



SIMULATION FOR RAILWAY CAPACITY DETERMINATION

An incremental capacity approach on the case study of the insertion of the Lisbon – Madrid High-Speed corridor on the Portuguese railway network

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Abstract

The increase reliance on private sector funding for transportation projects has emphasized the importance of accurate demand forecasts. Demand forecasts are essential for assessing financial feasibility of transportation projects as well for the planning process of a transportation system. The traditional approach for capacity planning of a transportation system is deterministic and irreversible, becoming inflexible to deal with uncertainty in demand forecasts.

This study addresses the construction of a new High-Speed line under budget constraints, using the Portuguese part of the Lisbon – Madrid High-Speed rail corridor as a case study. This document will focus on the question of planning a complex railway system, composed of conventional and High-Speed infrastructures and services, in a way to solve capacity constraints as traffic demand increases. In this specific case study the high values of the investments together with the financial crisis have forced the authorities to look for alternative solutions to implement the project. The proposed approach enables to postpone part of the investments, mitigating the risks of demand forecasts errors, since each capacity improvement step is optional, thus allowing to deal with budget constraints in an initial stage of the project.

This study enables to identify the Lisbon Metropolitan Area railway sections as the ones with capacity shortages. Since this is an area where the Portuguese High-Speed project comprises high value investments, and where the impacts in commercial speed of High-Speed trains due to the usage of a conventional infrastructure are smaller, this document focus on solving the capacity constraints that arise from the insertion of this rail corridor on the Portuguese railway network as the High-Speed traffic increases. However, in a medium to long term perspective, this High-Speed rail corridor should evolve to a solution with a dedicated infrastructure, in order to be a more competitive mode in relation to other transportation modes, being capable to generate and to attract demand.

An overview of the definitions of railway capacity and the main parameters affecting railway capacity are presented, followed by an insight into the state of the art in railway capacity evaluation methodologies. From the various approaches to determine railway capacity, the UIC leaflet 406 method is chosen to perform a preliminary evaluation of the capacity consumption and a simulation method is chosen to determine railway capacity on the bottleneck sections and to evaluate a set of scenarios for incremental capacity improvements. OPENTRACK software was used to perform the simulation.

The simulation results allowed to perform a capacity evaluation of each scenario, and to establish a set of different strategies for the infrastructure development as demand for High-Speed services increases.

Keywords: Railway Capacity, Simulation, High-Speed Train, Incremental Capacity Approach, UIC leaflet 406

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Glossary

ALT	<i>Alvito-A Station</i>
BCH	<i>Bifurcação de Chelas Junction</i>
BNS	<i>Bobadela Sul Station</i>
BPR	<i>Braço de Prata Station</i>
CDA	<i>Campolide Station</i>
CHE	<i>Chelas Station</i>
EPO	<i>Entrecampos-Poente Station</i>
ETC	<i>Entrecampos Station</i>
GSM-P	Portable GSM communication system
LSA	<i>Lisboa Santa Apolónia Station</i>
MOE	<i>Moscavide Station</i>
MVA	<i>Marvila Station</i>
ORI	<i>Lisboa Oriente Station</i>
PRN	Portuguese Railway Network
PRNO	Portuguese Railway Network in Operation
RAR	<i>Roma-Areeiro Station</i>
RSC	<i>Rádio Solo-Comboio TTT CP N Communication System</i>
SAC	<i>Sacavém Station</i>
SRI	<i>Sete Rios Station</i>

1. Introduction

1.1 Background

The increase reliance on private sector funding for transportation projects has emphasized the importance of accurate demand forecasts. Demand forecasts are essential for assessing financial feasibility of transportation projects as well for the planning process of a transportation system. The traditional approach for capacity planning of a transportation system is deterministic and irreversible, becoming inflexible to deal with uncertainty in demand forecasts.

Historically, demand forecasts in rail projects have displayed a significant optimism bias. For example, Fitch (2010) observed deviations from the initial forecast in 84% of a sample of rail projects, from which 90% were on the side of overestimation.

In this way, new approaches in the planning process of a railway system are needed, in order to reduce the risks related to uncertainty in demand forecasting. The recent financial crisis has emphasized the need for new design approaches. With this in mind, this study strives to explore a new design process in the development of the Portuguese part of the Lisbon – Madrid High-Speed rail corridor in order to solve capacity constraints as traffic demand increases.

1.2 Problem Formulation

This study addresses the construction of a new High-Speed line under budget constraints, using the Portuguese part of the Lisbon – Madrid High-Speed rail corridor as a case study. This document will focus on the question of planning a complex railway system, composed of conventional and High-Speed infrastructures and services, in a way to incrementally increase infrastructure capacity as demand increases. Instead of the traditional planning approach where the design process aims to provide capacity to the expected long term demand, this study will explore the prospect of an incremental capacity approach of the railway infrastructure as demand increases. It is important to be said that the impact of the studied solutions in travel times will not be analyzed, and consequently the analysis of the effects in demand for High-Speed services will not be evaluated.

This approach will be applied in a specific case study where the high values of the investments together with the financial crisis have forced the authorities to look for alternative solutions to implement the project. The proposed approach enables to postpone part of the investments, mitigating the risks of demand forecasts errors, since each capacity improvement step is optional, thus allowing to deal with budget constraints.

1.3 Objective and Methodology

The main objective of this study is to develop and evaluate intermediate scenarios for incremental capacity improvements for the case study of the Portuguese part of the Lisbon – Madrid High-Speed rail corridor.

To achieve this, an examination on the state of the art in railway capacity evaluation methodologies is needed. Next, this study aims to perform a global capacity assessment of the Portuguese Rail Network in Operation (PRNO), allowing the identification of the sections with capacity shortage. The careful examination of those sections, called of critical sections in this study, allows to diagnose the causes for the lack of capacity, which are an important input for the formulation of scenarios for the incremental capacity improvements.

To accomplish the stated objectives, the following methodology is followed:

1. Identification of a study area, creating a spatial research reference through the delimitation of the Portuguese Railway Network in Operation.
2. Capacity analysis of the study area for a preliminary evaluation of the current usage, allowing the identification of the critical sections concerning capacity consumption.
3. Identification of scenarios for incremental capacity improvements in the critical sections.
4. Detailed simulation of the operations of each scenario.
5. Capacity and performance evaluation of each scenario based on the results of the simulation.

1.4 Structure of the Thesis

This document presents in chapter 2 an introduction to the fundamentals in railway infrastructure and operations planning, followed by an overview regarding the incremental capacity approach proposed in this study, in chapter 3.

In chapter 4, this document gives an overview of the definitions and main parameters affecting railway capacity, followed by a presentation of the state of the art in railway capacity evaluation methodologies.

Chapter 5 gives a brief introduction on the Portuguese High-Speed project and on the Portuguese Railway Network, followed by the definition of the study area and identification of the critical sections through a capacity evaluation.

In chapter 6 the identification and simulation of the scenarios for incremental capacity improvements in the critical sections is performed followed by a capacity and performance evaluation of each scenario.

Finally, chapter 7 draws some conclusions based on the analysis performed in previous chapters and leave some hints for further researches in this topic.

The structure of this document is summarized in Figure 1.1.

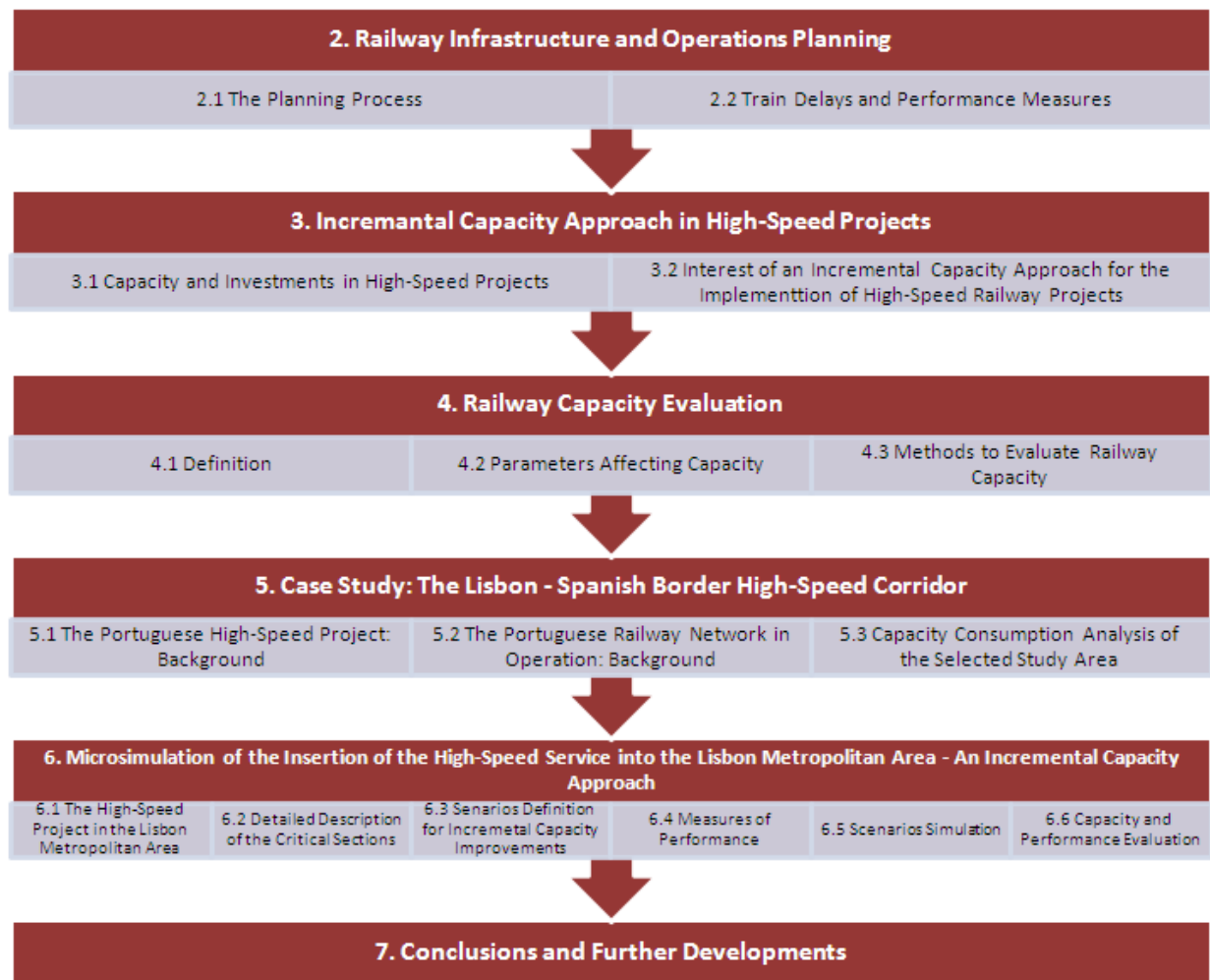


Figure 1.1- Structure of the Thesis

2. Railway Infrastructure and Operations Planning

2.1 The Planning Process

As in other sectors, in the railway planning process three planning levels can be identified: the strategic level, the tactical level and the operational level.

The strategic level is the first planning level and deals with forecasting future demand and transport network design. This is a long-term planning and the decisions at this level result in large scale investments, such as infrastructure or rolling stock investments. At a tactical level, the focus is on resource allocation planning. This is a mid-term planning, and it deals with timetable planning, rolling stock scheduling and crew scheduling. The operational level is a short-term planning and it deals with daily resources re-allocation due to unexpected causes (Goverde, 2005).

The railway planning process is summarized in Figure 2.1.



Figure 2.1 – Railway Planning Process

This thesis aims to deal with a partial strategic and tactical planning of a railway system, namely the rail network planning, the line system planning and the timetable planning.

2.1.1 Strategic Planning

The strategic planning level is composed by three stages: transport demand, rail network and line planning.

Transport demand determination is the first step of the strategic railway planning. It aims to forecast the future travel demand and it is the input for the next strategic planning stages (Goverde, 2005).

The **rail network** design is the step where the infrastructure network is defined. Line extensions, new stations or new lines are defined in this step. Multiple alternatives should be evaluated according to technical and economical factors, and decisions are mainly based on political reasoning (Bussieck et al. 1997).

The last step in the strategic planning is the **line planning**. In this step the trains services types are defined according to their routes, origin stations, destination stations, stopping stations and services frequencies. The connections between each service and travel times are also set up in this stage (Goverde, 2005).

2.1.2 Tactical Planning

In the tactical planning level, three planning stages can be distinguished: the railway timetable planning, the rolling stock scheduling and the crew scheduling.

Timetable is the process of scheduling arrival and/or departure times in each station on a train route, taking into account all technical and commercial constraints, such as the safety and signaling systems rules and train connections (Goverde, 2005). In practice timetable construction is performed by allocation of a time-space path to each trip, and specifying the track used in each station (Peeters, 2003). All train path conflicts due to absence of minimum headways times or other signaling conflict must be eliminated (Goverde et al. 2008).

The schedule times in each station is determined by calculation of the technically minimum trip time, which is the minimum trip time of a train if traveling at the maximum speed allowed. To ensure that small delays are absorbed, a recovery time is added to the technically minimum trip time (Peeters, 2003). In Portugal, the recovery time changes from 5% to 7% of the technically minimum trip time. Additional times can also be added in order to compensate time losses due to long-term speed restrictions and to eliminate train path conflicts.

The **rolling stock scheduling** is the process of assigning rolling stock to trips (Bussieck et al. 1997).

The last stage of the tactical planning is the **crew scheduling**. It consists of assigning the train crew to each trip (Goverde, 2005).

2.1.3 Operational Planning

In **operational planning** the rescheduling of timetable, rolling stock and crew planning is performed in order to face the real-time execution. This is influenced by unexpected events such as rolling stock breakdowns, accidents, timetable disturbances, crew shortages, or other incidents (Bussieck et al. 1997).

2.2 Train Delays and Performance Measures

2.2.1 Train Delays

During regular operations of a railway system, unforeseen events will occur, leading to train delays. Depending on the cause, delays can be classified into two classes: primary delays and secondary delays (Goverde, 2005).

Primary delays are delays caused by disturbances in the railway system, which can have several sources. Vromans (2005) identifies the following main sources of disturbance:

- Planning mistakes in timetable construction, rolling stock scheduling and crew scheduling;
- Infrastructure failures in the tracks, switches, electrification system and signaling system;
- Rolling stock due to malfunctioning traction, engine, brakes, doors, etc.;
- Human factors such as train drivers behavior;
- Accidents with other traffic such as accidents in rail-road crossings or suicides; The presence of humans and cattle along the track are also usual events, and cause speed restrictions;

- Vandalism in rolling stock or infrastructure elements
- Passengers due high passenger influx, support to disabled customers, aggressions or non-paying passengers;
- Weather conditions can cause infrastructure breakdowns or speed restrictions.

Secondary delays are delays caused by the delay of another train. Secondary delays arise from mutual hindering of trains due to conflicting train paths, and synchronization of trains due to passenger connections, rolling stock scheduling and crew scheduling (Goverde, 2005).

A main feature of primary delays is the unavoidability of their occurrence. On the other hand, secondary delays can be managed and reduced. The occurrence of secondary delays is bigger in a highly used and interconnected network (Goverde, 2005).

2.2.2 Performance Measures

Reliability, robustness and stability are three concepts frequently used in the railways industry and literature when describing the performance of a railway system.

