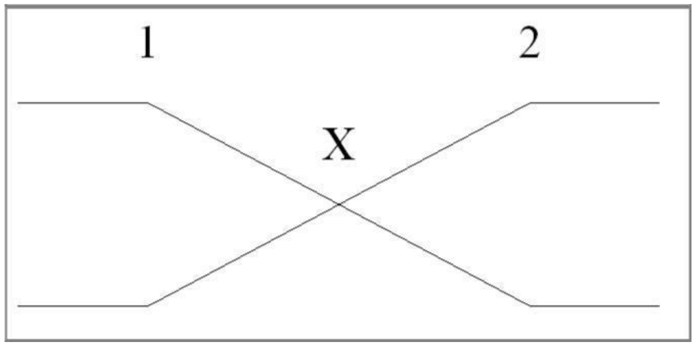

Figure 20: Example of simple node

If a train has to wait to another train transit, it will subtract the share of T available for its line a time of waiting. In general, therefore, the available time T is divided into three parts:

- Time needed to train to cross the intersection, composed by the times occupation whose sum will be indicated with the letter B
- Waiting time, or delay, whose sum will be indicated with the letter R
- Exceeding time available for further movements not foreseen in timetable

Therefore, the condition that makes possible to establish the compatibility between the station and timetable can be expressed analytically in the form:

$$T \geq B + R \quad \text{(XVI)}$$

The condition of equality in the formula expresses the station saturation, and then the lack of time margins available for other movements.

Let us take now an example slightly more complex than the previous case: the possible movements are not only the occupation of the node of a train at a time.

Even in this case, as for all other cases of greater complexity, the previous condition applies, but the application of B and R must consider the variety of possible situations.

In the case of simple intersection, the safety will be achieved if every time a train circulates on a line, the other is inhibited, through the signal disposal at danger. During the time interval T must happen the transit of n 1 trains on line 1 and n 2 trains on line 2.

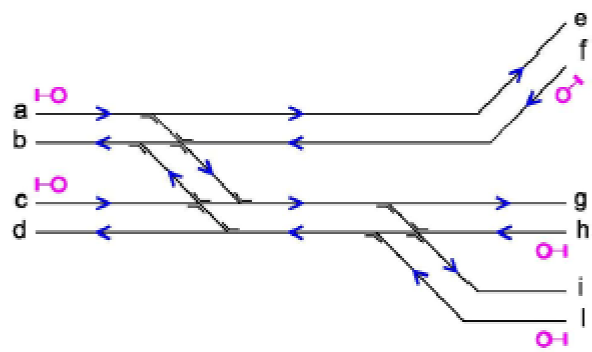

Figure 21: Example of a complex junction

In the moment when a train passes through the junction, it inhibits the movement on the other line from the instant at which the signal is disposed at danger and up to the instant in which its rear-end will not have passed a given point X, completely releasing the junction and making it available for further movements. This time interval is defined occupation time and is indicated with the symbols t_1 and t_2, respectively for the trains on line 1 and line 2. It is assumed that these times are constant for each line, moreover it assumes to give train a priority based on the FIFO rule. When there is an interdiction, the train that has its signal at danger will wait for a time ranging from zero to the occupation time of the crossing train, and this obviously depending on the instant of arrival of the second train. It may, suppose, neglecting the effects of braking and starting, that an interdicted train will suffer an average delay equal to $t_1/2$ or $t_2/2$. It will determine how much situations happens during the reference interval T: its value depends on timetable and on the probabilistic laws governing the arrivals process in the junction.

In the design phase, the first hypothesis to be considered consists in assuming constant in T the density of probability of a train arrival and predict inexistence of a defined timetable. This hypothesis is the truer as the narrower the time window T and intense the traffic. This density is:

$$\frac{1}{T} = cost \quad \text{(XVII)}$$

A generic train on line 1, have the probability to see a signal at danger equal to:

$$p_1 = n_2 \cdot \frac{1}{T} \cdot t_2 \quad \text{(XVIII)}$$

in which the product $(1/T)t_2$ expresses the intersection occupation probability by a line 2 and n_2 the number of times that this occurs during T. The train suffers an average delay equal to:

$$R_1 = p_1 \cdot \frac{t_2}{2} = \frac{n_2 \cdot t_2^2}{2T} \quad \text{(XIX)}$$

that must be interpreted as time subtracted to the line 1 operation. Finally, since on line 1 run n_1 trains, these suffer this overall delay:

$$R_1 = \frac{n_1 \cdot n_2 \cdot t_2^2}{2T} \quad \text{(XX)}$$

and symmetrically, those of the line 2 this overall delay:

$$R_2 = \frac{n_1 \cdot n_2 \cdot t_1^2}{2T} \quad \text{(XXI)}$$

Being the X point in common between the two lines, the time interval T should be thought as the sum of two separate times variously fractionated available for one or the other line. In addition, delays, as defined above, are to be considered time to be deducted from the availability of the respective lines. Therefore, the operating condition for the junction potentiality is expressed by:

$$T \geq n_1 \cdot t_1 + n_2 \cdot t_2 + \frac{n_1 \cdot n_2 \cdot (t_1^2 + t_2^2)}{2T} \text{ (XXII)}$$

Unlike a simple node in which the movement of a train takes place according to only two modes (in the presence or absence of a conflicting train) and considering that the only conceivable movement is the crossing of the same node, in a generic station is instead predictable a plurality of movements with compatibility and incompatibility situations that may affect more than two trains simultaneously; it is due to the presence of switches that allow a variable configuration. There are four movements that trains do in the stations:

- Arrival Route
- Departing Route
- Transit Route
- Maneuver

For arrival route means the path delimited by the station main signal to the platform departure signal. The departing route is the path bordered by platform departure signal to open line. The transit route consists in the path including between the corresponding arrival and departure routes. For maneuver means a shunting movement carried out within the station, including between two maneuver signals or to the bumper of a dead-end track.

In the assessment they will be considered only the routes that will be listed and compared between them to determine the mutual compatibility, defining in this way the Route Matrix. In this matrix to each row and each column correspond a list of routes; in this way, the various elements of a matrix will identify a given pair of routes and the elements in question will consist of conventional symbols, specifying the compatibility or incompatibility of the pair. Considered the fact that, by definition, the questioned matrix is square, adopting the convention of listing the routes in the same order on both lines and the columns, we get a symmetric matrix in which all the elements located on the main diagonal represent comparisons of the routes themselves.

A complex node, as already pointed out, differs from that simple especially for the multiplicity of combinations of routes that can be achieved. This is defined through the analysis of matrices of itinerary that indicate all possible eligible combinations allowed by the station layout. The set of all routes, simple and combinations of those that are compatible, expressed through numerical and physical parameters, are synthesized using arithmetic operations of weighted average. In other terms, it is possible to evaluate the average number of possible movements in a station, the average occupation time of the node, and finally the amount of delays generated by the process of circulation. It is possible then locate a verification condition of the complex node, quite like the one defined for the simple node.

If they were:

- $\bar{n}$: average number of simultaneous trains
- $\bar{t}$: average occupation time of a group of $\bar{n}$ trains
- T: reference time interval
- ΣR: delay generated by N trains
- N: total numbers of train running in station during T

It is assumed for each train a uniform presentation probability in the node during T. Based on the considerations here introduced, the operation process in the node can be schematized as a succession of N/$\bar{n}$ events, for each of which $\bar{n}$ trains circulate simultaneously occupying the node for $\bar{t}$. By applying this simplification, it is possible to replace a simple proxy node to the complex node. The schematized operation process allows to define the overall occupation time B as:

$$B = \frac{N}{\bar{n}}\bar{t} \quad \text{(XXIII)}$$

The delays should be evaluated both in general form, as the overall result of the individual incompatibility situations, and in relation to the effect which they have on proxy node. This allows to apply, as test condition, the relationship T ≥ B + R.

The total amount of delays will be the sum of the delays produced in any situation of incompatibility. To assess the effects of delays on the capacity of the proxy node, it must first keep in mind that the delays in question belong to groups of $\bar{n}$ trains each.

It follows that if we proceed to the calculation of the amount of delay globally generated in the node, already indicated by ΣR, the total amount of time that they subtract to the availability of operation is equal to:

$$\frac{\sum R}{\bar{n}}$$

and then the test condition of the overall node can be synthesized by:

$$T \geq \frac{N}{\bar{n}}\bar{t} + \frac{\sum R}{\bar{n}} \quad \text{(XXIV)}$$

It is time to explain the various terms that appear in it. The calculation of $\bar{n}$ has combinatorial complexities, for which there is no analytical resolution.

The formula should contemplate the combinations of the compatible route and the frequency of utilization of the routes themselves during T. Some authors who have dealt with this problem suggest an empirical evaluation based on the structure of the route matrix. It still retains the hypothesis according to which during T each route is used by one train, i.e.: *number of trains = number of routes*.

If all the boxes in the matrix were occupied by signs of incompatibility, it might have, obviously, only one movement at a time, namely: $n=1$. If all pairs of different routes were compatible, it might have many contemporaneous trains as many are the routes of the node; if these are n', it would be $n=n'$. They were examined the limit cases in between n can vary, so we can write: $n=1 \div n'$. Instead of analysing the combinations of routes that saturate the node, it can be use an empirical expression, which has the same applicability defined by the previous report. The expression in question allows to determine the number of $\bar{n}$ as the ratio between the number of boxes of a matrix and the number of boxes that show signs of incompatibility. It is easy to check how the variability field of $\bar{n}$, so determined, coincides with that of previous relation. It now wants to generalize this expression for the case in which, during T, the various routes are used by a different number of trains. That is, indicating with i and j two generic routes, may be at the limit: $n_i \neq n_j \rightarrow n_i \geq 1$ and $n_j \geq 1$.

It can think about extending the matrix of the routes repeating each row and each column many times as the trains must run a route. For example, if a route is run by 3 trains, the row will be repeated three times. Having to compile a matrix relative to a pair of routes used by 3 and 4 trains, in the box, the compatibility (or incompatibility) sign will be repeated 12 times. Each box of original matrix in other words, will have a weight equal to n_i x n_j.

If the total number of trains is $N=\Sigma n_i$, the above expression assumes the form:

$$\bar{n} = \frac{N^2}{\Sigma n_i n_j} \text{ (XXV)}$$

where the sum is extended only to that boxes showing incompatibility sign. For the average occupation time evaluation, to be introduced in the calculation of B, it is necessary to clarify the difference between occupation times and interdiction times. The occupation time consists of the stages of route decision, formation, and running and release by train, while defining interdiction times those related to the possibility of formation of a route related to the release of a previous one. Such timing may assume lower values in the stations where is installed an Interlocking system equipped with the progressive release of track circuits (elastic release) at the passage of the train.

The occupation and interdiction times thus determined are required to build the interdiction times matrix, which is derived from the routes matrix, in which each row and column represents a route. The elements of the matrix represent the combination of the effects, in terms of occupation or interdiction times, that the rows cause on the columns. Therefore, in the new matrix, the boxes on the main diagonal contain the occupation time t_{ij} of several routes; the boxes showing signs of incompatibility will report the interdiction times t_{ij} caused by route *i* on *j*.

In general, it will be: $t_{ji} \neq t_{ij}$. This means that the interdiction times matrix is not symmetrical with respect to the main diagonal. Each element of the matrix relates to a hypothetical number of possible events equal to $n_i \, x \, n_j$, i.e.

it will have a weight proportional to this number to undertake an evaluation of the time as weighted average of the times t_{ij}:

$$\bar{t} = \frac{\sum n_i n_j t_{ij}}{\sum n_i n_j} \quad \text{(XXVI)}$$

where the summations are extended to all incompatibility boxes, including those of the main diagonal for which $i = j$.

The cases of incompatibility are so many similar situations of simple node, for each of which produces an expected delay of:

$$R_{ij} = \frac{n_i n_j t_{ij}^2}{2T} \quad \text{(XXVII)}$$

Using the matrices $n_i n_j$ and $t_i t_j$ is then possible to construct the matrix R_{ij}, whereas the characteristic of a complex node has two types of incompatibility that cannot generate delayed, as characterized by the presence of a single train: the divergence and queuing.

It can be written:

$$T \geq \frac{\sum n_i n_j t_{ij}}{N} + \frac{\sum R_{ij} \sum n_i n_j}{N^2} \quad \text{(XXVIII)}$$

which allows to verify if a complex node can withstand or less the transit of $N = \Sigma n$ trains over a period T.

Finally, the total utilization rate Ut, as the amount of time in which the node is used in relation to time available, is defined by the following formula:

$$Ut = \frac{B+R}{T} \quad \text{(XXIX)}$$

To have a stable system, and therefore to avoid the saturation of the node, they are fixed the following acceptability thresholds of this coefficient:

0 < Ut < 0.6	Daily traffic
0.6 < Ut < 0.75	Rush hour traffic
Ut > 0.75	Unsustainable traffic (excess of delay)

Table 9: Utilization rate thresholds of a complex node

The adoption of the method, as long as supported by the reduced time window and the high traffic, has a problem in the upper utilization limit. The maximum rate cannot reach values close to 100%, as for the other methods, as the interdiction times do not contain regularity margins, which must therefore be considered limiting the rate within a specific threshold, usually placed by literature to 75% in the rush hour. To respond effectively to the objective of the work, the utilization rate calculated with Potthoff method was normalized with respect to the 100% (equivalent to hypothesize a regularity margin equal to 25% of the interdiction time).

6. Node analysis

6.1 Milan railway node

Among the local contexts in which it is expected the HD ERTMS implementation, there is the Milan Railway Nod, one of the largest and most complex of the national rail network. In it converge the lines from Turin, Venice, Bologna, Genoa, Domodossola and Chiasso, as well as a series less important lines. The node complexity lies in the variety of infrastructural elements and services that are performed. We find, in fact, double-track and quadruple-track adduction lines, complex stations in which occur both crossings and overpasses between the lines, as well as a railway tunnel specialized for suburban traffic. In terms of services, it is highlighted the coexistence of urban, regional and long-distance services, and freight along the so-called belt lines. Figure 22 shows an overview of the node, in which the HD ERTMS corridor has been highlighted in red.

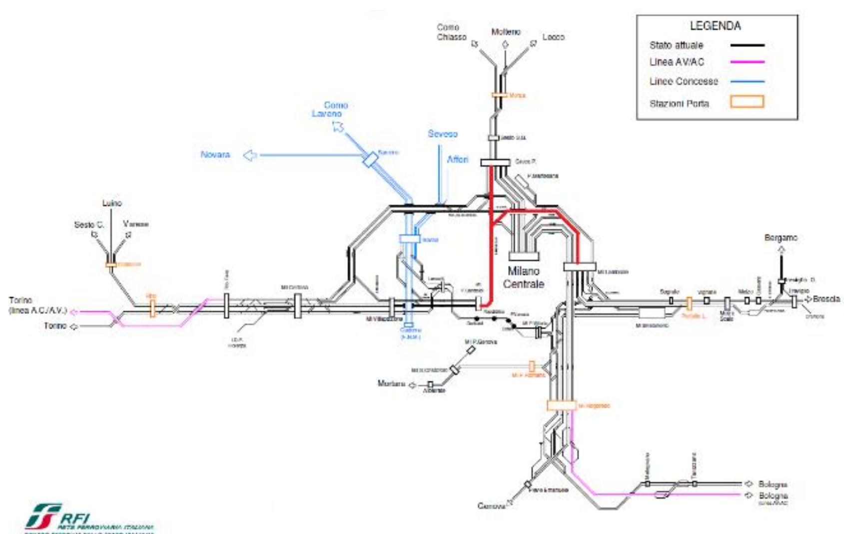

Figure 22: Milan railway node. In red the routes on which will be implemented HD ERTMS

The high traffic density led close to saturation in both some of addiction lines and some sections inside the node itself. The capacity analysis, however, confirmed by operation data, showed that the most charged stretch is the Milano Porta Garibaldi - Milano Greco Pirelli. 3984 meters long, it has a maximum traffic of 11 trains/hour/direction between Bivio Mirabello junction and Milano Porta Garibaldi in the rush hour 8:00-9:00. The presence of a junction at approximately half line poses considerable constraint to railway operation: the systematic crossings, which allow the route from the odd track towards PM Turro, affect the intense circulation on the even track. While the junction headway norm is equal to 3'00", whereas in other junctions it has values equal to 4'00" or higher, Bivio Mirabello is one of the critical locations of the Milan railway node. Traffic pikes are achieved during the rush hours of the morning (even sense) and afternoon (odd sense), where in addition to clock-faced services there are some others. In these time slots, the infrastructure utilization rate reaches the highest values, at the expense of operation regularity, making it easier creating disturbances and their propagation. For this reason, the stretch has been identified as a priority for the implementation of the new BS, so it is possible to benefit of the increase in regularity or to obtain an increase in traffic without affecting the regularity. The second corridor identified shares with the previous one the Milan Porta Garibaldi - Bivio Mirabello line, continuing by the latter

places to Milano Lambrate through PM Turro, for a total of 5688 meters of line. Also on this route there is a high traffic intensity, unbalanced between the two directions: in the morning in the even sense and in the afternoon in the odd one. It meets a series of conflicting points in succession, conditioning the timetable design, having to comply with the headway norm of the junctions, since the operational management in the event of disturbances. Finally, in Milano Lambrate station occurs the diversion, outgoing from the node, and the merging, incoming at the node, of the traffics by crossing between the lines.

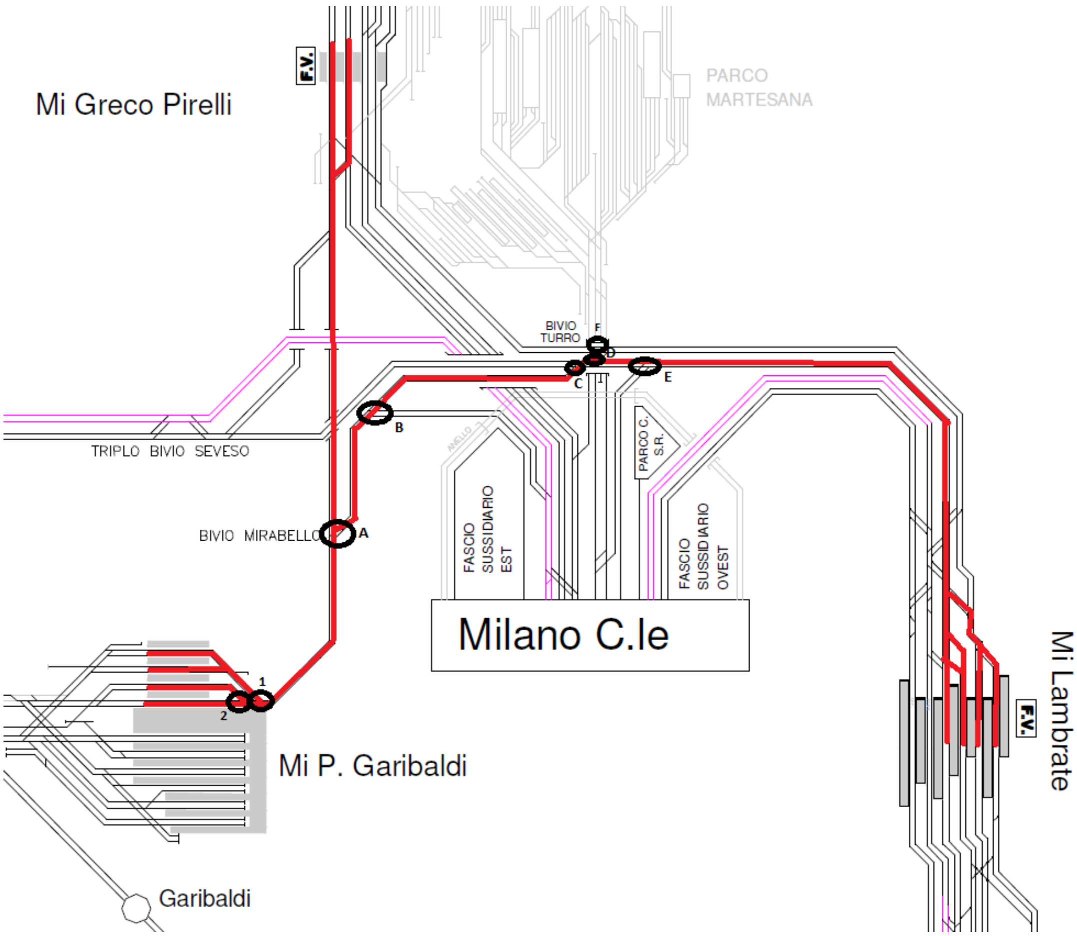

Figure 23: Detail of the Milan node. In red routes with HD ERTMS; rimmed in black the conflicting points

Figure 23 shows the lines that will be equipped with ERTMS HD. Specifically, in Milano Porta Garibaldi all platforms of the upper part of the station, which flow toward Bivio Mirabello; in Milano Greco Pirelli the platforms from I to

IV; in Milano Lambrate platforms from I to VIII, where are planned the arrivals and departures from and to various directions.

To respond effectively to the objective of the work, four scenarios of incremental traffic were examined and, for each of them, were obtained the utilization percentages of the various infrastructure elements in current conditions and subsequently the implementation of ERTMS HD, assuming that has been reached full equipment of the rolling stock. The scenarios are:

- "Current" Scenario, with the scheduled traffic in 2017 timetable
- "Framework Agreement" Scenario[21], wherein for each line has been hypothesized an increase in traffic as provided in Annex D of the Framework Agreement (27) with the Lombardy Region
- "Market" scenario, in which has been hypothesized the addition of market services from and directed towards the high-speed lines belonging to the node
- "Maximum load" Scenario, in which it has been hypothesized further increase in regional trains on lines equipped with HD ERTMS and were introduced freight trains on other nodal lines

The services provided on the corridor are shown in Figure 24, while the respective volumes in Table 10.

[21] Starting from this scenario, and for the next ones, it has also been hypothesized a change of routes in Milano Lambrate, aimed at stress the conflicting point "e" and the stretch PM Turro - Milano Lambrate.

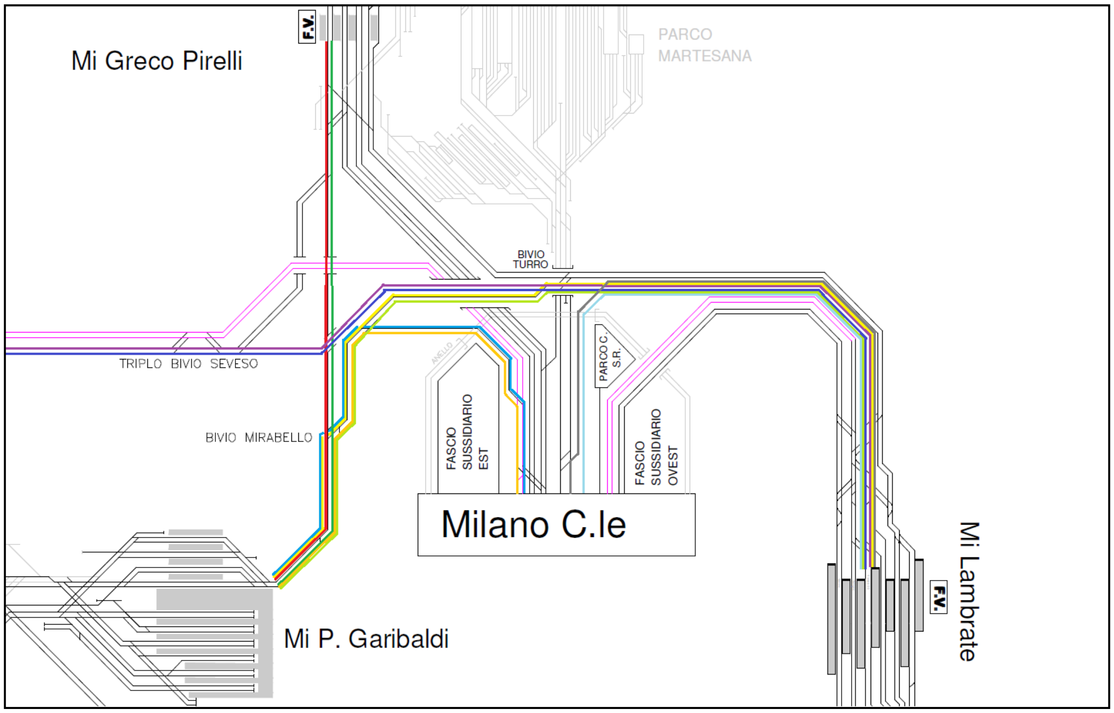

Figure 24: Services provided on lines equipped with ERTMS HD

Line	Traffic [trains/hour/direction]			
	Current	Framework Agreement	Market	Maximum load
Milano PG – Milano GP	7	8	8	10
Milano PG – Milano CLE	2	2	2	2
Milano PG – Milano LTE	1	1	2	2
TBV Seveso – Milano LTE	1	4	4	4
Milano CLE – Milano LTE	0	3	3	3
Milano GP – Milano PG	9	9	9	11
Milano CLE – Milano PG	2	2	2	2
Milano LTE – Milano PG	0	0	2	2
Milano LTE – TBV Seveso	5[22]	7[22]	7[22]	6
Milano LTE – Milano CLE	3	4	4	4

Table 10: Expected traffic volumes on lines equipped with ERTMS HD

The stretches of the high-density corridor that have been analysed are those in which the services overlap, and volumes are added:

- Milano Porta Garibaldi - Bivio Mirabello
- Bivio Mirabello - Milano Greco Pirelli
- Bivio Mirabello - PM Turro

[22] One freight train.