The broad meaning of **reliability** is the ability of a system to perform and maintain its functions. Vromans (2005) says that a system is reliable if *“the trains run properly on time”*, if *“only a small portion of the trains has delays or is not operated at all”*, and if *“both the average delay and the variation in the delays are low”*.

Robustness indicates how much a railway system is affected by external influences. This means that a system is not robust if disturbances can cause large delays which propagate throughout the system (Stok, 2005), causing secondary delays.

Goverde (2005) defines **stability** as the *“the possibility and effort necessary of returning to the steady state after disruptions”*. A system is stable if can recover quickly from a disturbance, and unstable otherwise.

In this study the evaluation of the railway system is done from the reliability point of view. There are several performances measures to evaluate the reliability of a railway system. Vromans (2005) uses the following reliability performance measures:

- **Punctuality** gives the percentage of trains that arrives or departures within a certain threshold from the scheduled time. Punctuality can also be measured as a weighted punctuality according to the number of passengers in each train.

The main drawback with punctuality is that this performance measure does not give information about the amount of delays.

- **Transfer punctuality** is the percentage of planned train connections that are maintained during operations. Such as in punctuality, transfer punctuality can also be weighted according to the number of passengers per transfer.
- **Canceled trains** are the number of trains that are cancelled due to unforeseen events. Usually, cancelled trains lead to large passenger delays and may cause train delays due to additional transfers.
- **Average train delay** is the measure that gives the average of all deviations from the scheduled time.
- **Average passenger delay** is the measure that gives the average delay experienced by passengers.

Bediru (2012) identifies also other statistical measures of interest to evaluate the reliability of a railway system:

- **Standard deviation** gives the dispersion of delays from their mean value.
- **Coefficient of variation** gives the ratio of the standard deviation of delays to the mean delay.

3. Incremental Capacity Approach in High-Speed Projects

3.1 Capacity and Investments in new High-Speed Lines

Capacity problems and the need to increase commercial speeds are linked with the origin of High-Speed Railway. Due to rail congestion, Japan began the operation of the Tokyo/Osaka line in 1964. The new line had a total extension of 515 km and maximum speeds of 210 km/h, which later were increased to 270 km/h.

The same reason led France to develop their first High-Speed Railway project, the TGV during the 60's and 70's. The *LGV Sud-Est* line began the operation in 27 September 1981, linking Paris and Lyon. It was the first European High-Speed line in operation and attracted a large market share, becoming a financial success.

Germany began High-Speed operations in 1991, with the ICE service. Spain, Italy, Netherlands, Belgium and United Kingdom have also developed High-Speed Railway networks.

The AVE, the Spanish High-Speed Railway system, started the service in 1992, with the Madrid/Seville line. With six more lines completed, today Spain has the largest High-Speed railway network in Europe.

The first High-Speed Lines were built as national projects, which led to the development of national technology standards, aiming the resolution of bottlenecks on the national networks. As national projects, the High-Speed networks followed different strategies in each country. If in France the High-Speed service was operated on a dedicated infrastructure, in Germany the option was the integration of the High-Speed service with the conventional railway lines (Nash & Weidmann, 2008). The option taken by some countries to operate in a dedicated infrastructure is not only due to capacity problems in the conventional railway lines, but arises also from the need to achieve time travels capable to compete with other transportation modes.

In order to overcome the lack of strategy in the transportation network, in 1992 the White Paper establishes a common transport policy. The Treaty of Maastricht introduced the Trans-European Network – Transport (TEN-T), which defines the main international corridors and international connections in the transport network. Thirty priority projects are selected, from which fourteen concern High-Speed Lines, showing that today the development of a common High-Speed Railway network is a goal of the European Union. The High-Speed Railway axis of southwest Europe, which includes the case study of this dissertation, ensures the continuity of the railway network between Portugal and Spain to the rest of Europe, is the European Union priority project number 3 (European Commission, 2010).

3.2 Interest of an Incremental Capacity Approach for the Implementation of High-Speed Railway Projects

Historically, demand forecasts in rail projects have displayed a significant optimism bias. For example, Fitch (2010) observed deviations from the initial forecast in 84% of a sample of rail projects, from which

90% were on the side of overestimation. Some examples of High-Speed projects with overestimated forecasts are listed below:

- The Eurotunnel project, where real demand totaled 45% of the forecast for the opening year.
- The French *Atlantique* line, where real demand fell short by around 25% in the first year of operations and by around 10% in the after ramp up period (3 to 6 years).
- The French *Nord* line, where real demand fell short by around 65% in the first year of operations and by around 50% in the after ramp up period.
- The French *Rhone-Alpes* line, where real demand fell short by around 15% in the first year of operations and by around 2% in the after ramp up period.
- The French *Méditerranée* line, where real demand fell short by around 10% in the first year of operations and by around 8% in the after ramp up period.
- The Spanish *Madrid – Barcelona* line, where the real demand fell short by around 5% in the first year of operations and by around 19% in the fourth year of operations.

In this way, new approaches in the planning process of a railway system are needed, in order to bring flexibility into the design, reducing the risks related to uncertainty in demand forecasting.

The common design practice in railway systems is to provide capacity for the forecasted demand. The problem with this approach is that future is uncertain and the design demand may not match the real demand. One way to address this problem is to incorporate flexibility in the design process. This way to address the problem is called a Flexible Design approach.

Cardin (2007) states that flexibility allows managers to adapt a system to unexpected circumstances in an efficient way. This means that a flexible system can adapt more efficiently towards changing environments, increasing the overall value and performance of the system.

Giving flexibility to a project prepares the system to uncertain conditions, giving several options to managers. Kalligeros (2006) categorizes those options:

- **Option to defer the investment or investment choice** giving the possibility to obtain more information about the uncertain variables.
- **Option to abandon** the project if the evolution of the uncertain variables is extremely unfavorable to the project.
- **Option to grow** the capacity of a system if the evolution of uncertain variables is favorable to the project.
- **Option to switch inputs or outputs** enabling the decision maker to adjust the inputs or outputs through the observation of the evolution of uncertain variables.

- **Options to alter operating scale** enabling to decrease temporarily the production in order to match a demand reduction. These are reversible options, which allow resuming the production in the future.
- **Combinations of the above options** since most of the projects involves several of the options mentioned before.

Flexibility can be achieved through the definition of a catalog of operating options suited for several uncertain variable scenarios (Cardin, 2007). Instead of choosing the initial design, this approach deals with demand uncertainty by creating several staged scenarios for incremental capacity improvements that are implemented if demand evolution is favorable. Therefore, first stage scenarios with lower capacity are generated, with the possibility of future expansion if demand is high. Those lower capacity scenarios have the advantage of being smaller investments than the initial design, which are expanded only if demand is high.

Volatile markets have given rise to alternative design approaches in order to deal with uncertainty. In an incremental design approach of a railway capacity improvement project, reliable and robust capacity evaluation methodologies are needed in order to develop staged operating plans.

4. Railway Capacity Evaluation

4.1 Definition

Railway capacity depends on several factors and it is a complex concept with a hard definition. An example of this complexity can be found in the UIC definition, which states that *“capacity as such does not exist”* (UIC, 2004). UIC (2004) develops a little further and clarifies that *“railway infrastructure capacity depends on the way it is utilized”* and the main *“basic parameters underpinning capacity are the infrastructure characteristics themselves and these includes the signaling system, the transport schedule and the imposed punctuality level”* (UIC, 2004). It finally concludes that *“the capacity of any railway infrastructure is the total number of possible paths in a defined time window, considering the actual path mix or known developments respectively and the Infrastructure Manager own assumptions”*.

For UIC (2004), *“on a given rail infrastructure, capacity is based on the interdependencies existing between”* the number of trains and their average speed, the stability goal of a timetable and the heterogeneity of trains.

Given the complexity underlying railway capacity, there is not a common and unique definition. Burdett & Kozan (2006) define capacity as *“the maximum number of trains that can transverse the entire railway or a certain critical section in a given duration of time”*. Abril et al. (2007) has a similar view and defines capacity as the *“maximum number of trains that would be able to operate on a given railway infrastructure, during a specific time interval, given the operational conditions”*.

Barter (2008) states that capacity should be measured according to the punctualities and performance targets. In fact, quality of operations is an important aspect of the capacity definition, since higher number of trains result in higher risk of delays (Landex, 2008). Landex (2008) argues that railway capacity depends on the railway infrastructure, on the operating plan (timetable and rolling stock scheduling) and on the operation quality goal.

For the purpose of this study, capacity is understood as the maximum number of trains that can be operated in a railway line or section, given the railway infrastructure, the timetable and the operation performance goals. This is usually called the **Practical Capacity**, since it is a realistic measure of railway capacity, with realistic assumptions regarding the train mix (different average speeds) and the expected operating quality. In railways it is also common to distinguish Theoretical Capacity, Used Capacity and Available Capacity. **Theoretical Capacity** gives an upper limit on the maximum number of trains, if operated in ideal conditions. The **Used Capacity** is the traffic volume that runs on a railway line or section. Finally, the **Available Capacity or Unused Capacity** is the difference between Practical Capacity and Used Capacity. Since not all Available Capacity can be used for additional train paths due to heterogeneity of trains, the Available Capacity is composed by a **Useful Capacity**, if new train paths can be added, and **Lost Capacity**, otherwise (Abril et al. 2007).

4.2 Parameters Affecting Capacity

There are several elements in a railway system which impacts the capacity of a rail section or network. Kontaxi and Ricci (2010) distinguish them in infrastructure parameters, operational parameters and traffic effects.

Kontaxi and Ricci (2010) identify the following infrastructure parameters:

- **Number of tracks** in a section is a basic parameter affecting capacity. One way to improve capacity is to increase the number of tracks in a section.
- The **distance between two crossing stations or two passing stations** is a critical parameter with impact on capacity. In single track sections, trains can only cross or overtake other trains in stations and in double track sections fast trains can only overtake slower trains in stations.
- **Maximum speed** determines the journey time and the block occupation time.

The authors identify the following operational parameters:

- The **operational model** implemented namely the timetable and train path chosen and the technical specifications for temporal and spatial separations between trains to perform the required crossing and overtaking operations.
- The **rolling stock features** such as traction power, braking capability, length and weight of the trains, among others, which determine the running time.
- **Traffic typology** with different speed profiles is a fundamental parameter to determine capacity, since it affects the Lost Capacity.
- The **headway** is the spatial distance between two following trains. With lower headways it is possible to obtain higher railway capacity.

The traffic effects identified by Kontaxi and Ricci (2010) with impact on capacity are the following:

- The **generation and propagation of delays** produced under operations reduce the capacity of a railway section.
- As mentioned before, the **required and expected quality of service** impacts capacity. With higher quality requirements, the Practical Capacity decreases to ensure the performance goals.

It is also to be noted that the reference time used to determine railway capacity as also an impact on railway capacity. Typically the time window used to determine railway capacity is the whole day or only the peak periods.

4.3 Methods to Evaluate Railway Capacity

There are several methods to evaluate railway capacity. Usually, in literature three subsets of methods are distinguished: the analytical methods, the optimization methods and the simulation methods.

Simulation for Railway Capacity Determination

An incremental capacity approach on the case study of the insertion of the Lisbon – Madrid High-Speed corridor on the Portuguese railway network

The **analytical methods** are the simplest methods for determining railway capacity. They usually obtain Theoretical Capacity through algebraic expressions, while Practical Capacity is obtained as a percentage of the Theoretical Capacity. Although the analytical methods are a good starting point to identify bottlenecks, the results are extremely dependent on the used method since different variables are taken into account (Abril et al. 2008).

Until 2004, the UIC leaflet 405 of 1983 (revised in 1996) method was recognized as the standard method to evaluate railway capacity, and it takes into account the number and order of trains. The main criticism is that it does not establish a link between capacity and railway performance quality (Abril et al. 2008).

More recently Burdett and Kozan (2006) developed other approaches to evaluate theoretical capacity, which incorporate several factors, such as the mix of trains, the signal locations and dwell times.

A review of analytical methods is presented by Abri et al. (2008) and it can be seen that several authors have formulated analytical methodologies with the incorporation of different parameters. Those methodologies are very raw simplifications of reality, and therefore should only be used for preliminary solutions.

The **optimization methods** use mathematical programming techniques to obtain better solutions to the capacity problem than the analytical methods. A widely used method is saturation, which obtains capacity by scheduling the maximum number of train paths, starting either from an empty or an initial base timetable (Abril et al. 2008).

Abril et al. (2008) considers the UIC 406 methodology as an optimization method. This is the most largely international accepted methodology which obtains railway capacity through timetable compaction and saturation. Landex (2008) describes a detailed application of the UIC method in the Danish railway network.

Abril et al. (2008) presents a review of optimization methods where several mathematical programming techniques are used. For instance, capacity problem can be modeled as a Job-Shop Scheduling Problem. Other authors use heuristics, such as algorithms to assign trains to the timetable in order to find an optimal allocation to maximize capacity, whereas others use local search, tabu search, genetic or hybrid heuristics, to find feasible solutions to the capacity problem.

The **simulation methods** are reproductions of the real world operations that are used to test solutions (Abril et al., 2008). There are several available commercial simulation tools that simulate rail traffic with different inputs and outputs data. Abril et al. (2008) presents the main features of the following simulation tools:

- DEMIURGE is the software used by SNCF, and it has capabilities to evaluate a network's capacity to absorb additional traffic, to locate bottlenecks, to calculate Unused Capacity of a timetable and to assist decision makers in future infrastructure investments.

- CMS from AEA Technology Rail is a system to plan railway Used Capacity through an automatic generation of timetables, which provides an easy scenario analysis.
- RAILCAP from Stratec gives an evaluation of the Used Capacity by a given timetable.
- VIRIATO from SMA and Partners is a tool mainly used for the development of future service concepts and gives the saturation rate of a railway section by compressing a given timetable
- CAPRES developed by Lucchini and Curchod in 2001 is a model for the elaboration and saturation of timetables, and determines all the available train paths.
- FASTTRACK II is software developed by Multimodal Applied Systems and it is used to determine the feasibility of a timetable given a track configuration, measuring both the Theoretical Capacity and Practical Capacity.
- MULTIRAIL is another software developed by Multimodal Applied Systems which traces train path conflicts
- OPENTRACK is software developed by OpenTrack Railway Technology used to answer questions about railway operations through the simulation of train movements under the constraints of the signaling system and timetable.
- SIMONE is a simulation model developed by Incontrol Enterprise Dynamics designed to determine the robustness of a timetable, to identify bottlenecks and to analyze the causes and effects of delays.

Kontaxi & Ricci (2010) present a comparative analysis concerning the functionality of 37 simulation tools. From this analysis the most fitted software to perform capacity analysis are CMS, DEMIURGE, IRCIM, MOM MALLAS, RAILCAP and RAILSYS, since they have the possibility to evaluate directly the Theoretical Capacity, Practical Capacity, Used Capacity and Available Capacity. CAPRES tool, which can determine Theoretical Capacity and Available Capacity, FAST TRACK II and RAILSIM tool, which can determine Theoretical Capacity and Practical Capacity are also presented as tools capable to perform capacity evaluations.

Finally, Kontaxi & Ricci (2010) present CASSANDRA, OPENTIMETABLE and SAMFOST tools as capable to determine Theoretical Capacity, RAILNET II and RAILSIM tools as able to determine Available Capacity, RASIM and SIMONE as able to determine Used Capacity.