- PM Turro - Milano Lambrate

The same volumes were used to calculate the utilization of conflicting points present along these routes, as illustrated in the previous chapter, identifying one by one which was the principal and which the secondary flow. At the same time, it has been assumed a route distribution inside the stations.

Figure 25 shows the schematic plan of Milano Lambrate railway station, limited to its west root, after the realization of the ACC[23], mandatory for the implementation of HD ERTMS in station.

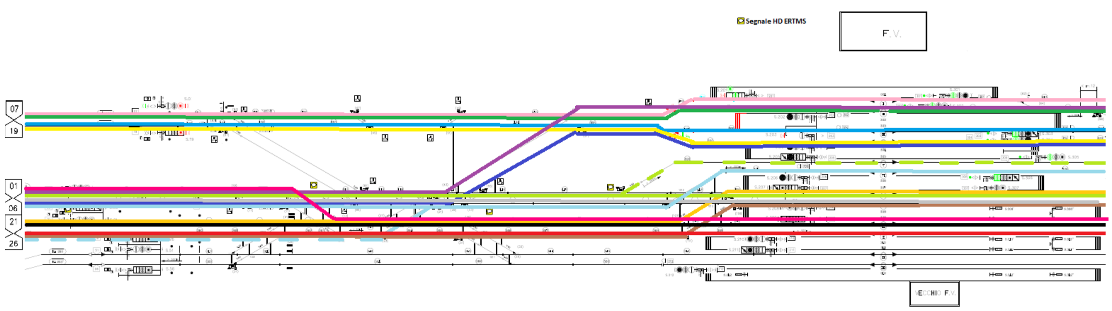

Figure 25: Scheduled routes at Milano Lambrate station

Route	Code	Traffic [trains/hour/direction]			
		Current	Framework Agreement	Market	Maximum load
07 – I	A	1	2	2	4
07 – II	B	4	4	4	7
01 – II	C	0	2	2	2
01 – V (dotted)	D	0	3	3	3
01 – VII	E	1	2	4	4
01 – IX	F	1	1	2	2
21 – VII	G	4	2	2	2
21 – IX	H	4	4	4	4
III – 19	I	2	3	3	4
IV – 19	L	5	5	5	8
IV – 06	M	0	2	2	2
VI – 06	N	5	6	6	6
VI – 26 (tratt.)	O	1	0	0	0
VIII – 06	P	2	2	4	4
VIII – 26	Q	2	2	2	2
X – 26	R	3	3	4	4
Total	-	35	43	49	58

Table 11: Expected traffic volumes in Milano Lambrate

[23] Scenario at 2021.

The station analysis was extended to all the routes in conflict with those arriving from 01 and departing towards 06. The method of analysis was Potthoff[24] as this, given the presence of many conflicting points located in different SBRs and the need to provide transit routes together with other arrival and departure ones, allows to appreciate with accuracy, through the variation of the interdiction time, the benefits of the densification in successive SBRs rather than reaching the route speed at switch toe.

For the same reason the Potthoff method was used to evaluate the use of Milano Greco Pirelli station[25], of which Figure 26 shows the routes planned and the points of conflict and Table 12 the relative traffic volumes.

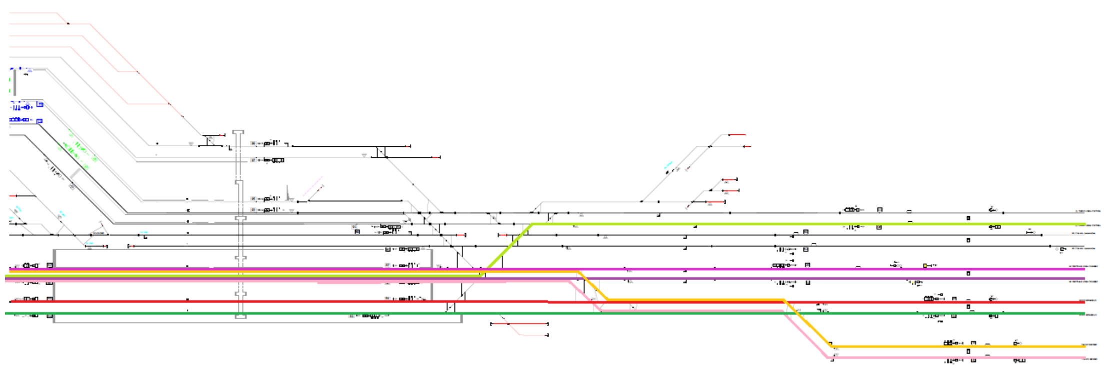

Figure 26: Scheduled routes in Milano Greco Pirelli

Route	Code	Traffic [trains/hour/direction]			
		Current	Framework Agreement	Market	Maximum load
52 – III	A	0	0	0	1
22 – I	B	7	8	8	10
02 – III	C	2	4	5	5
80 – III	D	2	2	2	2
II – 25	E	9	9	9	11
IV – 5	F	4	4	5	5
IV – 55	G	0	0	0	1
Total	-	24	27	29	35

Table 12: Expected traffic volumes in Milano Greco Pirelli

[24] Incompatibility, weight and interdiction time matrices of Milano Lambrate, for each scenario, are reported in the Annex A.

[25] Incompatibility, weight and interdiction time matrices of Milano Lambrate, for each scenario, are reported in the Annex B.

The Milan Porta Garibaldi station was analyzed only in its root side Bivio Mirabello by means of the method set out in (24). The root is composed of two junctions in succession which enable the double-track from Bivio Mirabello to open in 8 platforms. The station has been ideally divided into two parts, a "low" one which goes from the platform XIII to XVI and the other "high" which goes from platform XVII to XX, as shown in Figure 27.

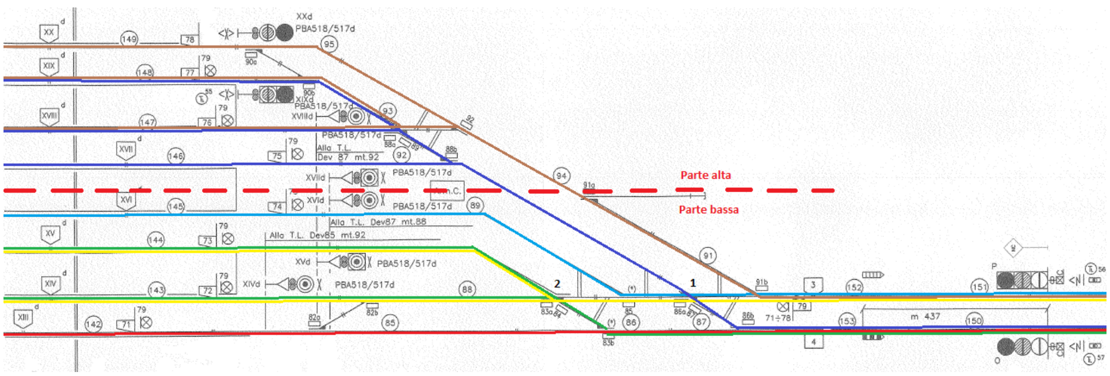

Figure 27: Schematic plan of Milano Porta Garibaldi. Rimmed in black the conflicting point analyzed; in assorted colors the routes assumed in the incremental scenarios

If the root analysis in the current scenario has been done considering scheduled placement, indicated in the specific Modulo M52[26], in the incremental scenarios it has considered the expected transformation of some terminal services into transit ones. For this reason, it has been hypothesized that some of these uses only the "high" part, the other the "low", to have the traffic volume insisting on the conflicting point depending on the considered better placement.

[26] It contains, for each service, the scheduled receiving platform inside a station, for better management of the same by signalman.

Service	Scheduled platform	Traffico [trains/hour/direcyion]		
		Framework agreement	Market	Maximum load
S7 even	XIV-XV	2	2	2
S7 odd	XIV-XV	2	2	2
S8 even	XX	2	2	4
S8 odd	XVII	2	2	4
S11 even	XVI	2	2	2
S11 odd	XIII	2	2	2
S18 even	XVII	3	3	3
S18 odd	XX	2	2	2
Malpensa Express even	XIII	2	2	2
Malpensa Express odd	XX	2	2	2
High speed even	XIII	0	2	2
High speed odd	XVI	1	2	2

Table 13: Expected traffic volumes in Milano Porta Garibaldi

Before analysing the scenarios, it has carried out a review of the junction headway norm inside the high-density corridor. Omitting the details about revision, the results are shown in Table 14.

Station or junction	Current norm	Revisited norm
PM Turro	4’00” (3’00” minimum)	3’00” (2’30” minimum)
Bivio Mirabello	3’00”	2’30” (2’00” minimum)
Milano P.G. – Inbound after Outbound	4’00”	4’00”
Milano P.G. – Outbound after Inbound	4’00”	3’00”

Table 14: Current and on HD ERTMS junction headway norms

6.2 Analysis of scenarios

6.2.1 Current scenario

The results of the application of the formulas outlined in the previous chapter with traffic data described above are shown in terms of the utilization rate of the infrastructural element encountered along the corridor equipped with ERTMS HD. The upper limit has been set equal to 85 percentage points; beyond this threshold the element is saturated. Moreover, it has been highlighted the percentages between 75 and 85 points, indicating the situations in which it is reaching saturation.

Line	Traffic [treni/ora/direzione]	Utilization rate	
		Automatic Block	HD ERTMS
Milano Porta Garibaldi – Bivio Mirabello	10	83%	50%
Bivio Mirabello – Milano Greco Pirelli	7	58%	35%
Bivio Mirabello – PM Turro	3	25%	15%
PM Turro – Milano Lambrate	2	17%	10%
Bivio Mirabello – Milano Porta Garibaldi	11	92%	55%
Milano Greco Pirelli – Bivio Mirabello	9	75%	45%
PM Turro – Bivio Mirabello	2	17%	10%
Milano Lambrate – PM Turro	8	67%	47%

Table 15: Lines utilization rates in Current scenario

Milano Lambrate			
B		Ut	
Automatic Block	HD ERTMS	Automatic Block	HD ERTMS
46%	43%	55%	51%
Milano Greco Pirelli			
B		Ut	
Automatic Block	HD ERTMS	Automatic Block	HD ERTMS
60%	52%	61%	53%

Milano Porta Garibaldi					
Ut_1		Ut_2		Ut_{1-2}	
Automatic Block	HD ERTMS	Automatic Block	HD ERTMS	Automatic Block	HD ERTMS
53%	45%	40%	37%	72%	65%

Table 16: Stations utilization rates in Current scenario

Conflicting point	Utilizzazion rate	
	Automatic Block	HD ERTMS
a	80%	55%
b	17%	17%
c	47%	37%
d	17%	10%
e	42%	32%
f	47%	47%
d-c	56%	43%
e-b	51%	43%
e-c	69%	57%

Table 17: Junctions utilization rates in Current scenario

Tables 15, 16 and 17 show that in the current scenario the Bivio Mirabello – Milano Porta Garibaldi stretch is the only saturated one, while are close to saturation, the corresponding odd stretch, the Milano Greco Pirelli – Bivio Mirabello stretch and the junction itself. There are no critic utilization rates at stations. Switching to HD ERTMS all analysed elements presents compatible utilization rates. With the current infrastructure, any increase in the commercial offer is going to insist on Bivio Mirabello – Milano Porta Garibaldi stretch would not be sustainable from the point of view of the regularity. Instead, it would be possible increases in traffic on the section between PM Turro and Milano Lambrate in both directions without effects on the regularity. In contrast, HD ERTMS permits a significant increase in the commercial offer on the entire corridor equipped.