It is also to be noted that Kontaxi & Ricci (2010) analysis was not able to determine the capacity evaluation ability in some simulation tools, such as OPENTRACK or MULTIRAIL.

In conclusion, although the application of analytical methods followed by optimization methods are good starting points for preliminary evaluations of railway capacity, a simulation method is needed to perform in depth capacity evaluations in railway networks.

5. Case Study: The Lisbon – Madrid High-Speed Corridor

5.1 The Portuguese High-Speed Project: Background

The Portuguese High-Speed Rail project has 5 axes: the Lisbon – Madrid axis, the Lisbon – Oporto axis, the Oporto – Vigo axis, the Aveiro – Salamanca axis and the Évora – Faro – Huelva axis, from which the first three are considered to be the priority axes. In 2003 and 2005 the Portuguese and Spanish Governments have established agreements for the international links in the Portuguese High-Speed Project.

The Lisbon – Madrid project comprises a 604 km High-Speed line of mixed traffic and has a maximum speed of 350 km/h. The travel time between Lisbon and Madrid is expected to be 2 hours and 45 minutes. The Portuguese section of this line has 207 km, and includes 3 stations: the Lisbon station, the Évora station and the international station of *Elvas/Badajoz*. The operations were planned to start in 2013.

The business model of this axis was disaggregated in 2 PPP's for the design, build, financing and maintenance (DBFM) of the rail substructure and superstructure, excluding the signaling and communications systems, for a period of 40 years. The first PPP concerns the section of Poceirão – Caia, and has an estimated cost of 1411 M€. The second PPP concerns the section of Lisbon – Poceirão and has an estimated cost of 928 M€.



Figure 5.1 - The Portuguese HSR Project

The connection between the port of Sines and the High-Speed Line is also included in the project.

In 2012, the Portuguese Government decided to postpone the project to a date to be set. The future of the Portuguese HSR remains uncertain and it is not clear if the decision is to cancel or postpone the entire or only part of the project.

5.2 The Portuguese Railway Network in Operation: Background

The Portuguese Railway Network (PRN) covers the majority of the Portuguese territory and has a full length of 3.618,792 km.

Not the entire PRN meets the minimum standards for running trains. The part that meets the minimum requirements for running trains is called the Portuguese Railway Network in Operation (PRNO), and has a full length of 2.613,299 km, from which 2.003,364 km are a single track sections and 609,935 km are a multiple track sections.

In the PRNO there are several systems being used concerning the track gauge, signaling, electrification, maximum weight, loading gauges and communications. The PRNO is used by 4 railway

undertakings: CP and FERTAGUS as passenger railway undertakings and CP CARGA and TAKARGO as freight railway undertakings. Those rail undertakings run approximately 2000 trains per day.

The following subchapters intend to summarize the main infrastructure systems in the PRNO and to describe its current usage.

5.2.1 Infrastructure's Main Features

5.2.1.1 Track Gauges

Currently there are two track gauges in use in the PRNO, a broad gauge, named as Iberian gauge, and a narrow gauge. The Iberian gauge, of 1.668 mm, is the most common gauge in the PRNO and it is used in 2.490,989 km of the PRNO. The narrow gauge, of 1.000 mm, is used only in 112,310 km of the PRNO.

5.2.1.2 Signaling and Safety Systems

Railway networks are equipped with safety and signaling systems which avoid the occurrence of accidents and collisions between trains. The railway infrastructure is divided into blocks, and the signaling systems ensure that there can be only one train in a block at any time. Additionally, trains are also equipped with safety systems that complement the signaling system, avoiding human errors or technical failures.

In the PRNO there are several signaling and safety systems in use. The three basic signaling systems are the phone block signaling system, the simplified phone block signaling system and the automatic block signaling system.

The phone block signaling is a signaling system used mainly in single track sections where train dispatching is performed by a movement authority located in the begin and end of each block. Each block starts and ends at a railway station, equipped with switches which enable train crossings and overtaking.

The simplified phone block signaling system is used only in single tracks sections where the train dispatching is made by a single movement authority which control all blocks.

In the automatic block signaling system the blocks are divided by signals which control the train movements between each signal. The automatic block signaling can be labeled as single directional or bi-directional, depending if it allows train movements in only one direction or in both directions.

The automatic blocking system is used in 1.639,480 km of the PRNO, while the phone block signaling and the simplified phone blocking systems are still used in 973,819 km.



Figure 5.2 - PRNO

In complement to the signaling system, the Automatic Train Protection is the main safety system in a railway network. In the PRNO there are two types of Automatic Train Protection systems: the CONVEL system and the automatic braking system. The CONVEL system (EBICAB700) prevents trains to exceed the speed limits, with the main purpose to increase safety levels. This system is composed by wayside devices (usually called balises) that communicate with on-board equipment which allow the supervision of the train speed. If the train driver does not obey the speed limits, the system stops the train. The automatic braking system is an older safety system that works using magnetos devices to stop a train when a train driver does not obey a stop sign indication. Unlike CONVEL system, the automatic braking system does not supervises the train speed.

In respect to the safety systems, the CONVEL system is installed in 1612,735 km of the PRNO, whereas the automatic braking system is used is only used in the *Cascais* Line, in a total length of 25,450 km.

5.2.1.3 Electrification Systems

There are 1.629,154 km lengths of railway sections in the PRNO with electrification systems available for rail traction.

The majority of the electrified sections in the PRNO, 1.603,704 km, use a system with a voltage of 25 kV of alternating current with a frequency of 50 Hz, using catenary as a contact system. The exception is in the *Cascais* Line, where it is used a system with a voltage of 1500 V of direct current, supplying the trains through a catenary.

5.2.1.4 Maximum Load

The broad gauge tracks are classified according to their maximum axle load and load per meter. The Table 5.1 summarizes the PRNO maximum load classification, which is based on the UIC leaflet 700.

The majority of the PRNO sections are classified as D4 concerning the maximum load. Some secondary sections of the PRNO are classified as D2, B2, B1 and A. Those sections are located in *Douro* Line, *Alfarelos* Line, *Oeste* Line, *Beira Baixa* Line and *Algarve* Line.

5.2.1.5 Loading Gauges

In the PRNO there are three loading gauges profiles: the narrow loading gauge, the CPb loading gauge and the CPb+ loading gauge.

Classification	Axle Load [T/axle]	Linear Load [T/m]
A	18	5
B1	18	5
B2	18	6,4
C2	20	6,4
C3	20	7,2
C4	20	8
D2	22,5	6,4
D3	22,5	7,2
D4	22,5	8

Table 5.1 – PRNO Maximum Load Classification

The CPb+ is the most common loading gauge in the PRNO, while the CPb is used in sections of *Minho* Line, *Oeste* Line, *Beira Baixa* Line, *Alentejo* Line, *Algarve* Line and in the entire *Cáceres* and *Leste* Lines. The *Vouga* Line is the only section of the PRNO classified as narrow loading gauge.

5.2.1.6 Communication Systems

Currently there are several systems being used in the PRNO that allow the communication between trains and the traffic control centre, such as:

- *Rádio Solo-Comboio* TTT - this system is used in *Cascais* Line and allows voice communications
- *Rádio Solo-Comboio* TTT CP N (RSC) - this system allows voice and data communications and it is used in 1.480,254 km of the PRNO.
- Portable GSM Communication System (GSM-P) - this system uses the GSM public network and allows voice communications. It is used in the section *Vendas Novas/Casa Branca* of the *Alentejo* Line and in the *Évora* Line.

5.2.2 Infrastructure Usage

There are 4 rail undertakings in the PRNO which run approximately 2000 trains per day. Those trains can be classified according to their service type. For the purpose of this project the trains are classified into 7 classes: international, long distance, regional, urban, freight, passenger empty trains and freight empty trains.

All the passenger trains are included in the international, long distance, regional or urban services. The international services are all the passenger trains with international origins/destinations. The long distance services are passenger trains that link Lisbon to the major Portuguese cities. The regional services are passenger trains that exist through all the PRNO and their main features are the low average speed and the large number of stops. The urban services are passenger trains that provide regular commuting trips between Lisbon, Porto and Coimbra and its suburban areas.

All freight trains types are integrated in the freight service, which includes the containers trains, multi-client trains, cars trains and bulk cargo trains (sand, ore, wood, cement, coal and steel products).

The empty trains are services types that include all trains used by operators for vehicle movements with no commercial purpose. The empty trains can be associated to passenger or freight operators.

The Figure 5.3 presents the number of trains running in the PRNO along the day per service type.

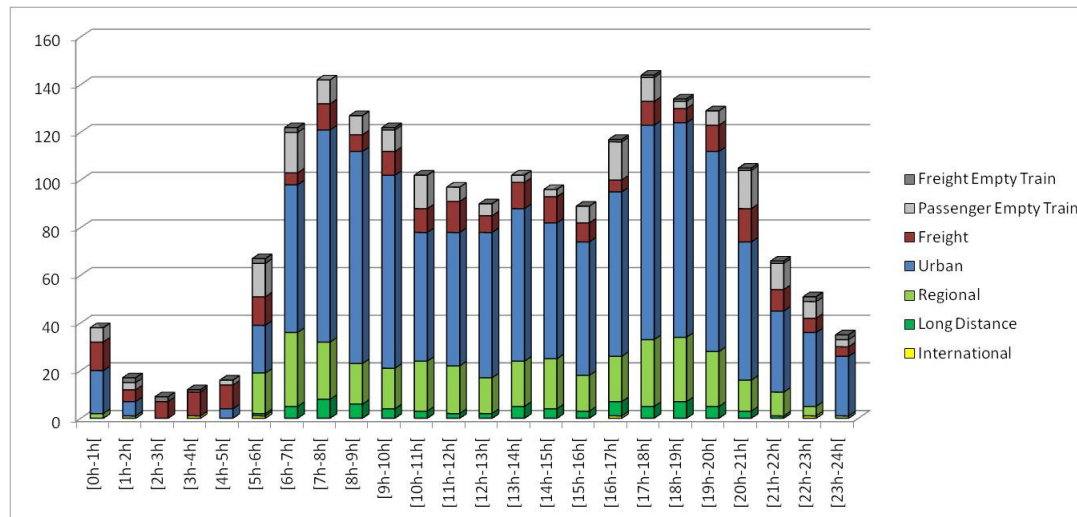


Figure 5.3 – Number of trains in the PRNO per service type and time band

As observed in Figure 5.3 the number of trains is variable along the day. The urban service is the prevailing service type with a weight of approximately 60% from the total number of trains, followed by the regional service with a weight of approximately 17% from the total number of trains. The freight trains have a weight of approximately 10% from the total number of trains and the passenger empty train service have a weight of approximately 9% from the total number of trains. The long distance service, with a weight of 3% from the total number of trains, the international service and the empty freight trains service, with a weight below 1% are the service types with the lowest number of trains.

From the Figure 5.3 it is also possible to infer that there is a clear effect of the peak hours, since the periods 6h-10h and 16h-20h are the most loaded periods.

5.3 Capacity Consumption Analysis of the Selected Study Area

5.3.1 Study Area

In order to pursue the objective of this project a study area is defined. This study area is a sub network of the PRNO and aims to include all the relevant sections that are affected by the change of patterns and flow increase generated by the connection with the Spanish High-Speed Railway Network.

The defined study area is composed by sections of the *Norte* Line, *Cintura* Line, *Sul* Line, *Alentejo* Line, *Évora* Line, *Vendas Novas* Line, *Poçoirão* Line and *Sines* Line.

With the proposed study area it is possible to capture all the main train movements when coming from or heading to Spain and perform a capacity consumption analysis on the affected sections.



Figure 5.4 - Study Area

5.3.2 Infrastructure Features

In this chapter a description of the study area infrastructure is performed concerning the systems identified in the previous chapter.

This information is resumed in the table presented in Appendix 1 – Detailed Features of the Study Area Infrastructure.

5.3.2.1 Norte Line Sections

In the Norte Line it is possible to identify 4 sections with a total length of 102,310 km and with distinct features among themselves: *Braço de Prata/Alverca*, *Alverca/Castanheira do Ribatejo*, *Castanheira do Ribatejo/Santana-Cartaxo Resguardo* and *Santana-Cartaxo Resguardo/Entroncamento*.

The features for each of those sections are:

- ***Braço de Prata/Alverca* Section**

Braço de Prata/Alverca is a section of 17,818 km, composed by a quadruple broad track, with bi-directional automatic block signaling. This section is electrified with a voltage of 25 kV of alternating current with a frequency of 50 Hz.

It is classified as D4 concerning the maximum load, and as CPb+ in relation to the loading gauges.

This section is equipped with RSC communication system.

- ***Alverca/Castanheira do Ribatejo* Section**

In this section, with a total length of 12,424 km, the *Norte* Line reduces the number of tracks to a triple broad track.

All the other parameters remain unchanged, which means that it is an electrified section (voltage of 25 kV of alternating current with a frequency of 50 Hz), equipped with a bi-directional automatic block signaling, classified as a D4 and as a CPb+ section concerning the maximum load and loading gauges, and it is equipped with RSC communication system.

- ***Castanheira do Ribatejo/Santana-Cartaxo Resguardo* Section**

Castanheira do Ribatejo/Santana-Cartaxo Resguardo is a section with a total length of 28,952 km, where the *Norte* Line reduces the number of tracks to a double broad track.

All the other parameters remain unchanged, with an electrification system with a voltage of 25 kV of alternating current with a frequency of 50 Hz, equipped with a bi-directional automatic block signaling, classified as a D4 and as a CPb+ section concerning the maximum load and loading gauges, and it is equipped with RSC communication system.

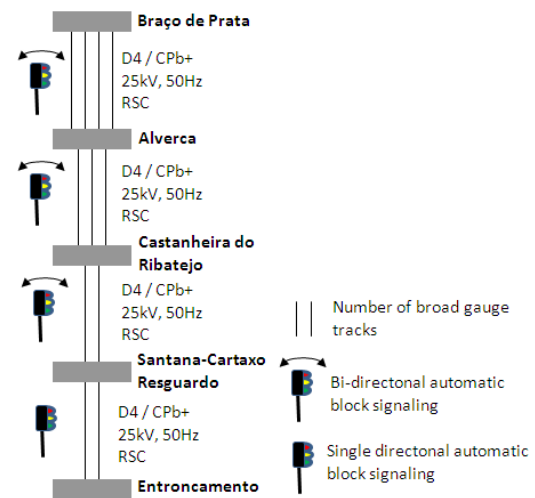


Figure 5.5 – Norte Line Sections Detailed Features Diagram

- **Santana-Cardaxo Resguardo/Entroncamento Section**

In this section, with a total length of 43,116 km, the *Norte* Line changes the signaling system to a single directional automatic block signaling.

The section remains as double broad track, with an electrification system with a voltage of 25 kV of alternating current with a frequency of 50 Hz, classified as a D4 and as a CPb+ section concerning the maximum load and loading gauges, and it is equipped with RSC communication system.

5.3.2.2 Cintura Line Sections

In the *Cintura* Line it is possible to identify 3 sections with a total length of 7,626 km and with distinct features among themselves: *Campolide A/Sete Rios*, *Sete Rios/Terminal Técnico de Chelas* and *Terminal Técnico de Chelas/Braço de Prata*.