6.2.2 Framework agreement scenario

Line	Traffic [treni/ora/direzione]	Utilization rate	
		Automatic Block	HD ERTMS
Milano Porta Garibaldi – Bivio Mirabello	11	92%	55%
Bivio Mirabello – Milano Greco Pirelli	8	67%	40%
Bivio Mirabello – PM Turro	3	25%	15%
PM Turro – Milano Lambrate	8	67%	40%
Bivio Mirabello – Milano Porta Garibaldi	11	92%	55%
Milano Greco Pirelli – Bivio Mirabello	9	75%	45%
PM Turro – Bivio Mirabello	2	17%	10%
Milano Lambrate – PM Turro	11	92%	62%

Table 18: Lines utilization rates in Framework Agreement scenario

Milano Lambrate			
B		Ut	
Automatic Block	HD ERTMS	Automatic Block	HD ERTMS
66%	60%	84%	76%

Milano Greco Pirelli			
B		Ut	
Automatic Block	HD ERTMS	Automatic Block	HD ERTMS
63%	55%	64%	56%

Milano Porta Garibaldi					
Ut_1		Ut_2		Ut_{1-2}	
Automatic Block	HD ERTMS	Automatic Block	HD ERTMS	Automatic Block	HD ERTMS
67%	58%	27%	25%	76%	69%

Table 19: Stations utilization rates in Framework Agreement scenario

Conflicting point	Utilizzazion rate	
	Automatic Block	HD ERTMS
a	80%	55%
b	17%	17%
c	63%	47%
d	42%	30%
e	78%	67%
f	47%	47%
d-c	79%	63%
e-b	82%	72%
e-c	92%	82%

Table 20: Junctions utilization rates in Framework Agreement scenario

In this scenario it has been speculated that some trains from and to Venezia use the HD ERTMS line between Milano Centrale and Milano Lambrate, passing through the conflicting point “e”, so as to be in Milano Lambrate on the main route and avoid incompatibilities between the G-P and H-Q routes. This change is preparatory to the increase in traffic in the market scenario.
The analysis shows that also Milano Lambrate – PM Turro and Milano Porta Garibaldi – Bivio Mirabello and the conflicting points "e-c" saturate. Other points reach utilization rates close to saturation. The timetable scheduling with these levels of traffic with Automatic Block is not advisable, unless accepting reduction in regularity. With HD ERTMS the utilization rates fall within the threshold.

6.2.3 Market scenario

Line	Traffic [treni/ora/direzione]	Utilization rate	
		Automatic Block	HD ERTMS
Milano Porta Garibaldi – Bivio Mirabello	12	100%	60%
Bivio Mirabello – Milano Greco Pirelli	8	67%	40%
Bivio Mirabello – PM Turro	4	33%	20%
PM Turro – Milano Lambrate	9	75%	45%
Bivio Mirabello – Milano Porta Garibaldi	13	108%	65%
Milano Greco Pirelli – Bivio Mirabello	9	75%	45%
PM Turro – Bivio Mirabello	4	33%	20%
Milano Lambrate – PM Turro	13	108%	72%

Table 21: Lines utilization rates in Market scenario

Milano Lambrate			
B		Ut	
Automatic Block	HD ERTMS	Automatic Block	HD ERTMS
82%	74%	110%	97%

Milano Greco Pirelli			
B		Ut	
Automatic Block	HD ERTMS	Automatic Block	HD ERTMS
63%	55%	65%	57%

Milano Porta Garibaldi					
Ut_1		Ut_2		Ut_{1-2}	
Automatic Block	HD ERTMS	Automatic Block	HD ERTMS	Automatic Block	HD ERTMS
73%	65%	27%	25%	80%	74%

Table 22: Stations utilization rates in Market scenario

Conflicting point	Utilizzazion rate	
	Automatic Block	HD ERTMS
a	82%	58%
b	27%	20%
c	68%	52%
d	50%	30%
e	95%	77%
f	47%	47%
d-c	84%	66%
e-b	96%	81%
e-c	98%	89%

Table 23: Junctions utilization rates in Market scenario

The expected traffic becomes unsustainable with Automatic Block while HD ERTMS shows good utilization rates in line and not so good in Milano Lambrate and in the use of successive conflicting points. Please note that up to this scenario a freight train path has been present on equipped corridor between Milano Lambrate and Triplo Bivio Seveso. It is possible that without it, which significantly engages the use of Milano Lambrate and PM Turro, utilization rates return acceptable.

6.2.4 Maximum load scenario

Line	Traffic [treni/ora/direzione]	Utilization rate	
		Automatic Block	HD ERTMS
Milano Porta Garibaldi – Bivio Mirabello	12	117%	70%
Bivio Mirabello – Milano Greco Pirelli	8	83%	50%
Bivio Mirabello – PM Turro	4	33%	20%
PM Turro – Milano Lambrate	9	75%	45%
Bivio Mirabello – Milano Porta Garibaldi	13	125%	75%
Milano Greco Pirelli – Bivio Mirabello	9	92%	55%
PM Turro – Bivio Mirabello	4	33%	20%
Milano Lambrate – PM Turro	13	100%	60%

Table 24: Lines utilization rates in Maximum load scenario

<table>
<tr><td colspan="6">Milano Lambrate</td></tr>
<tr><td colspan="3">B</td><td colspan="3">Ut</td></tr>
<tr><td>Automatic Block</td><td colspan="2">HD ERTMS</td><td colspan="2">Automatic Block</td><td>HD ERTMS</td></tr>
<tr><td>96%</td><td colspan="2">82%</td><td colspan="2">135%</td><td>112%</td></tr>
<tr><td colspan="6">Milano Greco Pirelli</td></tr>
<tr><td colspan="3">B</td><td colspan="3">Ut</td></tr>
<tr><td>Automatic Block</td><td colspan="2">HD ERTMS</td><td colspan="2">Automatic Block</td><td>HD ERTMS</td></tr>
<tr><td>99%</td><td colspan="2">73%</td><td colspan="2">111%</td><td>81%</td></tr>
<tr><td colspan="6">Milano Porta Garibaldi</td></tr>
<tr><td colspan="2">Ut_1</td><td colspan="2">Ut_2</td><td colspan="2">Ut_{1-2}</td></tr>
<tr><td>Automatic Block</td><td>HD ERTMS</td><td>Automatic Block</td><td>HD ERTMS</td><td>Automatic Block</td><td>HD ERTMS</td></tr>
<tr><td>87%</td><td>75%</td><td>27%</td><td>25%</td><td>90%</td><td>81%</td></tr>
</table>

Table 25: Stations utilization rates in Maximum load scenario

Conflicting point	Utilizzazion rate	
	Automatic Block	HD ERTMS
a	98%	68%
b	27%	20%
c	85%	62%
d	65%	55%
e	87%	65%
f	73%	73%
d-c	95%	83%
e-b	90%	72%
e-c	98%	87%

Table 26: Junctions utilization rates in Maximum load scenario

In this scenario there is a decrease in the use of the conflicting point "e" due to the displacement of a freight train path between Milano Lambrate and Triplo Bivio Seveso from equipped corridor to the belt-line, through the route that uses the points "d" and "c" in succession. This shift is due to the identification of a dedicated corridor for freight trains from Milano Lambrate to Milano Greco Pirelli and Triplo Bivio Seveso passing through PM Turro, and vice versa. It shows that stretches equipped with HD ERTMS does not reach the upper limit in the utilization rates. The conflicting points, thanks to the benefits of HD ERTMS, show no signs of saturation; instead of considering the use of successive points are noted critical situations in "d-c" and "e-c". The significant limit to development of traffic is, however, constituted by the capacity of the stations. Specifically, in Milano Lambrate the crossings necessary to distribute the traffic to various destinations is the major limitation to the increase in commercial offer. The regular utilization rate (B) does not exceed the saturation threshold, while considering the delays that would be generated, this is exceeded, and the same offer would have sold with a lower quality than the IM objectives.

7. Simulation

7.1 Opentrack®

By the development of simulation methods that reproduce the railway operation on a portion of infrastructure, becomes possible to highlight and analyse the variables involved in the design of the railway system.

In this work the simulation of railway operation, for the reasons discussed previously, was not used to stress the HD ERTMS with a fictitious timetable to determine the minimum headway, as done in Figure 9, but to highlights the benefits that the BS has been shown to be able to ensure, in such a way that it can serve as a support and inspiration for the analysis of the system, already carried out analytically.

The chosen simulator of railway networks is OpenTrack®; it is capable of reproducing and process the behaviour and performance of all rail elements: infrastructure, signalling, rolling stock and timetable.

Rail traffic is modelled by solving the equations of motion in accordance with the information provided by the signalling system. The input data are divided into three modules: rolling stock, infrastructure and timetable. All performance about the movement of trains are calculated through the information given by the infrastructural layout and train characteristics (resistance to motion, the radius of curvature, slope, maximum speed, tractive effort, etc.). The rolling stock is described through the key features of engines, wagons and moving parts. The required data are weight, length, maximum speed, adhesion in function of the climatic conditions and the traction effort-speed diagram. Each train, with its kinematic characteristics, is associated with a path; it is possible to define different prioritize routes and various levels of performance. The real-time simulation allows to view the run on the railway infrastructure, to assess the timetable goodness and to highlight the conflicts. It is also required an iterative procedure between the timetable design and its validation. If they were present conflicts, it should be possible to modify timetable, infrastructure or train characteristics. The software plots the train path, occupancy diagrams and block sections release, to adapt the schedule of trains through the displacement or the elongation of the conflicting path.

Opentrack® outputs consist in the Train Graph automatically plotted based on actual performance of each train and on the scheduled passages on the Punti Orario, from which it is possible to extract information on the movement in terms of delays. Looking at the plotted Train Graphs, are highlighted the conflicts occurred during the simulation and it is possible to highlight some design elements as the minimum spacing in line and at conflicting points.

In this work, the objective of the simulation is to verify the scheduled timetable stability according to the traffic volumes provided in the various scenarios.

The reference interval is in the range between 8:00 am and 9:00 am of an average weekday. In the simulation they were considered running trains on HD ERTMS routes and all those interfering with these, and especially the trains of Milano-Chiasso, Milano-Bologna and belt-line Milano Greco Pirelli-Milano Lambrate. The simulation has followed the following steps:

- Loading on OpenTrack® the infrastructure, according to Schematic Plans, and rolling stock
- Acquisition of scheduled train paths in the considered period and allocation of planned or hypothesized routes
- Allocation of delays to trains for simulation in perturbed conditions
- Analysis of Train Graphs and numerical output

7.2 Application

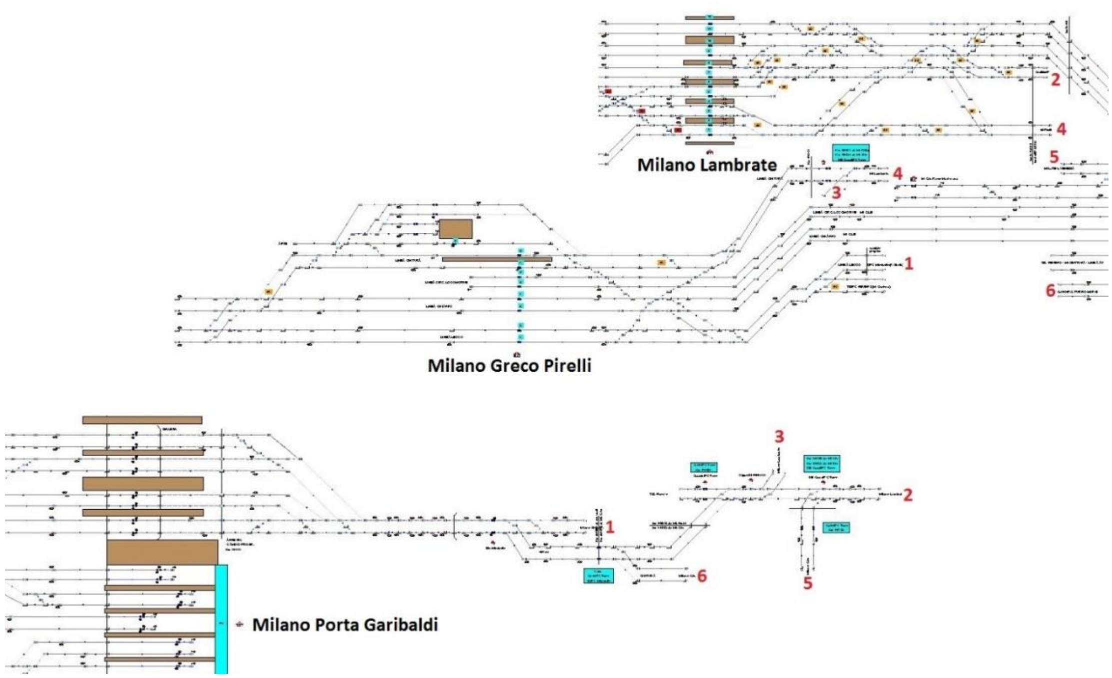

Figure 28: Functional layout of Milan railway node. In red the connections

After building the functional layout of the Milan node, shown in Figure 23, the routes in Figures 24, 25, 26 and 27 have been uploaded. The paths scheduled in the current scenario were acquired by Piattaforma Integrata Circolazione (PIC), an internal RFI tool; paths inserted in incremental traffic scenarios were obtained by duplicating the existing ones for the same type of service; subsequently the routes previously created were assigned to the path provided in the various scenarios. The following scenarios were investigated:

- Scenario 0: Current traffic and current infrastructure
- Scenario 1: Current traffic and HD ERTMS infrastructure
- Scenario 2: Framework Agreement traffic and HD ERTMS
- Scenario 3: Market traffic and HD ERTMS
- Scenario 4: Maximum load traffic and HD ERTMS

From the comparison between the scenarios 0 and 1, it is possible to derive the benefits in regularity provided by HD ERTMS; while from the scenario 1 compared with the scenarios 2, 3 and 4, it is possible to verify the stability of the system against the increments in traffic. Moreover, in scenarios 2, 3 and 4 also flows on other lines were increased.