The features for each of those sections are:

- **Campolide A/Sete Rios Section**

Campolide A/Sete Rios is a section of 1,140 km, composed by a double broad track, with bi-directional automatic block signaling. This section is electrified with a voltage of 25 kV of alternating current with a frequency of 50 Hz.

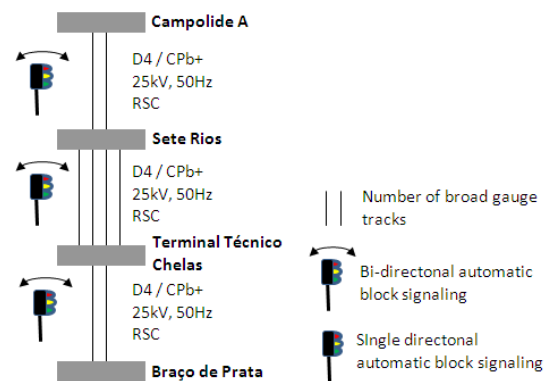


Figure 5.6 –*Cintura* Line Sections Detailed Features Diagram

It is classified as D4 concerning the maximum load, and as CPb+ in relation to the loading gauges, and it is equipped with RSC communication system.

- **Sete Rios/Terminal Técnico de Chelas Section**

In this section, with a total length of 3,650 km, the *Cintura* Line increases the number of tracks, becoming a quadruple broad track.

All the other parameters remain unchanged, with an electrification system with a voltage of 25 kV of alternating current with a frequency of 50 Hz, equipped with a bi-directional automatic block signaling, classified as a D4 and as a CPb+ section concerning the maximum load and loading gauges. It is equipped with RSC communication system.

- **Terminal Técnico de Chelas/Braço de Prata Section**

In this section, with a total length of 2,836 km, the *Cintura* Line reduces the number of tracks to a double broad track.

This section remains with an electrification system with a voltage of 25 kV of alternating current with a frequency of 50 Hz, equipped with a bi-directional automatic block signaling, classified as a D4 and

as a CPb+ section concerning the maximum load and loading gauges. It is equipped with RSC communication system.

5.3.2.3 Sul Line Sections

In the *Sul* Line it is possible to identify 4 sections with a total length of 121,450 km and with distinct features among themselves: *Campolide A/Alvito A*, *Alvito A/Pragal*, *Pragal/Pinhal Novo* and *Bifurcação de Águas de Moura Sul/Ermidas-Sado*.

The features for each of those sections are:

- **Campolide A/Alvito A Section**

Campolide A/Alvito A is a section of 2,552 km, composed by a double broad track, with bi-directional automatic block signaling. This section is electrified with a voltage of 25 kV of alternating current with a frequency of 50 Hz.

It is classified as a D4 concerning the maximum load, and as a CPb+ in relation to the loading gauges, and it is equipped with RSC communication system.

- **Alvito A/Pragal Section**

In this section, with a total length of 5,100 km, the *Cintura* Line has a reduction on the maximum load allowed. The maximum load is 20,4 t/axle and varies between 1,74 t/m and 4,08 t/m, depending on the train type and composition. The maximum total weight also varies between 695 t and 1408 t depending on the same factors. These constraints are related with the *25 de Abril* bridge.

All the other parameters remain unchanged, since the section remains as a double broad track, with an electrification system with a voltage of 25 kV of alternating current with a frequency of 50 Hz, equipped with a bi-directional automatic block signaling, classified as a CPb+ section concerning loading gauges and it is equipped with RSC communication system.

- **Pragal/Pinhal Novo Section**

Pragal/Pinhal Novo is a section with a total length of 29,506 km, where the classification concerning the maximum load is D4.

The section remains as double broad track, with an electrification system with a voltage of 25 kV of alternating current with a frequency of 50 Hz, classified as a CPb+ section concerning the loading

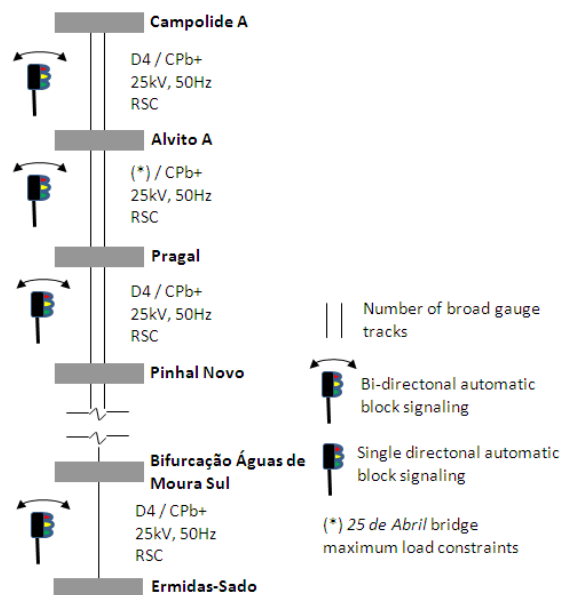


Figure 5.7 – Sul Line Sections Detailed Features Diagram

gauges and it is equipped with RSC communication system and a bi-directional automatic block signaling.

- ***Bifurcação de Águas de Moura Sul/Ermidas-Sado Section***

This section has a total length of 84,292 km in single broad track, electrified (voltage of 25 kV of alternating current with a frequency of 50 Hz) and classified as a D4 concerning the maximum load, and as a CPb+ in relation to the loading gauges.

It is equipped with a bi-directional automatic block signaling and with RSC communication system.

5.3.2.4 Alentejo Line Sections

In the *Alentejo* Line it is possible to identify 3 sections with a total length of 74,967 km and with distinct features among themselves: *Pinhal Novo/Poceirão*, *Poceirão/Vendas Novas* and *Vendas Novas/Casa Branca*.

- ***Pinhal Novo/Poceirão Section***

Pinhal Novo/Poceirão is a section of 14,968 km, composed by a double broad track, with bi-directional automatic block signaling. This section is electrified with a voltage of 25 kV of alternating current with a frequency of 50 Hz.

It is classified as D4 concerning the maximum load, and as CPb+ in relation to the loading gauges, and it is equipped with RSC communication system.

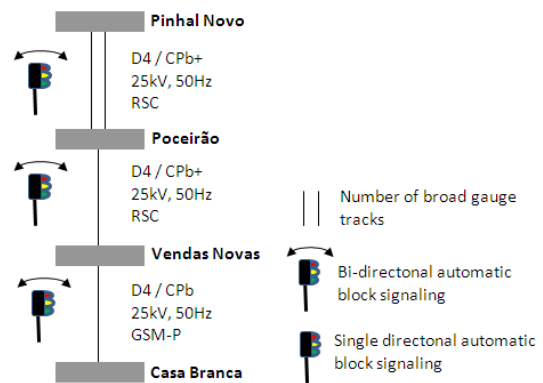


Figure 5.8 – *Alentejo* Line Sections Detailed Features Diagram

- ***Poceirão/Vendas Novas Section***

In this section, with a total length of 26,431 km, the *Alentejo* Line reduces the number of tracks to a single broad track.

This section remains with an electrification system with a voltage of 25 kV of alternating current with a frequency of 50 Hz, equipped with a bi-directional automatic block signaling, classified as a D4 and as a CPb+ section concerning the maximum load and loading gauges. It is equipped with RSC communication system.

- ***Vendas Novas/Casa Branca Section***

The *Vendas Novas/Casa Branca* is a section with a total length of 33,568 km where the classification concerning the loading gauges changes to CPb and the communication system used is the GSM-P.

This section is equipped with a bi-directional automatic block signaling and it is classified as a D4 concerning the maximum load.

The electrification system works with a voltage of 25 kV and alternating current with a frequency of 50 Hz.

It is to be noticed that due to a capacity constraint in the electrical substation of *Pegões*, the total number of simultaneous trains in this section is limited to 1. This constraint, also applicable to the *Évora* Line imposes that the section *Vendas Novas/Casa Branca/Évora* is a single block in respect to train crossings and headways.

5.3.2.5 Évora Line

The *Évora* Line (*Casa Branca/Évora*) has a total length of 26,049 km, composed by a single broad track, with bi-directional automatic block signaling. It is classified as a D4 concerning the maximum load, and as a CPb+ in relation to the loading gauges. The communication system used is the GSM-P.

This section is electrified with a voltage of 25 kV of alternating current with a frequency of 50 Hz, and the constraint identified for the capacity in the electrical substation of *Pegões* is also applied in the *Évora* Line.

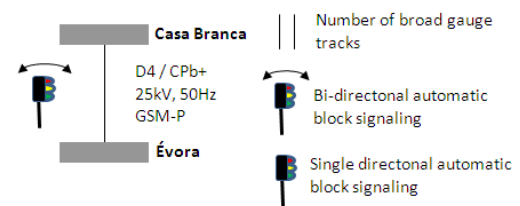


Figure 5.10 – *Évora* Line Sections Detailed Features Diagram

5.3.2.6 Vendas Novas Line

The *Vendas Novas* Line (*Setil/Vendas Novas*) has a total length of 69,609 km, composed by a single broad track, with bi-directional automatic block signaling. It is classified as D4 concerning the maximum load, and as CPb+ in relation to the loading gauges, and it is equipped with RSC communication system. This section is electrified with a voltage of 25 kV of alternating current with a frequency of 50 Hz.

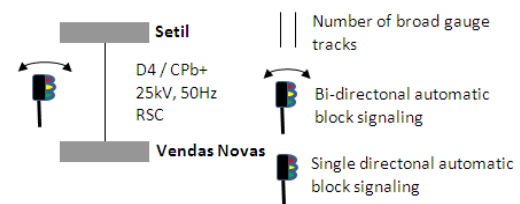


Figure 5.9 – *Vendas Novas* Line Sections Detailed Features Diagram

5.3.2.7 Poceirão Line Sections

The *Poceirão* Line links the *Alentejo* Line and the *Sul* Line. It is possible to identify 2 sections with a total length of 8,162 km and with distinct features among themselves: *Bifurcação do Poceirão/Bifurcação Águas de Moura Norte* and *Bifurcação Águas de Moura Norte/ Bifurcação Águas de Moura Sul*.

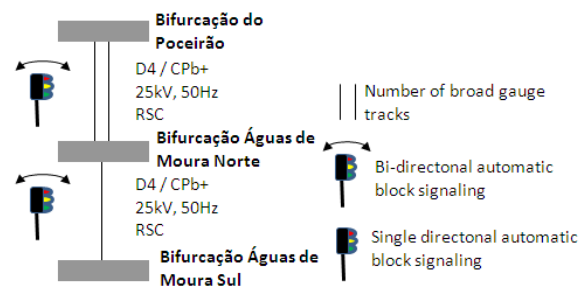


Figure 5.11 – *Poceirão* Line Sections Detailed Features Diagram

• Bifurcação do Poceirão/Bifurcação Águas de Moura Norte Section

Bifurcação do Poceirão/Bifurcação Águas de Moura Norte is a electrified (voltage of 25 kV of alternating current with a frequency of 50 Hz) double track section with a total length of 5,357 km, equipped with a bi-directional automatic block signaling

It is classified as D4 concerning the maximum load, and as CPb+ in relation to the loading gauges, and it is equipped with RSC communication system.

- **Bifurcação Águas de Moura Norte/Bifurcação Águas de Moura Sul Section**

In this section, with a length of 2,805 km, the number of tracks is reduced to a single broad track.

All the other features remain unchanged, since it has an electrification system with a voltage of 25 kV of alternating current with a frequency of 50 Hz, equipped with a bi-directional automatic block signaling, classified as D4 and as CPb+ section concerning the maximum load and loading gauges. It is equipped with RSC communication system.

5.3.2.8 Alcácer Line

The *Alcácer Line (Pinheiro/Grândola Norte)* has a total length of 29,740 km, composed by a single broad track, with bi-directional automatic block signaling. It is classified as D4 concerning the maximum load, and as CPb+ in relation to the loading gauges, and it is equipped with RSC communication system. This section is electrified with a voltage of 25 kV of alternating current with a frequency of 50 Hz.

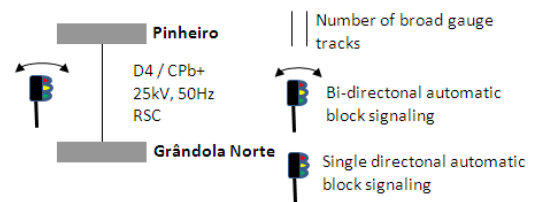


Figure 5.12 – Alcácer Line Sections Detailed Features Diagram

5.3.2.9 Sines Line

The *Sines Line (Ermidas-Sado/Porto de Sines)* has a total length of 50,539 km, composed by a single broad track, with bi-directional automatic block signaling. It is classified as a D4 concerning the maximum load, and as a CPb+ in relation to the loading gauges, and it is equipped with RSC communication system. This section is electrified with a voltage of 25 kV of alternating current with a frequency of 50 Hz.

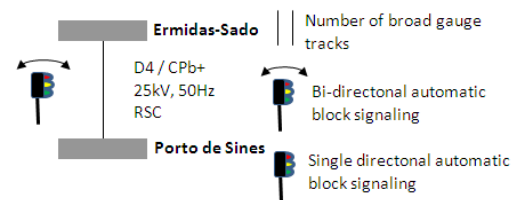


Figure 5.13 – Sines Line Sections Detailed Features Diagram

5.3.3 Infrastructure Usage

In this chapter the study area infrastructure is characterized in relation to its current usage. For this purpose the number of trains by service type and time band in each relevant section of the study area is identified. A sub section in each section is selected as sample to perform this analysis.

As defined in the chapter 5.2.2 Infrastructure Usage, the trains are classified into 7 classes: international, long distance, regional, urban, freight, passenger empty trains and freight empty trains.

5.3.3.1 Norte Line Sections

Taking into account the current timetable, the sections identified to perform this analysis in the *Norte* Line are *Braço de Prata/Lisboa Oriente*, *Lisboa Oriente/Alverca*, *Alverca/Setil* and *Setil/Entroncamento*.

- ***Braço de Prata/Lisboa Oriente* Section**

The *Braço de Prata/Lisboa Oriente* section is intensely used through almost the entire day. It is predominantly used by the urban service type and therefore there is a clear effect of the peak hours. It is also noticeable the heterogeneity of this section regarding the train service type and therefore the heterogeneity regarding train speeds.

The maximum number of trains per hour in this section is approximately 30.