For each of these projected scenarios, 31 simulations were performed, of which the first, defined "hourly", in the absence of delays at the input and all the others, defined as "perturbed", having the following distribution of delays, extracted from PIC and referred to the average monthly inbound delays in Milan node.

Regional trains average			**Market trains average**			**Freight trains average**		
From	To	%	From	To	%	From	To	%
0	60	37	0	60	27	0	60	0
60	180	29	60	180	26	60	120	50
180	300	12	180	300	12	120	180	22
300	600	18	300	600	18	300	600	5
600	1800	14	60	1800	14	600	900	5
1800	2400	3	1800	2400	3	900	1800	2
-	-	-	-	-	-	1800	2400	10

Table 27: Inbound delay distribution in Milano railway node

7.3 Results

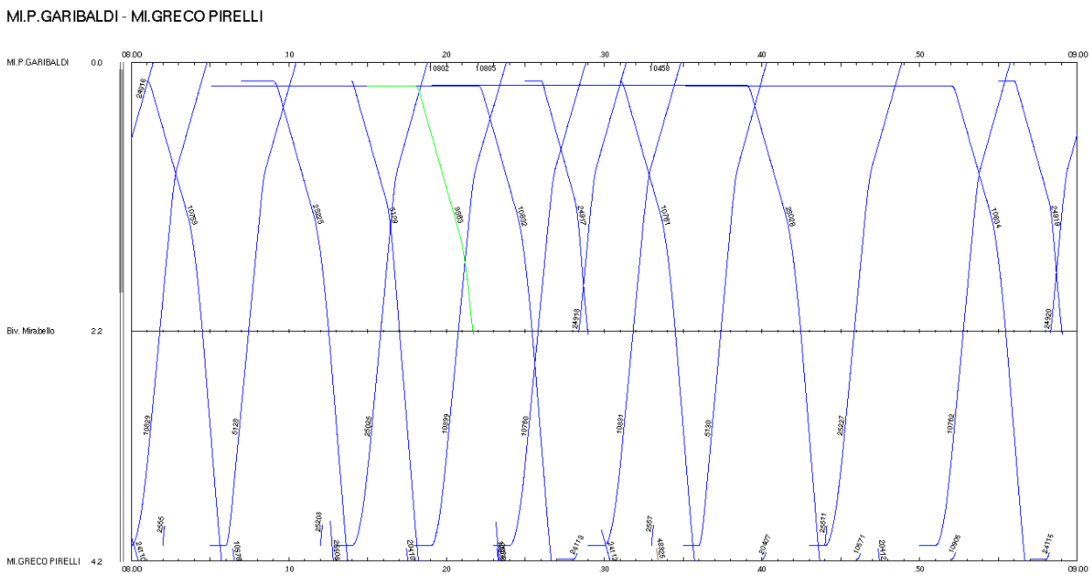

Figure 29: Hourly Train Graph in the Scenario 0

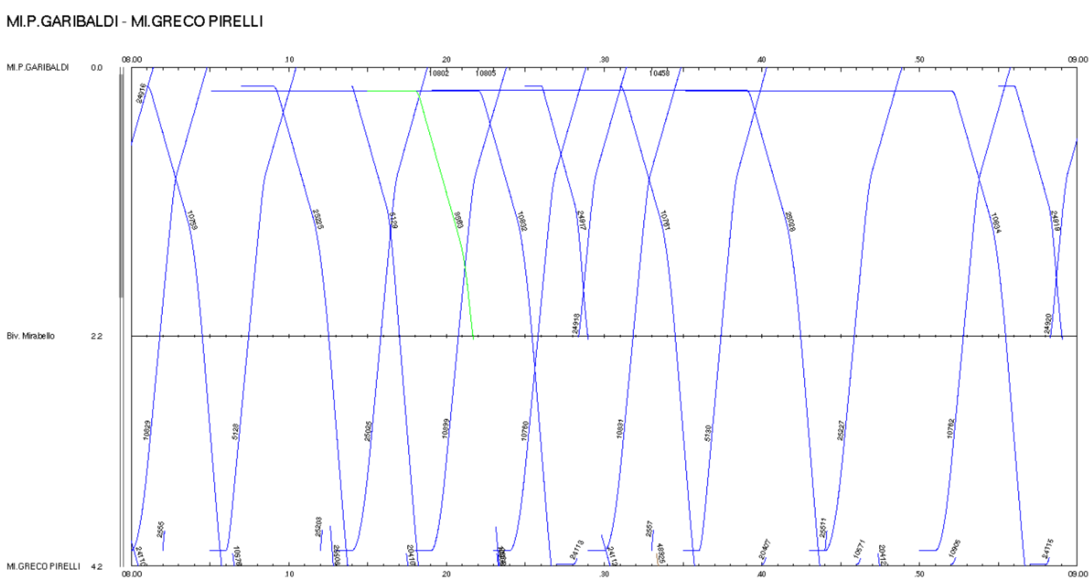

Figure 30: Hourly Train Graph in the Scenario 1

Figures 29 and 30 show that the current timetable transposed to HD ERTMS infrastructure HD ERTMS does not present conflicts or delays due to the perception of a restrictive aspect by signalling: the operation takes place in exactly the same way. The management of the operation in the two scenarios becomes different considering the perturbated conditions. The figures below show what happens when trains have an input delay in accordance with the distribution of Table 27.

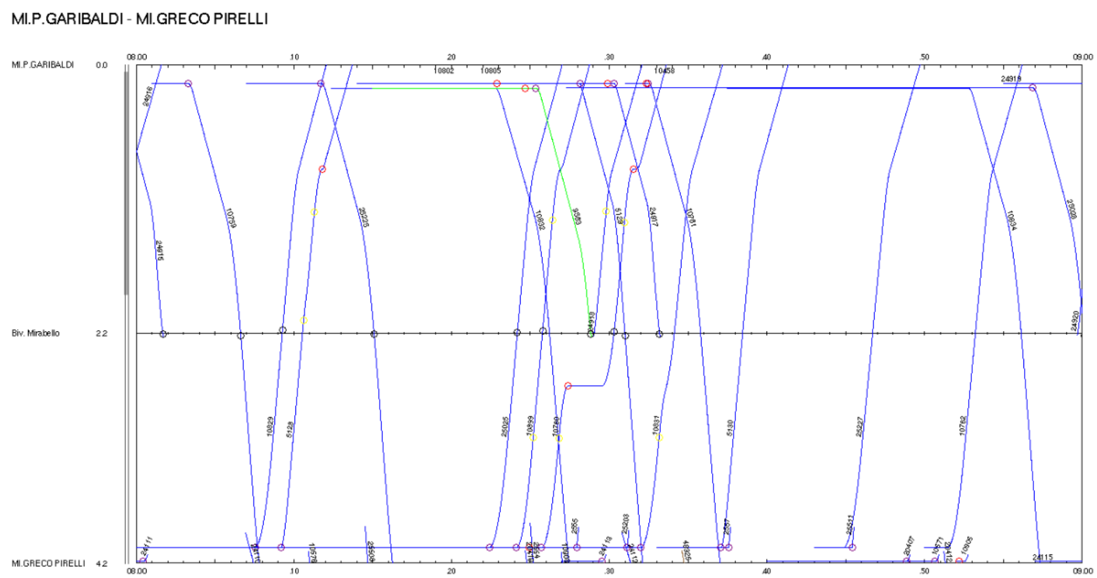

Figure 31: 16th simulation in perturbed conditions in the Scenario 0

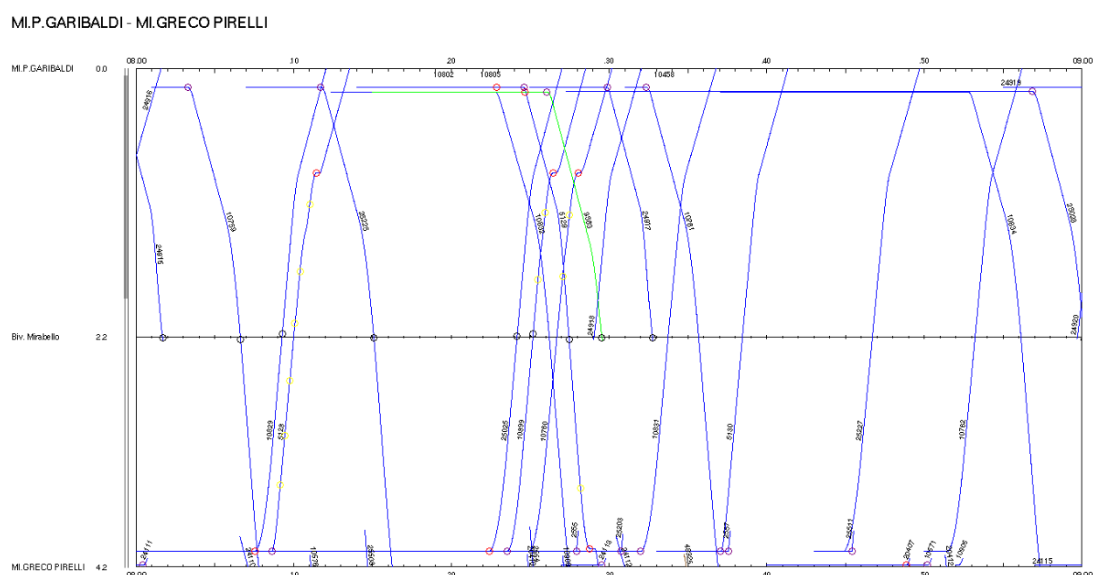

Figure 32: 16th simulation in perturbed conditions in the Scenario 1

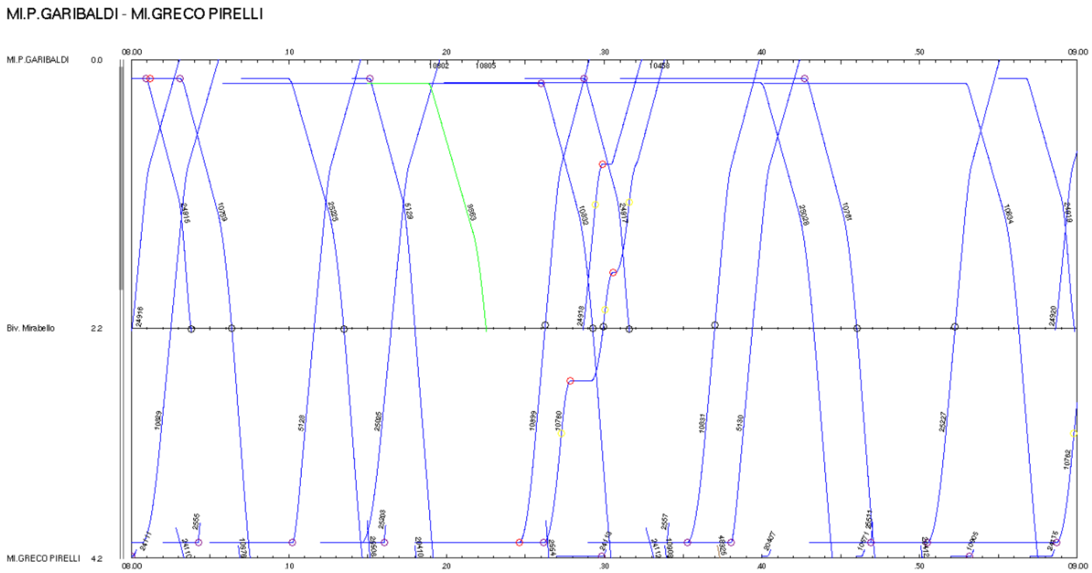

Figure 33: 20th simulation in perturbed conditions in the Scenario 0

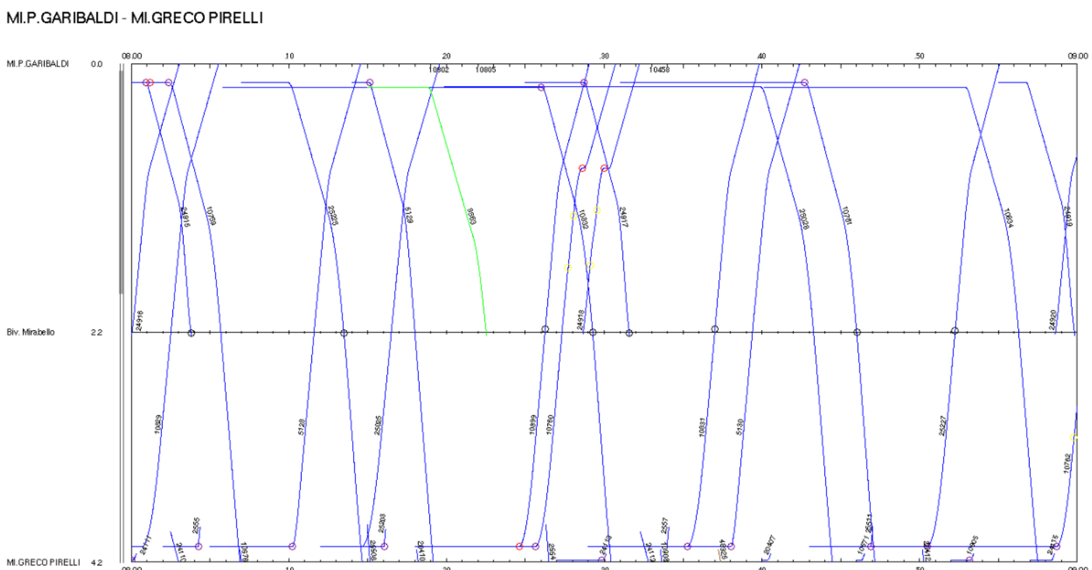

Figure 34: 20th simulation in perturbed conditions in the Scenario 1

Figure 31 shows a train that makes a stop at the main signal of Bivio Mirabello, engaged by the transit of the crossing train in green. The train reach its destination at minute 34. From a comparison with Figure 32 is noted as the train itself can densify to the previous one, being able to engage Bivio Mirabello before that is completed the route formation for the green crossing train. This allows the train in question to arrive at destination at minutes30: it was shown as HD ERTMS permits, in perturbed situations, a delay recovery with respect to the automatic block. The same conclusion follows from a comparison of Figures 33 and 34, where in the Scenario 0 is there is a train forced to stop at the main signal of Bivio Mirabello and, later, on line, while in Scenario 1, densifying to the previous, avoids the stop at signal. In this case, the difference between the times of arrival at the destination is 3 minutes. The highlighted cases are two of the many that would have been possible to extract investigating all perturbed simulations. For reasons of time, it was decided to limit to two significant cases.

Improvements in traffic management have suggested analysing the trends of delays of scheduled trains on the equipped corridor. The used indicators are: average output delay, number of delayed trains in output, reduction of delay and weighted average delay. The latter is derived from the weighting of the average delay value with the proportion of delayed trains, as an indicator that tries to find a common point between two opposite situations: the presence of many delayed trains with a low average value and the presence of a low number of delayed trains with a high average value.

To understand the benefits of the new BS, the delays have been analysed referring to both the equipped corridor and the whole influence area.

	Traffic [trains/hour]	Increase [%]	Average delay in output [s]	Delayed trains in output [s]	Weighted average delay in output [s]	Change [%]
Scenario 0	16	-	404	58	235	-
Scenario 1	16	0%	390	57	223	-5%
Scenario 2	17	6%	368	58	213	-4%
Scenario 3	20	25%	368	60	221	-1%
Scenario 4	24	50%	500	66	331	48%

Table 28: Delay indicators for Milano Porta Garibaldi - Milano Greco Pirelli

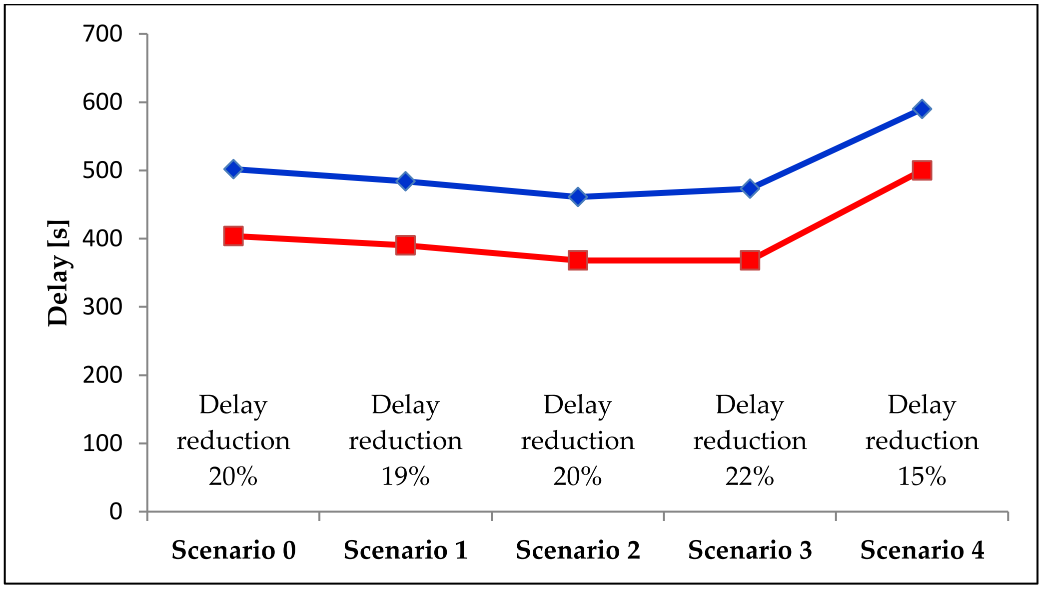

Figure 35: Average delay between Milano Porta Garibaldi and Milano Greco Pirelli; in blue the average delay in input and in red the average delay in output

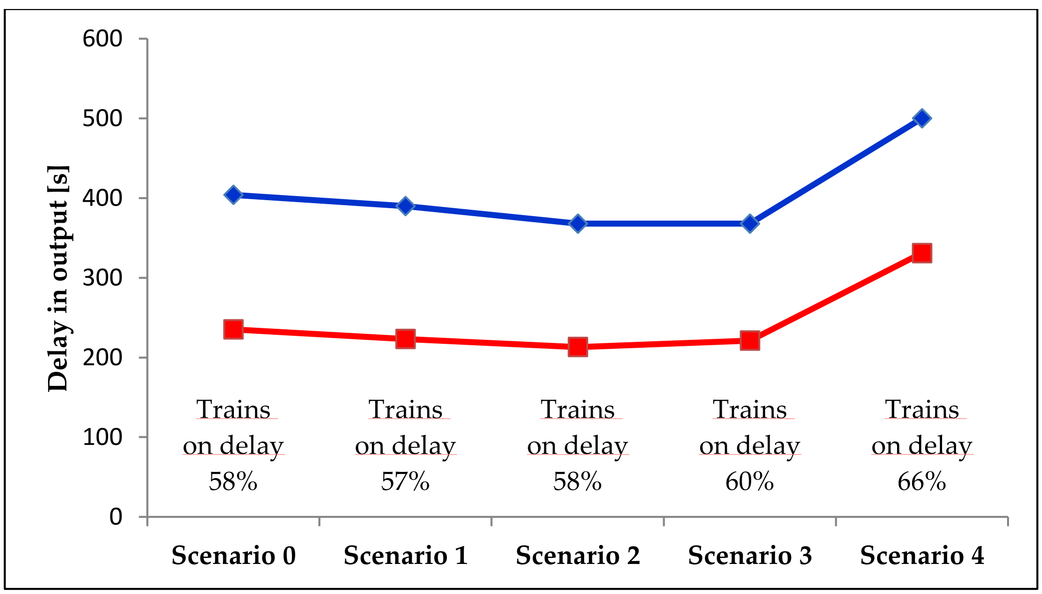

Figure 36: Weighted average delay in output between Milano Porta Garibaldi and Milano Greco Pirelli; in blue the avergage delay and in red the weighted average delay

Analyzing data on the Milano Porta Garibaldi – Milano Greco Pirelli line, it can be noticed how HD ERTMS enables a net benefit of 5% with respect to the automatic block; it should be noted both a decrease in the average delay that in the number of delayed trains in output. Looking at the increase in traffic on the line, in the Scenarios 2 and 3, the rising in the volumes is relative mainly to the trains up to Bivio Mirabello, therefore the examined trains suffers only secondary delays due to major induced disturbances. It can be thus explained the further delay reduction highlighted in Scenarios 2 and 3, despite the increase in traffic. It is only with the substantial increase of volumes that greatly grow the delay indicators; however, looking at the data of the recovered delay, it is noted that the system allows to recover part of imposed delay, it can therefore define stable.

	Traffic [trains/hour]	Increase [%]	Average delay in output [s]	Delayed trains in output [s]	Weighted average delay in output [s]	Change [%]
Scenario 0	16	-	459	60	277	-
Scenario 1	16	0%	469	57	268	-3%
Scenario 2	23	44%	475	68	324	21%
Scenario 3	28	75%	459	72	330	23%
Scenario 4	32	100%	501	76	381	42%

Table 29: Delay indicators for Milano Porta Garibaldi - Milano Lambrate

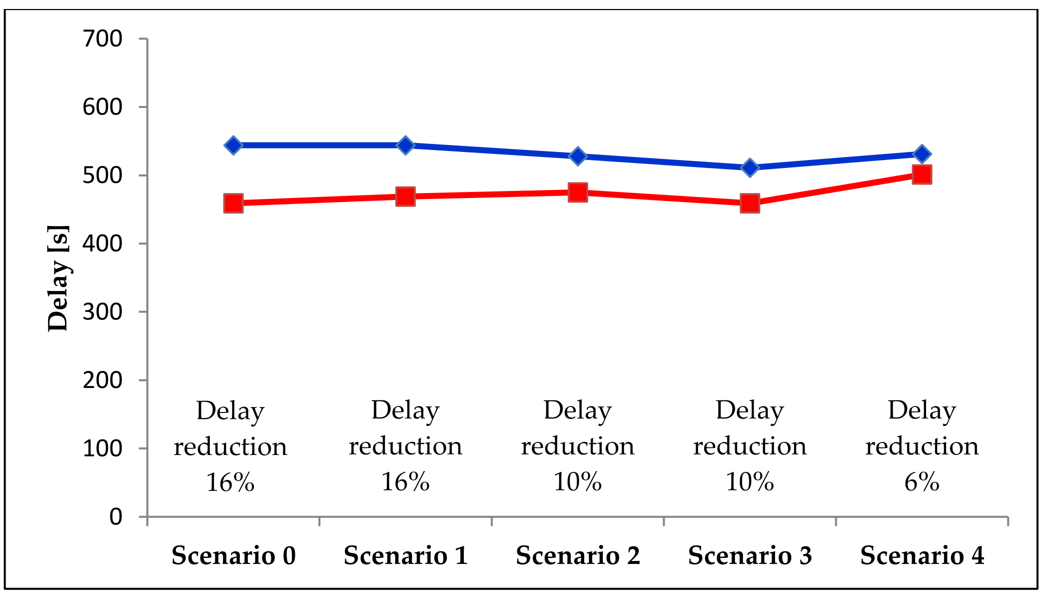

Figure 37: Average delay between Milano Porta Garibaldi and Milano Lambrate; in blue the average delay in input and in red the average delay in output

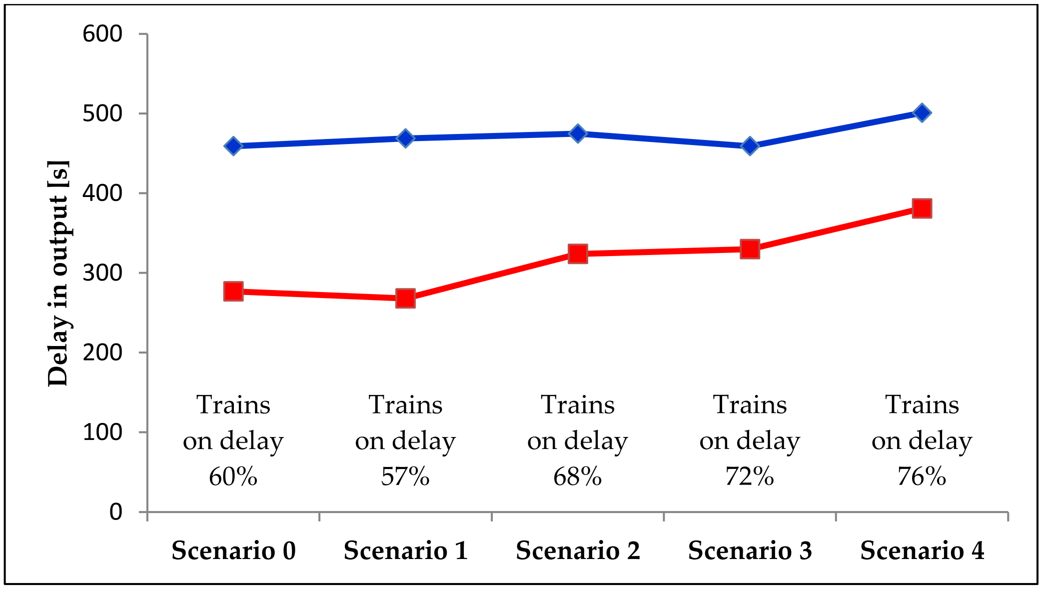

Figure 38: Weighted average delay in output between Milano Porta Garibaldi and Milano Lambrate; in blue the avergage delay and in red the weighted average delay

Analyzing data on the Milano Porta Garibaldi – Milano Lambrate line, it can be noticed how HD ERTMS enables a net benefit of 3% with respect to the automatic block; it should be noted an increase in the average delay and a decrease in the number of delayed trains, which leads to an overall decrease in the weighted average delay. Looking at the values of the indicators related to incremental traffic scenarios, it notes an increase starting from the Scenario 2. The presence of conflicting points encountered in succession and the introduction of services that will insist on them causes significant reciprocal influences between the paths. In any case, the system keeps its regularity because there is a minimal delay recovery percentage with respect to the imposed in input one. Combining these results with those shown in previous Chapter, despite a better operation in the stations, their high utilization remains critical and represents the greatest obstacle to the increase in the commercial supply.