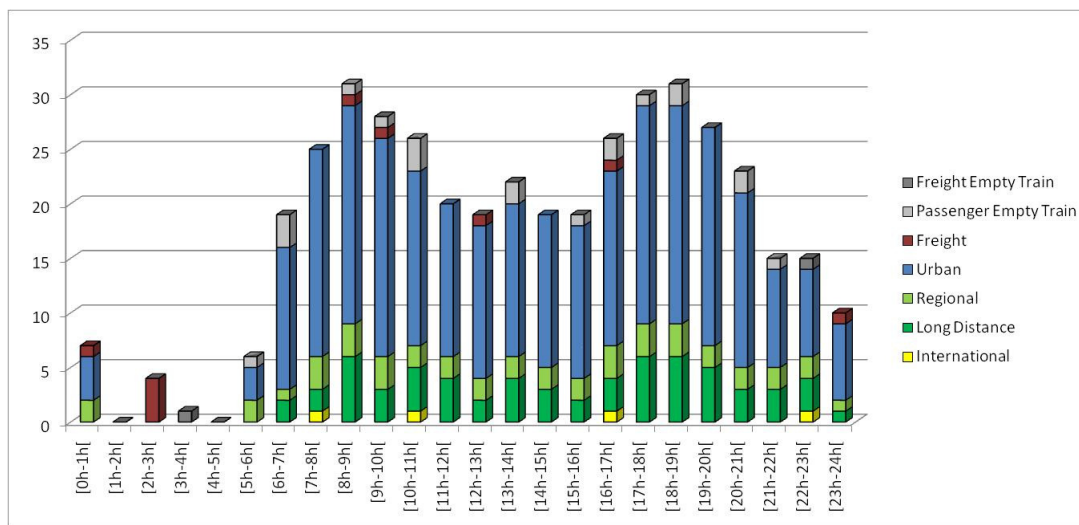
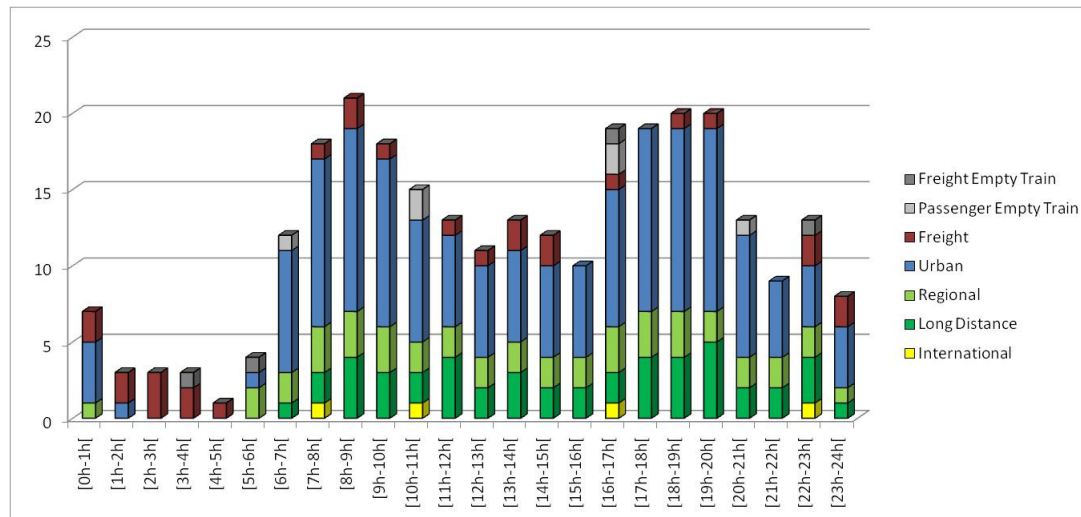


Figure 5.14 – Number of trains per service type and time band, *Braço de Prata/Lisboa Oriente* section

- ***Lisboa Oriente/Alverca* Section**

The *Bobadela S/Bobadela N* section was used as sample for the *Lisboa Oriente/Alverca* section. This section is used mainly by urban trains, and there is a reduction in the number of trains if compared with the *Braço de Prata/Lisboa Oriente*.

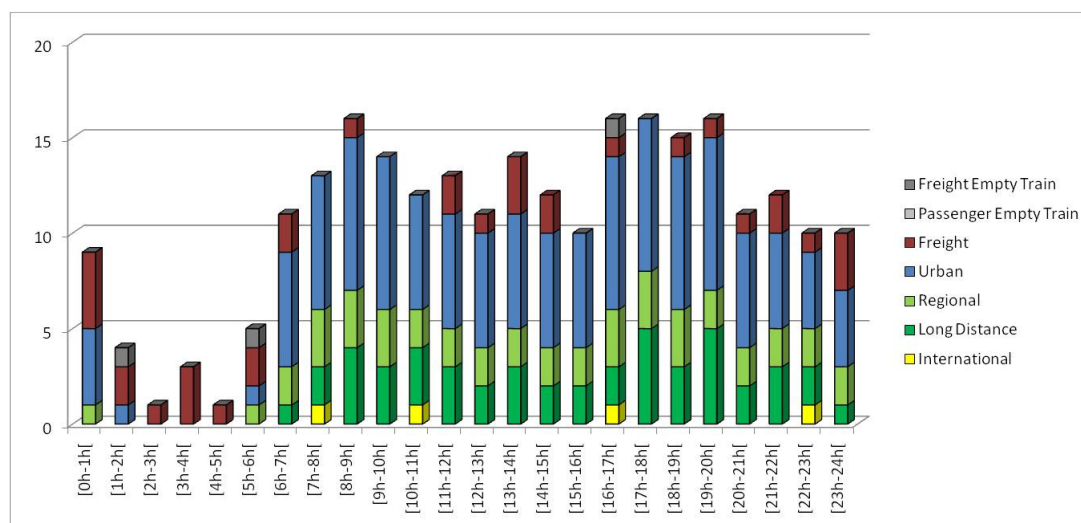
The maximum number of trains per hour in this section is approximately 20.

Figure 5.15 – Number of trains per service type and time band, *Lisboa Oriente/Alverca* section

- **Alverca/Setil Section**

The *Alverca/Alhandra* section was used as sample for the *Alverca/Setil* section. The urban trains are still prevailing, although not as clear as in previous sections. It is also noticeable the heterogeneity of this section regarding the train service type and therefore the heterogeneity regarding train speeds.

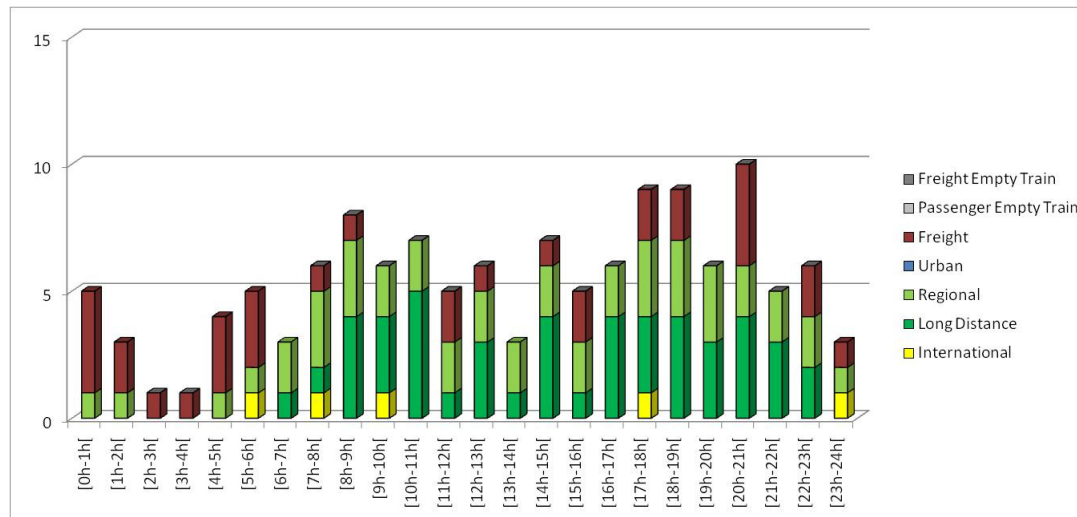
The maximum number of trains per hour in this section is approximately 15.

Figure 5.16 – Number of trains per service type and time band, *Alverca/Setil* section

- **Setil/Entroncamento Section**

The *Riachos/Entroncamento* section was used as sample for the *Setil/Entroncamento* section. In this section there are no urban trains and the prevailing services are the long distance and regional during the day and the freight in the night.

The maximum number of trains per hour in this section is approximately 10.

Figure 5.17 – Number of trains per service type and time band, *Setil/Entroncamento* section

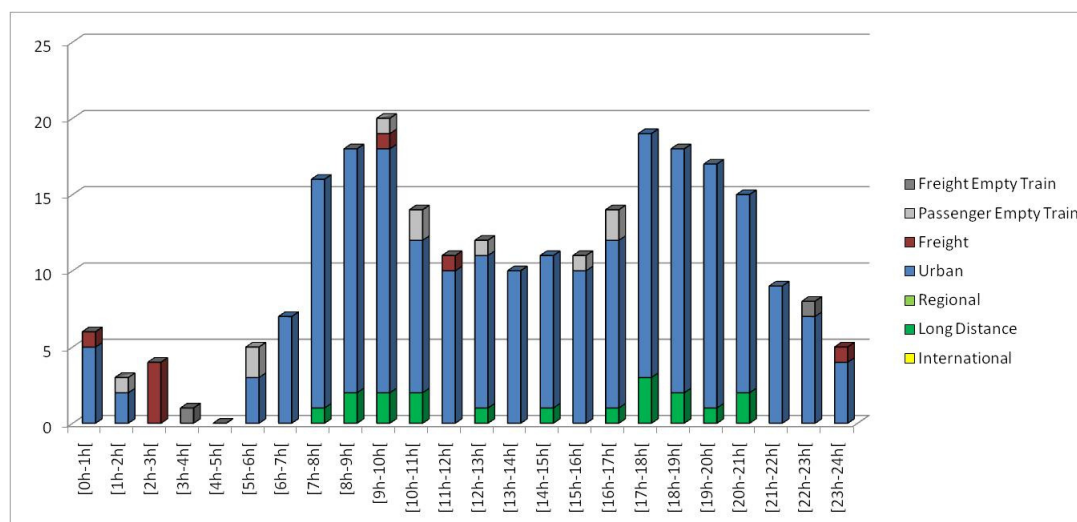
5.3.3.2 Cintura Line Sections

Taking into account the current timetable, the sections identified to perform this analysis in the *Cintura* Line are *Campolide A/Sete Rios*, *Sete Rios/Terminal Técnico de Chelas* and *Terminal Técnico de Chelas/Braço de Prata*.

• *Campolide A/Sete Rios* Section

This section is used almost exclusively by urban trains. Due to this fact the peak hours are the most loaded periods of the day.

The maximum number of trains per hour in this section is approximately 20.

Figure 5.18 – Number of trains per service type and time band, *Campolide A/Sete Rios* section

• *Sete Rios/Terminal Técnico de Chelas* Section

The *Sete Rios/Roma Areeiro* section was used as sample for the *Sete Rios/Terminal Técnico de Chelas* section. The urban trains are the prevailing service in this section, which is intensely used through almost the entire day.

The maximum number of trains per hour in this section is 33.

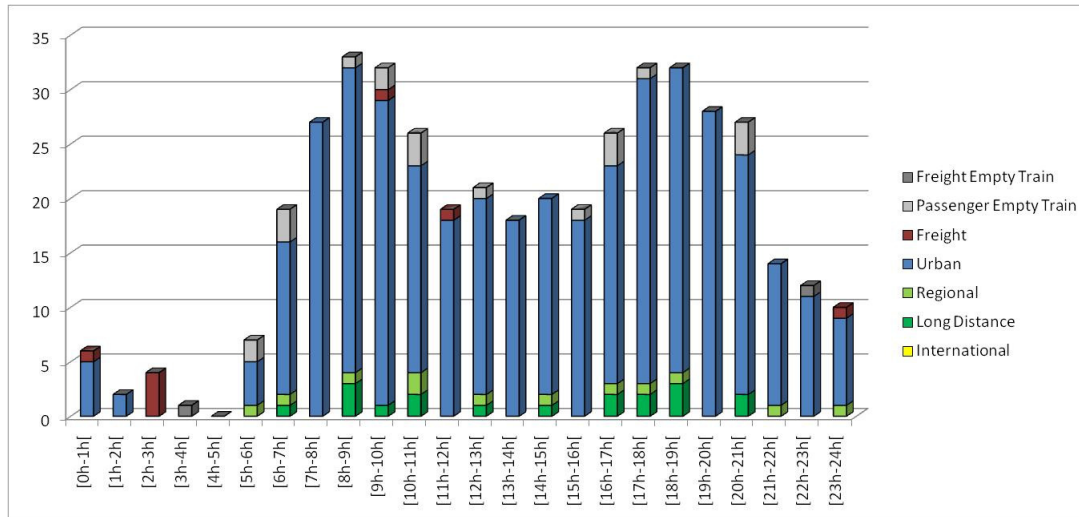


Figure 5.19 – Number of trains per service type and time band, *Sete Rios/Terminal Técnico de Chelas* section

- ***Terminal Técnico de Chelas/Braço de Prata* Section**

As in the other *Cintura* Line sections, in *Terminal Técnico de Chelas/Braço de Prata* section the urban service is the prevailing service type.

During the peak hours the total number of trains per hour reaches 20.

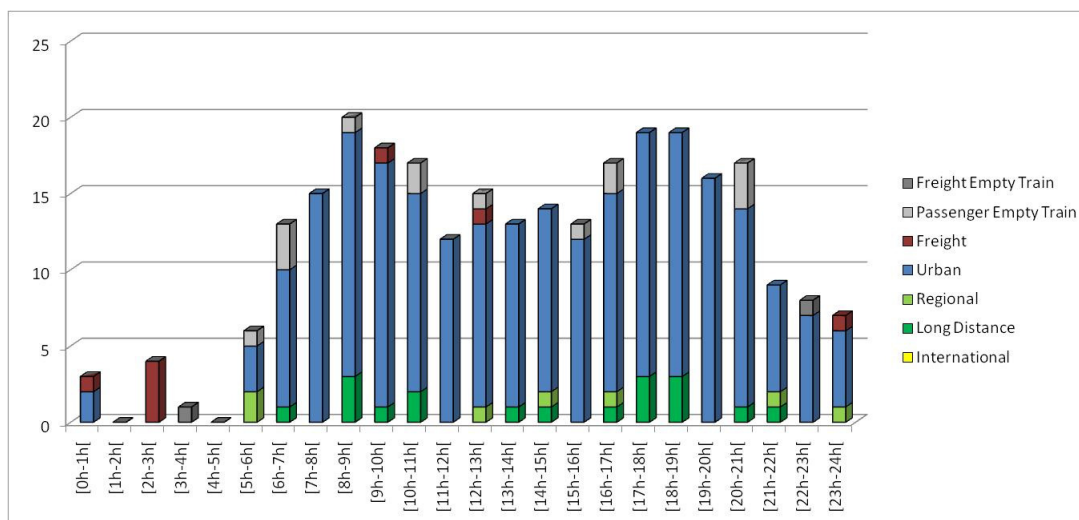


Figure 5.20 – Number of trains per service type and time band, *Terminal Técnico de Chelas/Braço de Prata* section

5.3.3.3 Sul Line Sections

Taking into account the current timetable, the sections identified to perform this analysis in the Sul Line are *Alvito A/Pragal*, *Pragal/Pinhal Novo*, *Bifurcação de Águas de Moura Sul/Pinheiro*, *Pinheiro/Grândola Norte* and *Grândola Norte/Ermidas-Sado*.

- **Alvito A/Pragal Section**

This section is used mainly by urban trains and long distance trains. The peak hours are the most loaded periods of the day, with a maximum of 15 trains per hour.

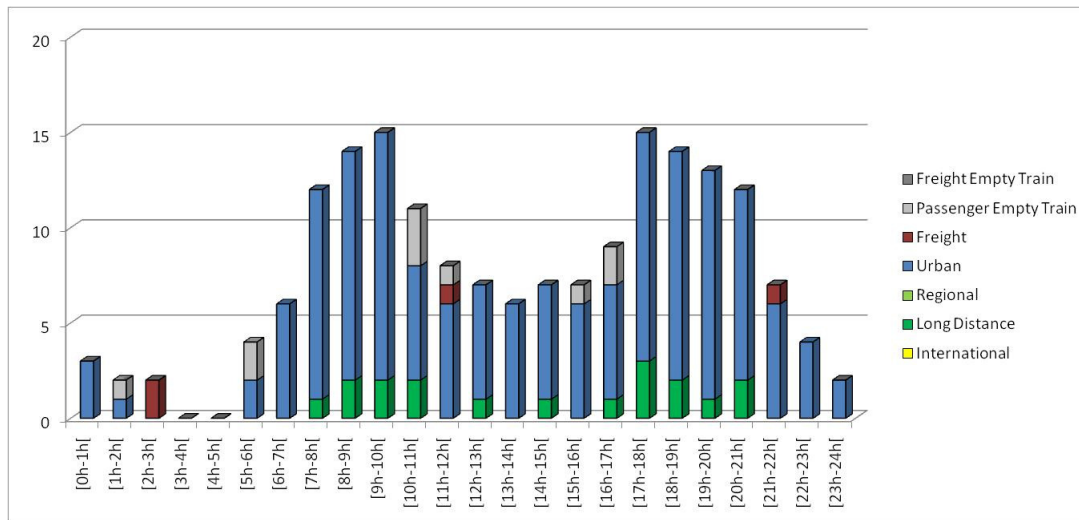
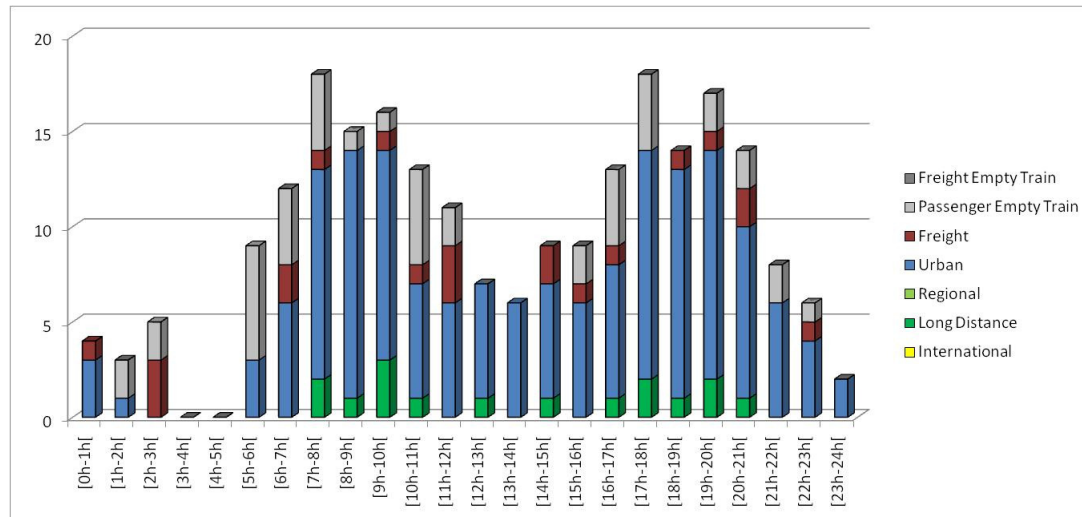


Figure 5.21 – Number of trains per service type and time band, Alvito A/Pragal section

- **Pragal/Pinhal Novo Section**

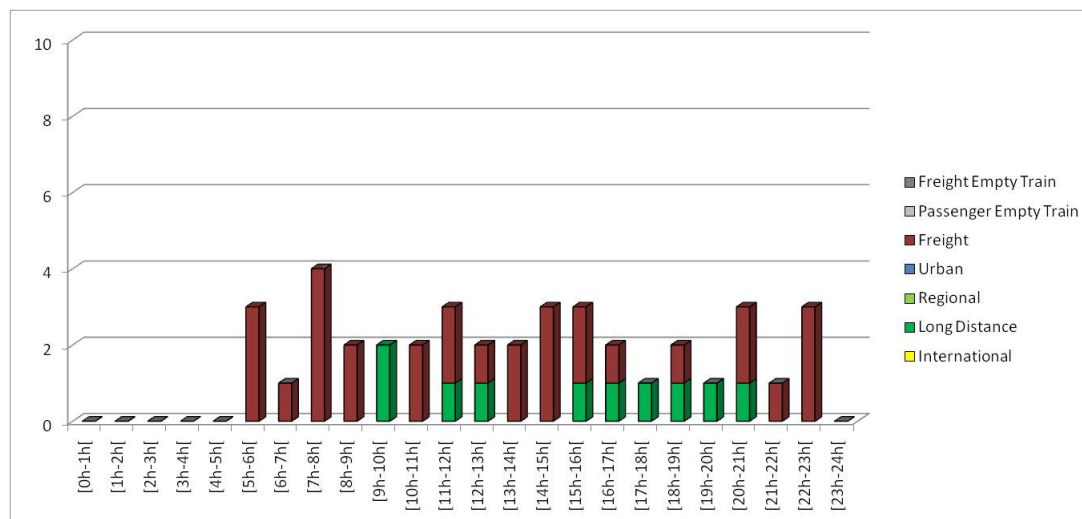
This section is used by several types of trains, although the urban trains are predominant. The peak hours are the most loaded periods of the day, with a maximum of 18 trains in an hour.

It is also noticeable the number of passenger empty trains, namely in the beginning and end of peak periods.

Figure 5.22 – Number of trains per service type and time band, *Pragal/Pinhal Novo* section

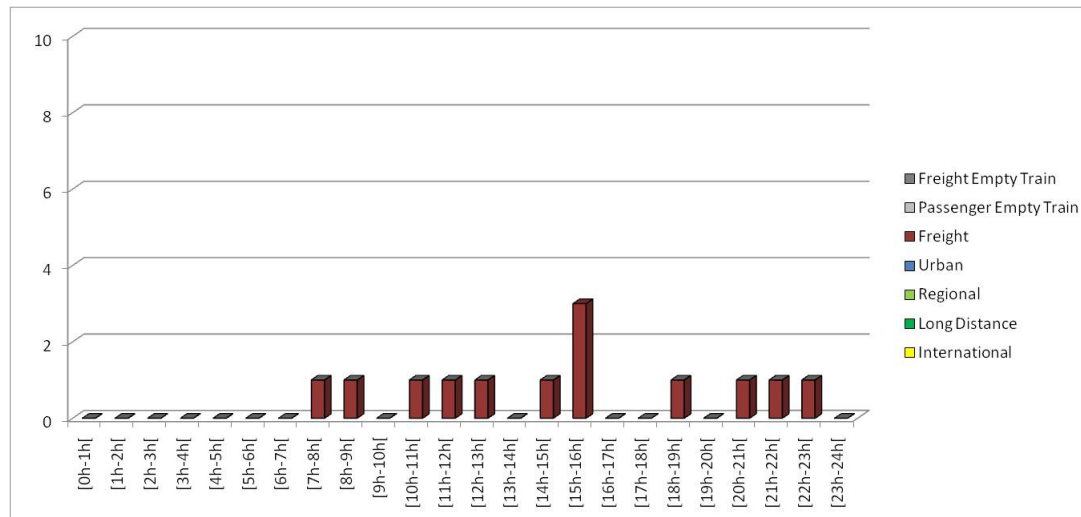
- **Bifurcação de Águas de Moura Sul/Pinheiro Section**

This section is only used by freight trains and long distance trains. The freight trains have a weight of 75% from the total number of trains, which reaches a maximum of 4 trains per hour.

Figure 5.23 – Number of trains per service type and time band, *Bifurcação de Águas de Moura Sul/Pinheiro* section

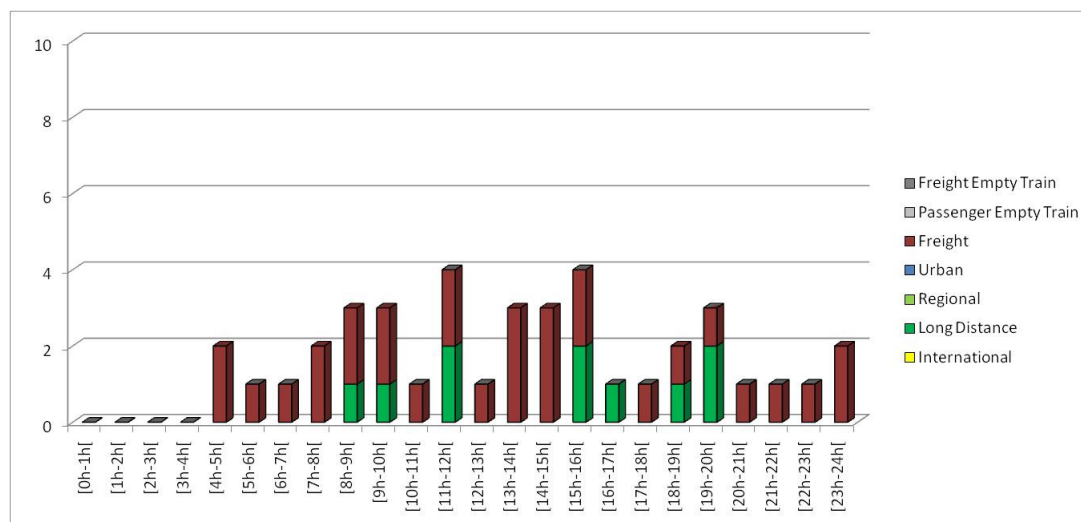
- **Pinheiro/Grândola Norte Section**

The *Monte Novo-Palma/Alcácer do Sal* section was used as sample for the *Pinheiro/Grândola Norte* section. Currently it is used exclusively by freight trains and it is possible to observe the low usage along the day. The typical value for the total number of trains per hour varies from 0 to 1, although in the time band 15h-16h it is used by 3 trains.

Figure 5.24 – Number of trains per service type and time band, *Pinheiro/Grândola Norte* section

- **Grândola Norte/Ermidas-Sado Section**

The *Canal Caveira/Lousal* section was used as sample for the *Grândola Norte/Ermidas-Sado* section. It is used by freight trains and long distance trains and its maximum usage along the day is 4 trains per hour.

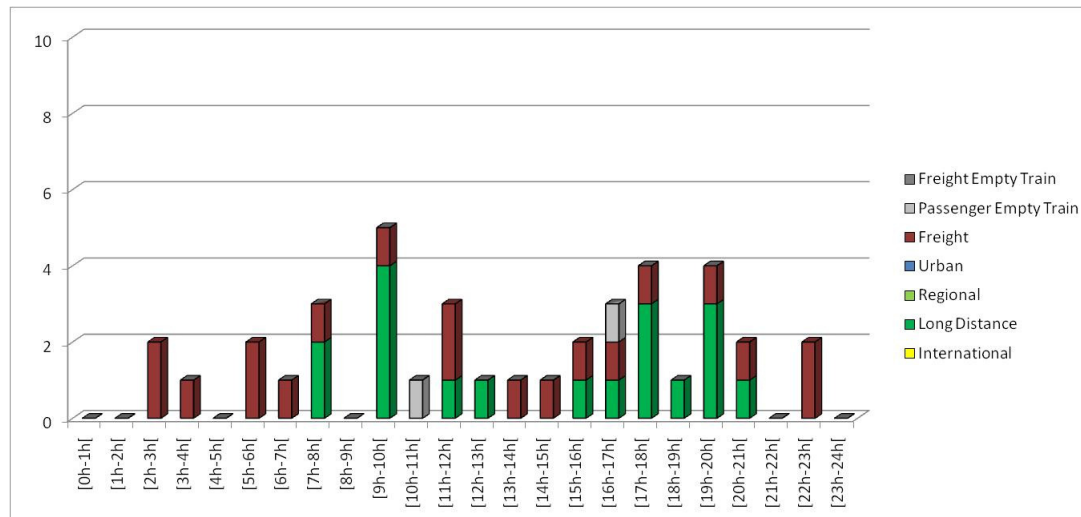
Figure 5.25 – Number of trains per service type and time band, *Grândola Norte/Ermidas-Sado* section

5.3.3.4 Alentejo Line Sections

Taking into account the current timetable, the sections identified to perform this analysis in the *Alentejo* Line are *Pinhal Novo/Poceirão*, *Poceirão/Vendas Novas* and *Vendas Novas/Casa Branca*.

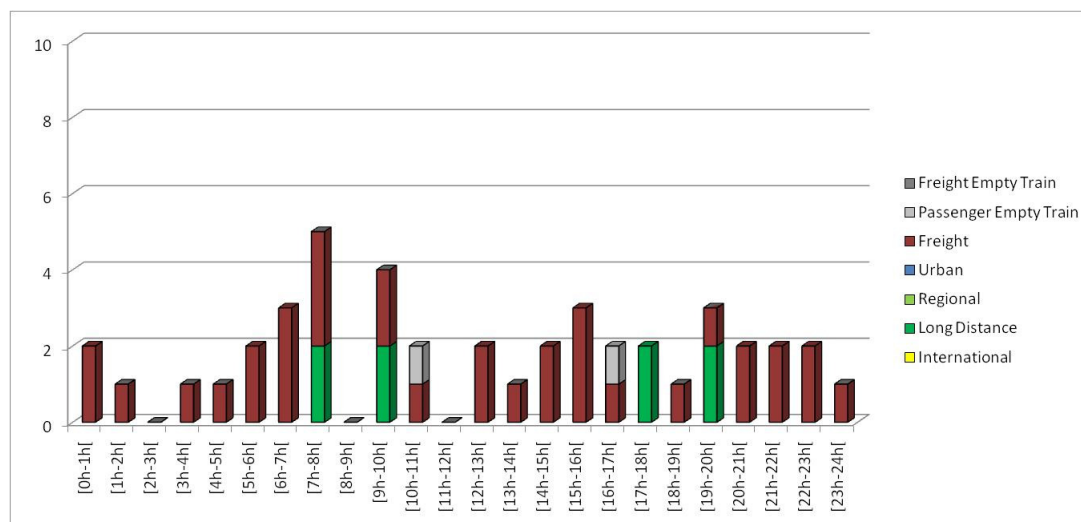
- **Pinhal Novo/Poceirão Section**

The *Pinhal Novo/Bifurcação do Poceirão* section was used as sample for the *Pinhal Novo/Poceirão* section. It is mainly used by freight trains and long distance trains and its maximum usage along the day is 5 trains per hour.