	Traffic [trains/hour]	Increase [%]	Average delay in output [s]	Delayed trains in output [s]	Weighted average delay in output [s]	Change [%]
Scenario 0	67	-	501	64	322	-
Scenario 1	67	0%	454	61	278	-18%
Scenario 2	73	9%	464	63	292	5%
Scenario 3	82	22%	478	67	320	15%
Scenario 4	97	45%	544	70	381	37%

Table 30: Delay indicators for HD ERTMS influence zone

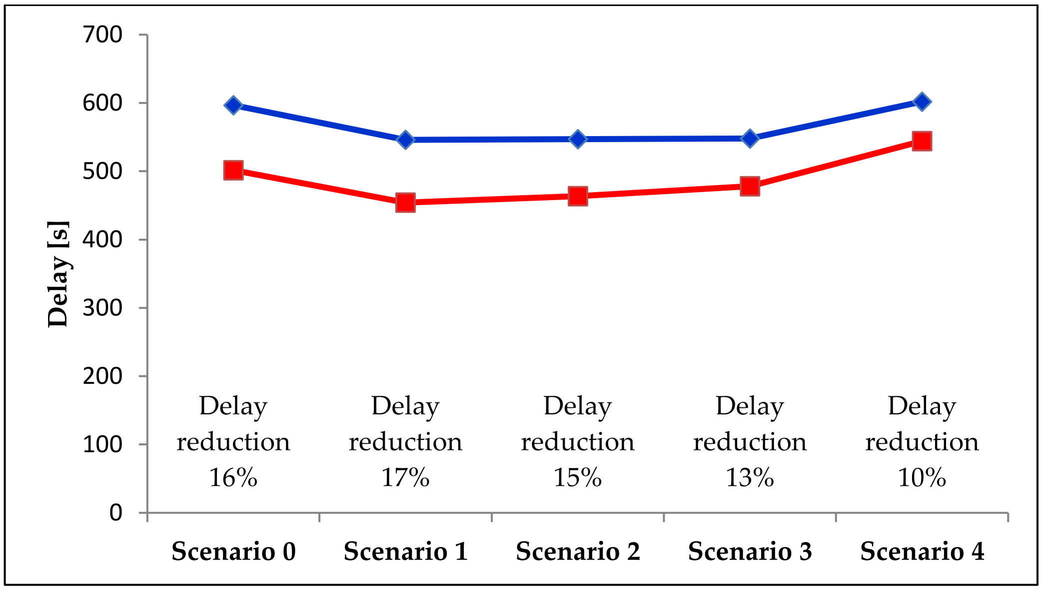

Figure 39: Average delay for HD ERTMS influence zone; in blue the average delay in input and in red the average delay in output

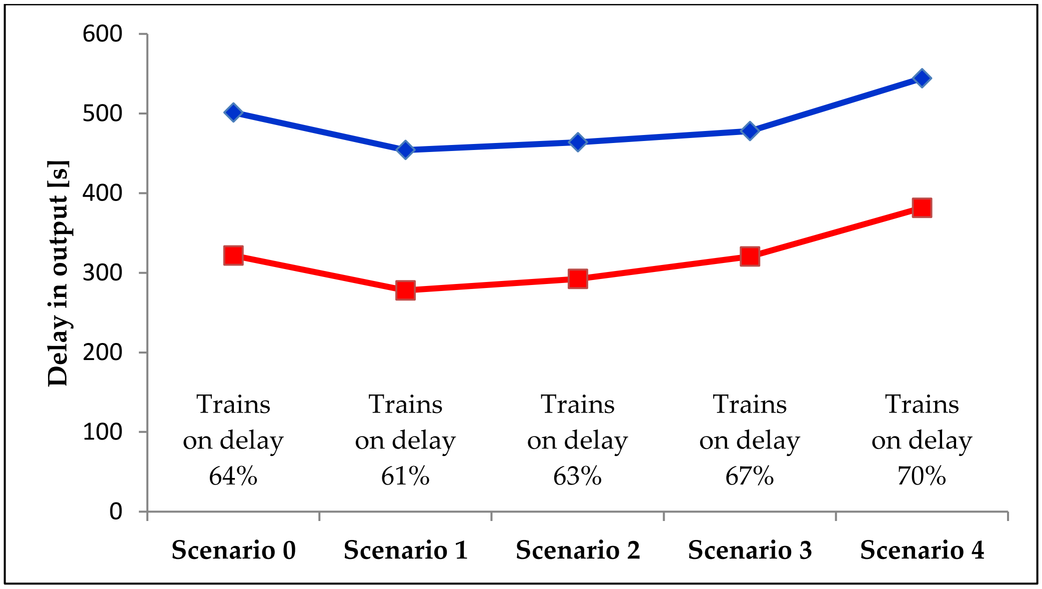

Figure 40: Weighted average delay for HD ERTMS influence zone; in blue the avergage delay and in red the weighted average delay

Analysing data relating to the node portion in which it is assumed will reflect the benefits of HD ERTMS, Table 30 shows how the net benefit is equal to 18%, significantly higher than lines analysed previously and, also in incremental Scenarios are found minor increments in weighted average delay. Finally, the system confirms the ability to recover part of the delay imposed in input. Considering that Milano Lambrate and Milano Greco Pirelli stations are equipped with ERTMS Level 2, the possibility of realizing the densification in station and reaching the route speed at switch tip for all trains entails considerable benefits to the whole system. This results in a significant functional input: the benefits of HD ERTMS are the more relevant the wider the ERTMS implementation (L2 or HD) within the node.

8. Conclusions

The study showed the potentiality of the HD ERTMS system first at a theoretical level, by analysing the technical part, then constructing a model able to highlight the relationships between capacity, regularity and equipment of rolling stock. Subsequently, the same system was analysed both analytically and through simulation software, taking as case study the Milan railway node.

The general study of the HD ERTMS system confirmed that the system allows greater benefits where the pre-existing automatic block headway norms are rather large, allowing increases in capacity even with the equipment of the rolling stock not complete. In the case of narrower norms, in order to obtain appreciable benefits in terms of capacity, the percentages of the equipped rolling stock must be equal to the totality. It was possible to identify the first approximation percentages for the communication to railway companies of the HD ERTMS benefits in terms of capacity. Operatively, it may be necessary to indicate on the PIR the minimum percentages of the rolling stock equipment, linking them to the capacity level of an elementary section.

The application case showed that the HD ERTMS system offers great potentiality, demonstrating with an increase in traffic, within certain limits, the system maintains its regularity. The expected decongestion, confirmed by the analytical study of the node, has not proved to be very significant in the application at simulator. The explanation of this inconsistency must be looked for in the context of the analysis, which focused on the initial and terminal sections of the railway services, where the shortness of the same did not allow to fully exploit and quantify the benefits offered. It is believed that analytical analysis are an excellent support for railway planning and that this inconsistency needs to be deepened, perhaps with simulation tools able to more accurately replicate the railway operation in presence of the innovations introduced by HD ERTMS. In any case, the indicators evaluated at nodal level have shown that the benefits of HD ERTMS are greater the more the ERTMS implementation area, even without the high-density functionality, is extended.

As already mentioned, the main problem is represented by the need for a transitory phase of progressive equipment. A joint effort between Infrastructure Manager and Railway Undertakings is considered necessary so that, together with the implementation of the system on the infrastructure, the companies equip the rolling stock. Without this effort, with the only implementation of HD ERTMS and with low percentages of equipped rolling stock, the benefits are not very appreciable and the request for improvement in terms of capacity and regularity is not fully met.

The study has always referred to passenger trains with a maximum length equal to the shorter HD section. In any case, the influence of a freight train, comparable to an unequipped one, has been quantified and it has emerged that with the current freight traffic there are consequences on the potentiality that must be contextualised in the timetable.

Although not having analysed the costs of a surrogate infrastructural upgrading and the equipment of rolling stock, it is believed that the same HD ERTMS represents a valid alternative to the realization of new linear infrastructures, however, with reduced implementation times. Operation in station and junctions, although improved, remains the critical point of the operation of the railway system. If it is possible to create the infrastructural conditions for a timetable in which conflicts between conflicting routes are minimized, then HD ERTMS would be the optimal completion to achieve the expected increases in the commercial supply within the urban railway nodes.

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Annex A (Milano Lambrate)

MATRICE INCOMPATIBILITA			stop	transit	stop	transit	stop	stop	stop	transit	stop	transit	stop	transit	stop	stop	transit	stop	stop	stop	transit	transit
			20	20	20	20	17	17	17	17	15	15	III	III	IV	IV	IV	VI	VI	VIII	VIII	VIII
			I	I	II	II	II	V	VII	IX	VII	VII	19	19	16	19	19	14	16	14	14	16
stop	20	I	d	d	s	s	z															
transit	20	I	d	d	s	s	z															
stop	20	II	s	s	d	d	z															
transit	20	II	s	s	d	d	z															
stop	17	II	z	z	z	z	d	s	s	s			x	x		x	x					
stop	17	V					s	d	s	s					x							
stop	17	VII					s	s	d	s	z	z			x			x	x			
transit	17	IX					s	s	s	d	z	z			x			x	x	x	x	x
stop	15	VII							z	z	d	d						x				x
transit	15	VII							z	z	d	d						x				x
stop	III	19					x						d	d	z	z	z					
transit	III	19					x						d	d	z	z	z					
stop	IV	16						x	x	x			z	z	d	s	s	s	z			z
stop	IV	19					x						z	z	s	d	d					
transit	IV	19					x						z	z	s	d	d					
stop	VI	14							x	x	x	x			s			d	s	z	z	z
stop	VI	16							x	x					z			s	d			z
stop	VIII	14								x								z		d	d	s
transit	VIII	14								x								z		d	d	s
transit	VIII	16								x	x	x			z			z	z	s	s	d

Table 31: Incompatibility matrix

MATRICE INTERDIZIONI			stop	transit	stop	transit	stop	stop	stop	transit	stop	transit	stop	transit	stop	stop	transit	stop	stop	stop	transit	transit
			20	20	20	20	17	17	17	17	15	15	III	III	IV	IV	IV	VI	VI	VIII	VIII	VIII
			I	I	II	II	II	V	VII	IX	VII	VII	19	19	16	19	19	14	16	14	14	16
stop	20	I	221	278	114	114	114															
transit	20	I	218	218	137	137	137															
stop	20	II	139	139	213	328	213															
transit	20	II	150	150	226	226	226															
stop	17	II	135	135	238	314	238	111	111	93			110	110		110	110					
stop	17	V					111	231	120	93					95							
stop	17	VII					99	105	205	85	135	205			86			111	87			
transit	17	IX					93	93	93	0	0	0			102			0	102	0	110	102
stop	15	VII							303	0	239	341						0				131
transit	15	VII							159	0	159	227						0				131
stop	III	19					103						137	274	103	134	274					
transit	III	19					192						185	185	192	185	185					
stop	IV	16						113	113	127			109	109	148	109	109	117	129			129
stop	IV	19					103						134	264	103	140	264					
transit	IV	19					183						205	205	183	205	205					
stop	VI	14							101	0	0	0			119			113	113	0	0	119
stop	VI	16							101	138					137			119	143			137
stop	VIII	14								0								0		0	0	102
transit	VIII	14								0								0		0	0	150
transit	VIII	16								184	156	156			232			203	232	181	181	232