Figure 5.26 – Number of trains per service type and time band, *Pinhal Novo/Poçoirão* section

- **Poçoirão/Vendas Novas Section**

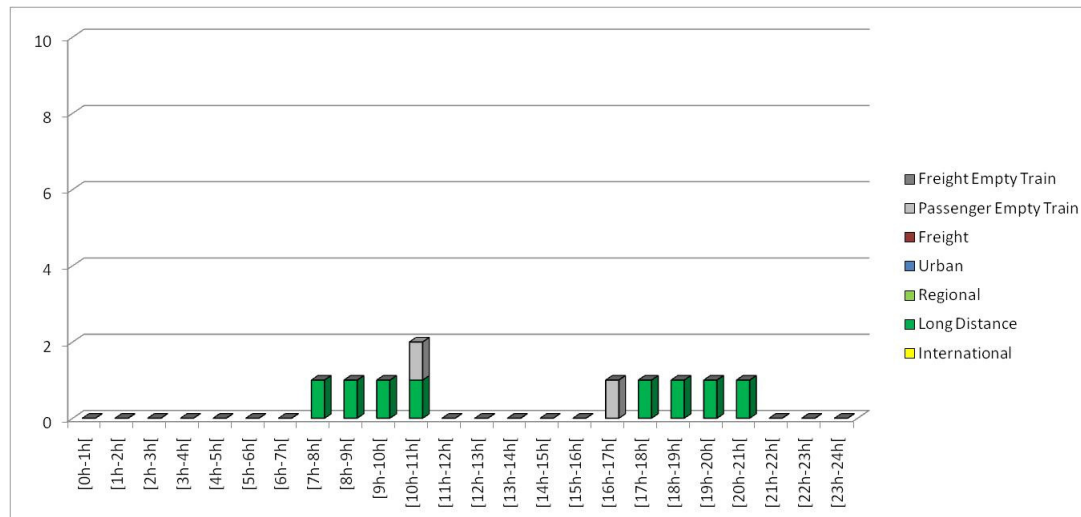
The *Poçoirão/Pegões* section was used as sample for the *Poçoirão/Vendas Novas* section. Many freight trains running on a North/South route uses this section. This is the reason why the freight service type is predominant in this section, and the maximum number of trains reaches 5 per hour.

Figure 5.27 – Number of trains per service type and time band, *Poçoirão/Vendas Novas* section

- **Vendas Novas/Casa Branca Section**

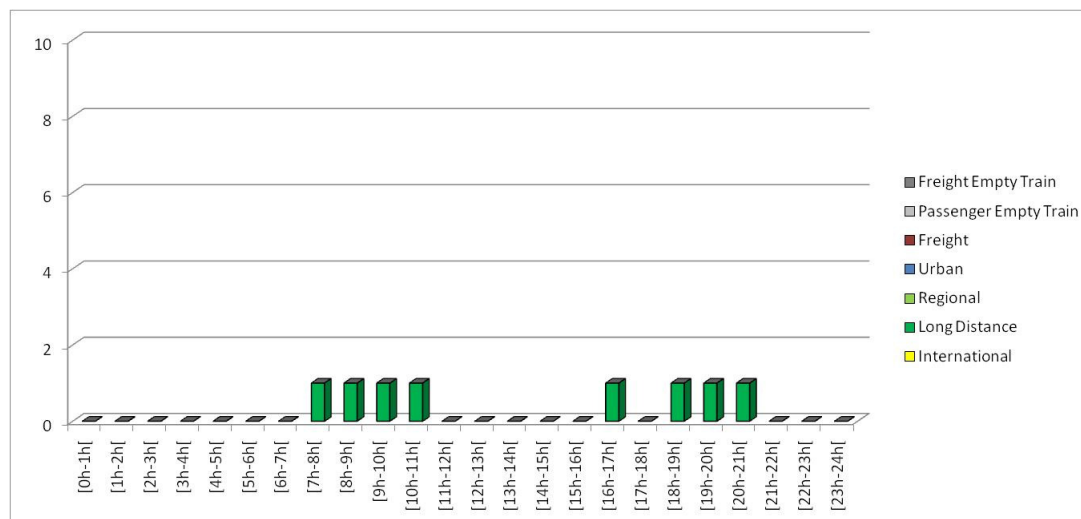
The *Vendas Novas/Torre da Gadanha* section was used as sample for the *Vendas Novas/Casa Branca* section.

This section has a very low usage, with a maximum of 2 trains in an hour.

Figure 5.28 – Number of trains per service type and time band, *Vendas Novas/Casa Branca* section

5.3.3.5 Évora Line

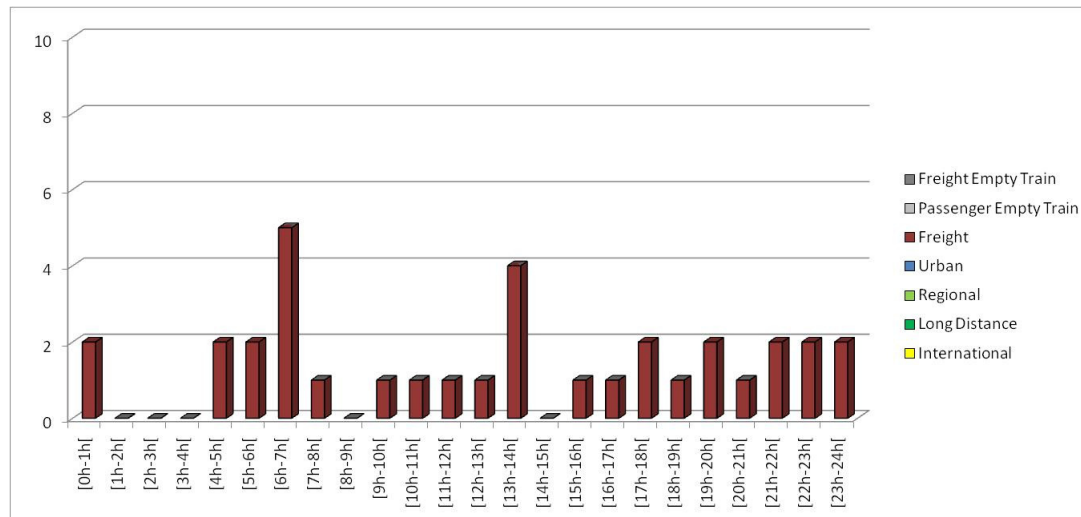
For the *Évora* Line it was used the *Casa Branca/Monte das Flores* section as a sample. It has the same low usage pattern as the *Vendas Novas/Casa Branca* section, with a maximum of 1 train per hour.

Figure 5.29 – Number of trains per service type and time band, *Évora* Line

5.3.3.6 Vendas Novas Line

For the *Vendas Novas* Line it was used the *Desvio ao km 19,5/Agolada* section as a sample. It is exclusively used by freight trains and it is a main itinerary for North/South route for freight trains.

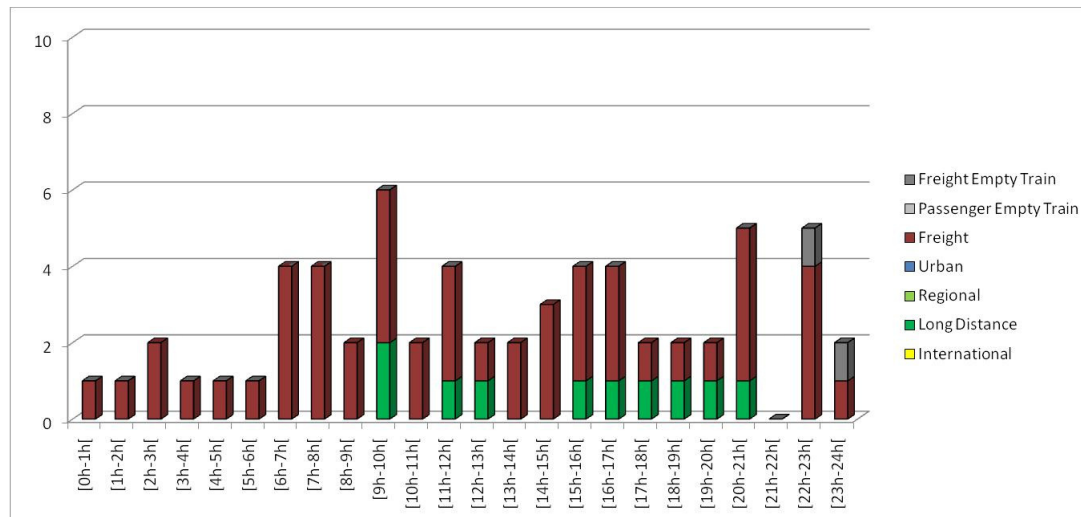
This section has a maximum of 5 trains per hour.

Figure 5.30 – Number of trains per service type and time band, *Vendas Novas* Line

5.3.3.7 Poceirão Line Sections

The *Poceirão* Line links the *Alentejo* Line with the South Line and it is the shortest path in the North/South route. The sample section used was *Bifurcação de Agualva/Bifurcação de Águas de Moura Norte*.

This line is mainly used by freight and long distance trains and there is a maximum of 6 trains running in this section in an hour.

Figure 5.31 – Number of trains per service type and time band, *Poceirão* Line

5.3.3.8 Alcácer Line

The *Alcácer* Line is the shortest North/South path and it is preferentially used by all trains with a North/South route. It is used by freight and long distance trains and there is a maximum of 4 trains running in an hour.

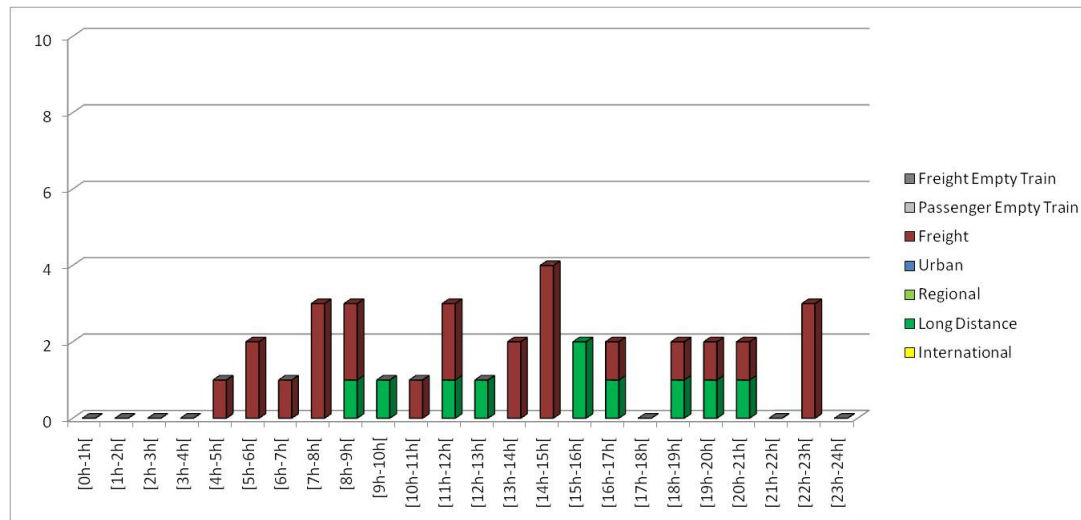


Figure 5.32 – Number of trains per service type and time band, Alcácer Line

5.3.3.9 Sines Line

The Sines Line is the access to the Port of Sines, one of the main Portuguese ports. It is only used by freight trains and there is a maximum of 3 trains running in an hour.

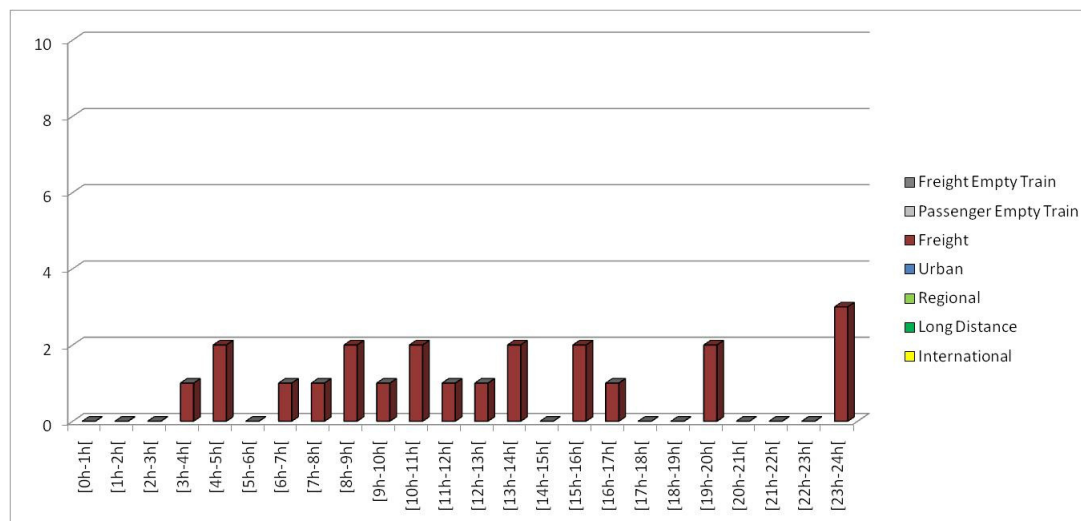


Figure 5.33 – Number of trains per service type and time band, Sines Line

5.3.4 Capacity Consumption

To measure the railway capacity consumption the UIC leaflet 406 methodology is applied. This methodology prescribes the compression of the timetable graphics so that the buffer times are equal to zero.

As it is difficult or even impossible to compress the timetable graphic for an entire network, the infrastructure should be divided into smaller line sections which easily can be handled by the UIC 406 methodology. This is the first step to measure the capacity consumption.

The next step is the selection of a time window to perform the capacity consumption calculation. Because capacity consumption varies along the day, the time window selection should be made in a careful way in order to capture a typical infrastructure usage.

After the line sections definition and the time window selection, the timetable compression is performed so that the minimum headway times and/or crossing times are satisfied.



With the timetable compression, and therefore with the minimum infrastructure occupation ratio, the capacity consumption evaluation is performed.

Figure 5.34 – UIC 406 Capacity Consumption Methodology

The Figure 5.34 summarizes the described methodology.

5.3.4.1 Line Sections Definition

For the line sections definition in the study area, both the timetable and the infrastructure features should be taken into account. With this in mind, the study area is divided into 18 sections concerning the capacity consumption analysis. The line sections are identified in Table 5.2 and Figure 5.35.

Line Sections		Line Sections	
Begin	End	Begin	End
Setil	Entroncamento	Pinhal Novo	Poçoirão
Alverca	Setil	Poçoirão	Vendas Novas
Lisboa Oriente	Alverca	Vendas Novas	Évora
Braço de Prata	Lisboa Oriente	Setil	Vendas Novas
Terminal Técnico Chelas	Braço de Prata	Poçoirão	Pinheiro
Sete Rios	Terminal Técnico de Chelas	Pinheiro	Grândola Norte (*)
Alvito A	Sete Rios	Pinheiro	Grândola Norte (**)
Alvito A	Pragal	Grândola Norte	Ermidas-Sado
Pragal	Pinhal Novo	Ermidas-Sado	Porto de Sines

(*) Through Sul Line

(**) Through Alcácer Line

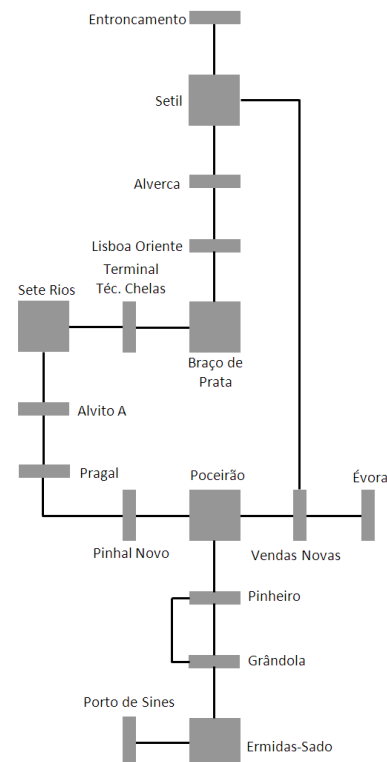


Table 5.2 – Study Area Line Sections Definition

Figure 5.35 – Study Area Line Sections Diagram

5.3.4.2 Time Window Selection

Following the UIC leaflet 406 recommendations, a peak period of two hours is selected for the capacity consumption analysis. Thus, the selected time window for all line sections is from 7h to 9h on 27th June of 2012 (Wednesday).