Table 32: Interdiction times matrix in Scenario 0

MATRICE INTERDIZIONI			stop	transit	stop	transit	stop	stop	stop	transit	stop	transit	stop	transit	stop	stop	transit	stop	stop	stop	transit	transit
			20	20	20	20	17	17	17	17	15	15	III	III	IV	IV	IV	VI	VI	VIII	VIII	VIII
			I	I	II	II	II	V	VII	IX	VII	VII	19	19	16	19	19	14	16	14	14	16
stop	20	I	221	278	114	114	98															
transit	20	I	218	218	137	137	120															
stop	20	II	109	109	206	321	197															
transit	20	II	142	142	218	218	210															
stop	17	II	128	128	232	307	222	92	92	93			110	110		110	110					
stop	17	V					92	202	95	93					95							
stop	17	VII					92	88	135	85	108	135			86			111	87			
transit	17	IX					93	93	93	0	0	0			102			0	70	0	110	102
stop	15	VII							303	0	239	341						0				131
transit	15	VII							159	0	159	227						0				131
stop	III	19					87						137	274	103	134	274					
transit	III	19					176						185	185	192	185	185					
stop	IV	16						97	97	127			109	109	148	109	109	117	113			113
stop	IV	19					87						134	264	103	140	264					
transit	IV	19					167						205	205	183	205	205					
stop	VI	14							85	0	0	0			119			113	107	0	0	119
stop	VI	16							85	138					107			119	109			119
stop	VIII	14								0								0		0	0	102
transit	VIII	14								0								0		0	0	150
transit	VIII	16								184	156	156			227			203	188	181	181	188

Table 33: Interdiction times matrix in Scenario 1

MATRICE INTERDIZIONI			stop	transit	stop	transit	stop	stop	stop	transit	stop	transit	stop	transit	stop	stop	transit	stop	stop	stop	transit	transit
			20	20	20	20	17	17	17	17	15	15	III	III	IV	IV	IV	VI	VI	VIII	VIII	VIII
			I	I	II	II	II	V	VII	IX	VII	VII	19	19	16	19	19	14	16	14	14	16
stop	20	I	221	278	114	114	98															
transit	20	I	218	218	137	137	120															
stop	20	II	109	109	206	321	197															
transit	20	II	142	142	218	218	210															
stop	17	II	128	128	232	307	222	92	92	93			110	110		110	110					
stop	17	V					92	202	95	93					95							
stop	17	VII					92	88	135	85	108	135			86			111	87			
transit	17	IX					93	93	93	0	0	0			102			0	70	0	110	102
stop	15	VII							303	0	239	341						0				131
transit	15	VII							159	0	159	227						0				131
stop	III	19					87						137	274	103	134	274					
transit	III	19					176						185	185	192	185	185					
stop	IV	16						97	97	127			109	109	148	109	109	117	113			113
stop	IV	19					87						134	264	103	140	264					
transit	IV	19					167						205	205	183	205	205					
stop	VI	14							85	0	0	0			119			113	107	0	0	119
stop	VI	16							85	138					107			119	109			119
stop	VIII	14								0								0		0	0	102
transit	VIII	14								0								0		0	0	150
transit	VIII	16								184	156	156			227			203	188	181	181	188

Table 34: Interdiction times matrix in Scenario 2

MATRICE INTERDIZIONI			stop	transit	stop	transit	stop	stop	stop	transit	stop	transit	stop	transit	stop	stop	transit	stop	stop	stop	transit	transit
			20	20	20	20	17	17	17	17	15	15	III	III	IV	IV	IV	VI	VI	VIII	VIII	VIII
			I	I	II	II	II	V	VII	IX	VII	VII	19	19	16	19	19	14	16	14	14	16
stop	20	I	221	278	114	114	98															
transit	20	I	218	218	137	137	120															
stop	20	II	109	109	206	321	197															
transit	20	II	142	142	218	218	210															
stop	17	II	128	128	232	307	222	92	92	93			110	110		110	110					
stop	17	V					92	202	95	93					95							
stop	17	VII					92	88	135	85	108	135			86			111	87			
transit	17	IX					93	93	93	0	0	0			102			0	70	0	110	102
stop	15	VII							303	0	239	341						0				131
transit	15	VII							159	0	159	227						0				131
stop	III	19					87						137	274	103	134	274					
transit	III	19					176						185	185	192	185	185					
stop	IV	16						97	97	127			109	109	148	109	109	117	113			113
stop	IV	19					87						134	264	103	140	264					
transit	IV	19					167						205	205	183	205	205					
stop	VI	14							85	0	0	0			119			113	107	0	0	119
stop	VI	16							85	138					107			119	109			119
stop	VIII	14								0								0		0	0	102
transit	VIII	14								0								0		0	0	150
transit	VIII	16								184	156	156			227			203	188	181	181	188

Table 35: Interdiction times matrix in Scenario 3

MATRICE INTERDIZIONI			stop	transit	stop	transit	stop	stop	stop	transit	stop	transit	stop	transit	stop	stop	transit	stop	stop	stop	transit	transit
			20	20	20	20	17	17	17	17	15	15	III	III	IV	IV	IV	VI	VI	VIII	VIII	VIII
			I	I	II	II	II	V	VII	IX	VII	VII	19	19	16	19	19	14	16	14	14	16
stop	20	I	221	278	114	114	98															
transit	20	I	218	218	137	137	120															
stop	20	II	109	109	206	321	197															
transit	20	II	142	142	218	218	210															
stop	17	II	128	128	232	307	222	92	92	93			110	110		110	110					
stop	17	V					92	202	95	93					95							
stop	17	VII					92	88	135	85	108	135			86			111	87			
transit	17	IX					93	93	93	0	0	0			102			0	70	0	110	102
stop	15	VII							303	0	239	341						0				131
transit	15	VII							159	0	159	227						0				131
stop	III	19					87						137	274	103	134	274					
transit	III	19					176						185	185	192	185	185					
stop	IV	16						97	97	127			109	109	148	109	109	117	113			113
stop	IV	19					87						134	264	103	140	264					
transit	IV	19					167						205	205	183	205	205					
stop	VI	14							85	0	0	0			119			113	107	0	0	119
stop	VI	16							85	138					107			119	109			119
stop	VIII	14								0								0		0	0	102
transit	VIII	14								0								0		0	0	150
transit	VIII	16								184	156	156			227			203	188	181	181	188

Table 36: Interdiction times matrix in Scenario 4

PESI			Scenario				
			0	1	2	3	4
stop	20	I	1	1	2	2	2
transit	20	I	0	0	0	0	2
stop	20	II	4	4	4	4	4
transit	20	II	0	0	0	0	1
stop	17	II	0	0	2	2	2
stop	17	V	0	0	3	3	3
stop	17	VII	1	4	2	4	4
transit	17	IX	1	1	1	2	2
stop	15	VII	2	1	2	2	2
transit	15	VII	2	0	0	0	0
stop	III	19	1	1	2	2	2
transit	III	19	1	1	1	1	2
stop	IV	16	0	0	2	2	2
stop	IV	19	5	5	5	5	5
transit	IV	19	0	0	0	0	1
stop	VI	14	1	0	0	0	0
stop	VI	16	5	6	6	6	6
stop	VIII	14	2	2	2	2	2
transit	VIII	14	0	0	0	0	0
transit	VIII	16	2	2	2	4	4

Table 37: Weights matrix

The computation of the interdiction times has taken into account the subsequent hyphotesis:

- Elastic release of the entities
- Length of trains equal to:
  - Regional: 250 meters
  - High Speed: 350 meters
  - Freight: 750 meters
- Constant acceleration and deceleration:
  - Regional: 0.525 m/s^2
  - High Speed: 0.375 m/s^2

    - Freight: 0.225 m/s^2
- Constant stop time for Regional trains equal to 60 seconds
- Train departure and arrival in correspondance of main signal at end of platform
- Time for route formation equal to 60 seconds

Annex B (Milano Greco Pirelli)

INCOMPATIBILITA GRECO			52	22	2	2	80	II	IV	IV	IV
			III	I	III	III	III	25	5	5	55
transit	52	III	d	z	z	z	z	x			
stop	22	I	z	d							x
stop	2	III	z		d	d	z				x
transit	2	III	z		d	d	z				x
stop	80	III	z		z	z	d		x	x	x
departure	II	25	x					d			x
departure	IV	5					x		d	d	s
transit	IV	5					x		d	d	s
transit	IV	55		x	x	x	x	x	s	s	d

Table 38: Incompatibility matrix

INTERDIZIONI GRECO			52	22	2	2	80	II	IV	IV	IV
			III	I	III	III	III	25	5	5	55
transit	52	III	342	274	342	342	342	274			
stop	22	I	104	236							
stop	2	III	219		219	219	219				80
transit	2	III	140		140	140	140				102
stop	80	III	284		284	284	284				149
departure	II	25	93					258			117
departure	IV	5					94		240	240	218
transit	IV	5					107		137	137	108
transit	IV	55		308	300	300	293	308	300	300	464

Table 39: Interdiction times matrix in Scenario 0

INTERDIZIONI GRECO			52	22	2	2	80	II	IV	IV	IV
			III	I	III	III	III	25	5	5	55
transit	52	III	315	234	315	315	315	234			
stop	22	I	104	196							
stop	2	III	219		219	219	219				80
transit	2	III	140		140	140	140				102
stop	80	III	269		269	269	269				135
departure	II	25	93					219			117
departure	IV	5					94		240	240	218
transit	IV	5					107		137	137	108
transit	IV	55		223	126	126	119	223	205	205	375

Table 40: Interdiction times matrix in Scenario 1

INTERDIZIONI GRECO			52	22	2	2	80	II	IV	IV	IV
			III	I	III	III	III	25	5	5	55
transit	52	III	315	234	315	315	315	234			
stop	22	I	104	196							
stop	2	III	219		219	219	219				80
transit	2	III	140		140	140	140				102
stop	80	III	269		269	269	269				135
departure	II	25	93					219			117
departure	IV	5					94		240	240	218
transit	IV	5					107		137	137	108
transit	IV	55		223	126	126	119	223	205	205	375

Table 41: Interdiction times matrix in Scenario 2

INTERDIZIONI GRECO			52	22	2	2	80	II	IV	IV	IV
			III	I	III	III	III	25	5	5	55
transit	52	III	315	234	315	315	315	234			
stop	22	I	104	196							
stop	2	III	219		219	219	219				80
transit	2	III	140		140	140	140				102
stop	80	III	269		269	269	269				135
departure	II	25	93					219			117
departure	IV	5					94		240	240	218
transit	IV	5					107		137	137	108
transit	IV	55		223	126	126	119	223	205	205	375

Table 42: Interdiction times matrix in Scenario 3

INTERDIZIONI GRECO			52	22	2	2	80	II	IV	IV	IV
			III	I	III	III	III	25	5	5	55
transit	52	III	315	234	315	315	315	234			
stop	22	I	104	196							
stop	2	III	219		219	219	219				80
transit	2	III	140		140	140	140				102
stop	80	III	269		269	269	269				135
departure	II	25	93					219			117
departure	IV	5					94		240	240	218
transit	IV	5					107		137	137	108
transit	IV	55		223	126	126	119	223	205	205	375

Table 43: Interdiction times matrix in Scenario 4

PESI			Scenario				
			0	1	2	3	4
transit	52	III	0	0	0	0	1
stop	22	I	7	7	8	8	8
stop	2	III	0	0	0	0	0
transit	2	III	2	2	4	5	5
stop	80	III	2	2	2	2	2
stop	II	25	9	9	9	9	9
stop	IV	5	0	0	0	0	0
transit	IV	5	4	4	4	5	5
transit	IV	55	0	0	0	0	1

Table 44: Weights matrix

The computation of the interdiction times has taken into account the subsequent hypotheses:

- Elastic release of the entities
- Length of trains equal to:
    - Regional: 250 meters
    - High Speed: 350 meters
    - Freight: 750 meters
- Constant acceleration and deceleration:
    - Regional: 0.525 m/s2
    - High Speed: 0.375 m/s2
    - Freight: 0.225 m/s2
- Constant stop time for Regional trains equal to 60 seconds
- Train departure and arrival in correspondence of main signal at end of platform
- Time for route formation equal to 60 seconds

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