It is expected that the study area network is heavily loaded during the selected time window.

5.3.4.3 Timetable Compression

For each line section in the selected time window, the timetable is compressed. The compression is the process where all single train paths are pushed together up to the minimum theoretical headway according with their timetable order, without changing the timetable running times, overtaking times, crossing times and stopping times.

The compression is performed by a graphical analysis, using the timetable graphics. The Figure 5.36 shows this process applied into the *Sete Rios/Alvito A* section.

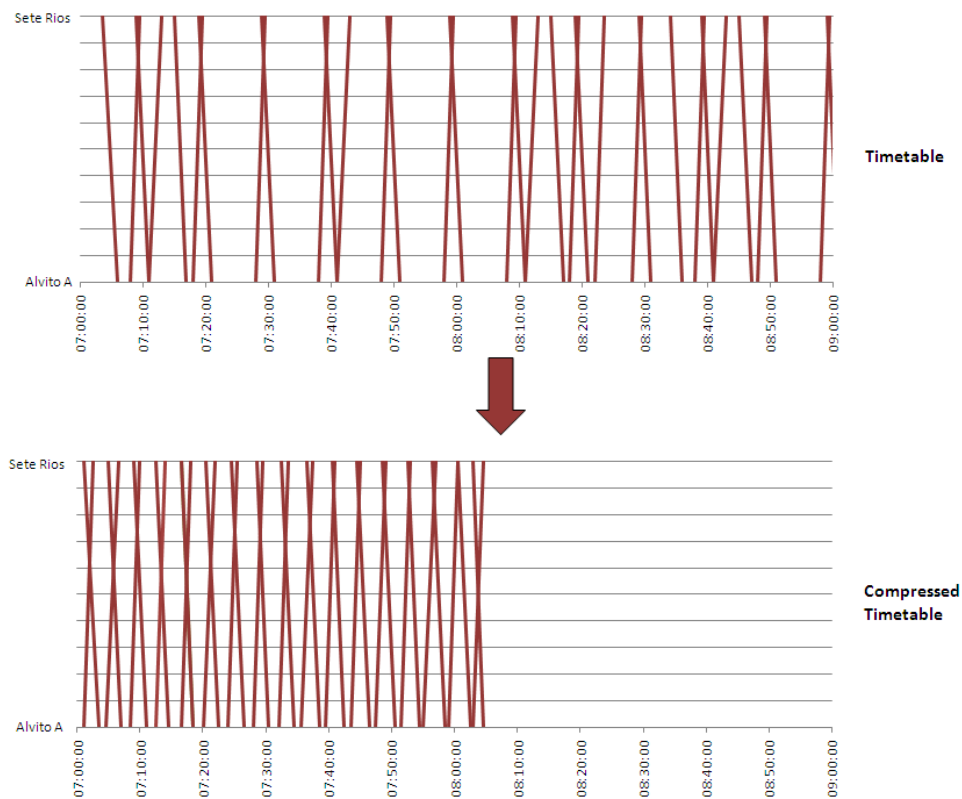


Figure 5.36 – Timetable Compression, *Sete Rios/Alvito A* Section

5.3.4.4 Capacity Consumption Evaluation

The capacity consumption calculation is given by the ratio of the total consumption time in the chosen time window. It can be determined by the following formula:

$$K = \frac{k \cdot 100}{U}$$

Equation 5.1 – Capacity Consumption, UIC Leaflet 406

Where,

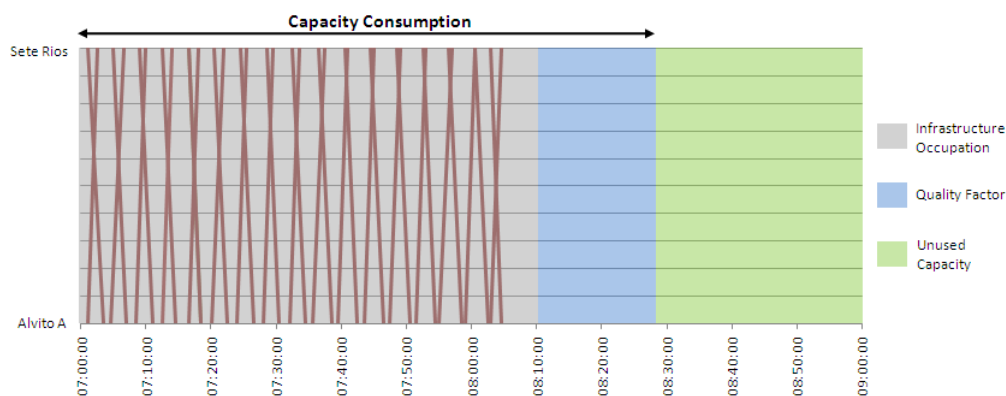
- K Is the capacity consumption [%]
 k is the total consumption time [min]
 U is the chosen time window [min]

The total consumption time is given by the infrastructure occupation time that is obtained in the timetable compression process amplified by a quality factor.

The quality factor is used to ensure a high quality operation that ensures a satisfactory punctuality and it can be estimated as a percentage of the infrastructure occupation time. Following the UIC leaflet 406 recommendations for mixed-traffic line during peak periods, the quality factor adopted is 25%.

The difference between capacity consumption and the chosen time window is the Unused Capacity. Not all Unused Capacity can be used for additional train paths, since there is some capacity that is lost due to the heterogeneity and average speed of trains that use a line section.

The Figure 5.37 presents a graphical illustration of the capacity consumption evaluation for the *Sete Rios/Alvito A* section.

Figure 5.37 – Capacity Consumption Evaluation, *Sete Rios/Alvito A* Section

There is the possibility that the capacity consumption exceeds 100%, which means that in that section the trains operation will not achieve a satisfactory stability/punctuality.

Table 5.3 and Figure 5.38 present the capacity consumption evaluation for the entire study area.

Line Sections		Capacity Consumption
Begin	End	
Setil	Entroncamento	63%
Alverca	Setil	62%
Lisboa Oriente	Alverca	55%
Braço de Prata	Lisboa Oriente	110%
Terminal Técnico Chelas	Braço de Prata	78%
Sete Rios	Terminal Técnico de Chelas	75%
Alvito A	Sete Rios	73%
Alvito A	Pragal	63%
Pragal	Pinhal Novo	67%
Pinhal Novo	Poceirão	20%
Poceirão	Vendas Novas	59%
Vendas Novas	Évora	54%
Setil	Vendas Novas	8%
Poceirão	Pinheiro	63%
Pinheiro	Grândola Norte	22% (*)
Pinheiro	Grândola Norte	59% (**)
Grândola Norte	Ermidas-Sado	64%
Ermidas-Sado	Porto de Sines	58%

(*) Through Sul Line

(**) Through Alcácer Line

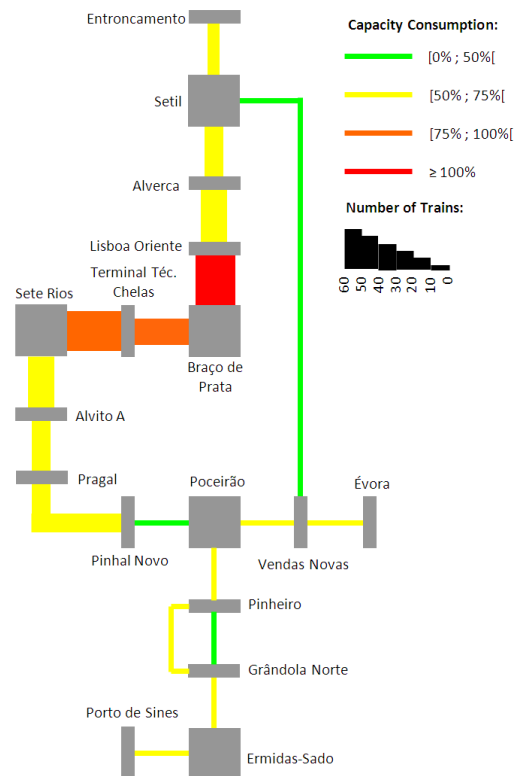


Table 5.3 – Study Area Capacity Consumption Evaluation

Figure 5.38 – Study Area Capacity Consumption Diagram

It can be observed that the sections between *Alvito A* and *Lisboa Oriente* are the bottleneck sections of the study area. The sections *Alvito A/Sete Rios*, *Sete Rios/Terminal Técnico de Chelas* and *Terminal Técnico de Chelas/Braço de Prata* are operating near their capacity limits, with a range of capacity consumption values between 73% and 78%. The section *Braço de Prata/Lisboa Oriente* exceeded its capacity limits since it presents a capacity consumption of 110%.

It can be inferred that the capacity shortages are located in the Lisbon Metropolitan Area. In fact this is the area where the insertion of the Lisbon High-Speed Railway line into the PRNO has more advantages due to the possibility to postpone some of the high investments planned for this area. It also allows to reduce negative impacts in travel times that arises from using the conventional railway infrastructure, since those are the last kilometers where the High-Speed train acceleration/deceleration occurs. The next chapter develops and evaluates several scenarios of incremental infrastructure improvements in order to solve the observed capacity constraints, taking into account that High-Speed and conventional trains share the same infrastructure in the Lisbon Metropolitan Area.

6. Microsimulation of the insertion of the High-Speed Service into the Lisbon Metropolitan Area – An Incremental Capacity Approach

6.1 The High-Speed Project in the Lisbon Metropolitan Area

The insertion of the High-Speed service into the Lisbon Metropolitan area in the Portuguese High-Speed project is part of the second PPP of the Lisbon – Madrid High-Speed line, which concerns the design, build, financing and maintenance of the rail substructure and superstructure, excluding the signaling and communications systems, in the Lisbon – *Poçoirão* section, for a period of 40 years. This PPP has a total length of 38 km and a total cost of 928M€ (without the third Tagus River bridge).

A main element of this project is the third Tagus River bridge. This element structures the insertion of the High-Speed line in Lisbon and has an estimated total cost of 2000M €. The planned insertion of the High-Speed line into the Lisbon Metropolitan area is presented in Figure 6.1. The High-Speed Lines are displayed in red.

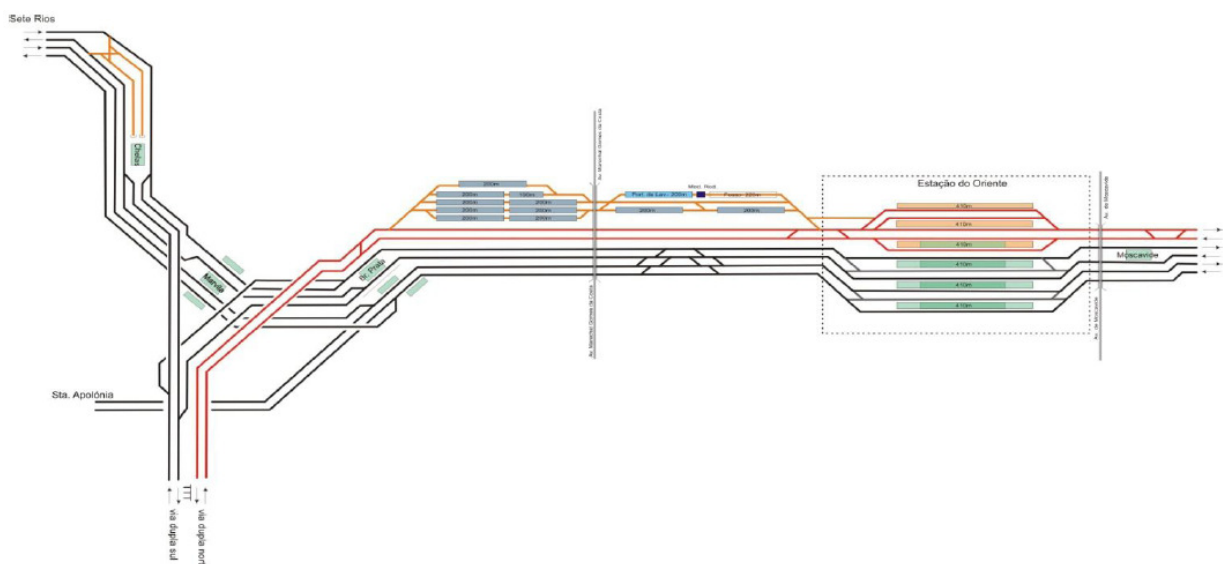


Figure 6.1 – Portuguese High-Speed Project – Insertion into the Lisbon Metropolitan Area, *Terminal Técnico de Chelas/Braço de Prata* section

This chapter explores the prospect of implementing the High-Speed project in a staged way, differing some of the initial investments, such as the construction of the third Tagus River bridge. Thus several staged scenarios for improvements in railway infrastructure capacity will be evaluated for several infrastructure demand scenarios. This will be performed through simulation of the critical sections concerning capacity consumption.

It is important to notice that this staged approach of the High-Speed project have an impact on High-Speed train travel times and therefore will have an impact on demand for these services, which are not evaluated in this study.

6.2 Detailed Description of the Critical Sections

The capacity consumption analysis performed in chapter 5 allowed to detect a lack of capacity in the sections located between *Lisboa Oriente* and *Alvito A*. This is the critical section of the study area regarding capacity consumption. The range of values for the capacity consumption changes from 73%, in *Sete Rios/Alvito A* section, to 110%, in *Lisboa Oriente/Braço de Prata* for the selected time window.

To understand the possible causes for the observed bottleneck, a detailed analysis for the critical section is performed.

6.2.1 Detailed Infrastructure Features

The *Lisboa Oriente/Alvito A* section has a total length of 12,666 km. The main points identified in the infrastructure, such as stations, junctions and/or terminals are: *Lisboa Oriente*, *Braço de Prata*, *Bifurcação de Chelas*, *Terminal Técnico de Chelas*, *Roma Areeiro*, *Entrecampos*, *Sete Rios*, *Campolide* and *Alvito A*.

Those main points and respective distances are presented in Figure 6.2, as well as the connections with other PRNO sections.



Figure 6.2 – Critical Sections

Table 6.1 resumes the information concerning the number of tracks and number of tracks with platform for each station/junction/terminal.

Acronym	Railway Stations/Junctions/Terminals		Number of Tracks	Number of Tracks with Platform
ORI	<i>Lisboa Oriente</i>	Station	8	8
BPR	<i>Braço de Prata</i>	Station	4	4
BCH	<i>Bifurcação de Chelas</i>	Junction	3	0
TTC	<i>Terminal Técnico de Chelas</i>	Terminal	8	0
RAR	<i>Roma Areeiro</i>	Station	4	4
ETC	<i>Entrecampos</i>	Station	4	4
SRI	<i>Sete Rios</i>	Station	4	4
CDA	<i>Campolide</i>	Station	5	5
ALT	<i>Alvito A</i>	Station	4	4

Table 6.1 – Main Stations/Junctions/Terminals, Critical Section

6.2.2 Traffic Patterns

The traffic patterns for the critical section in the selected time window are presented in Figure 6.3.

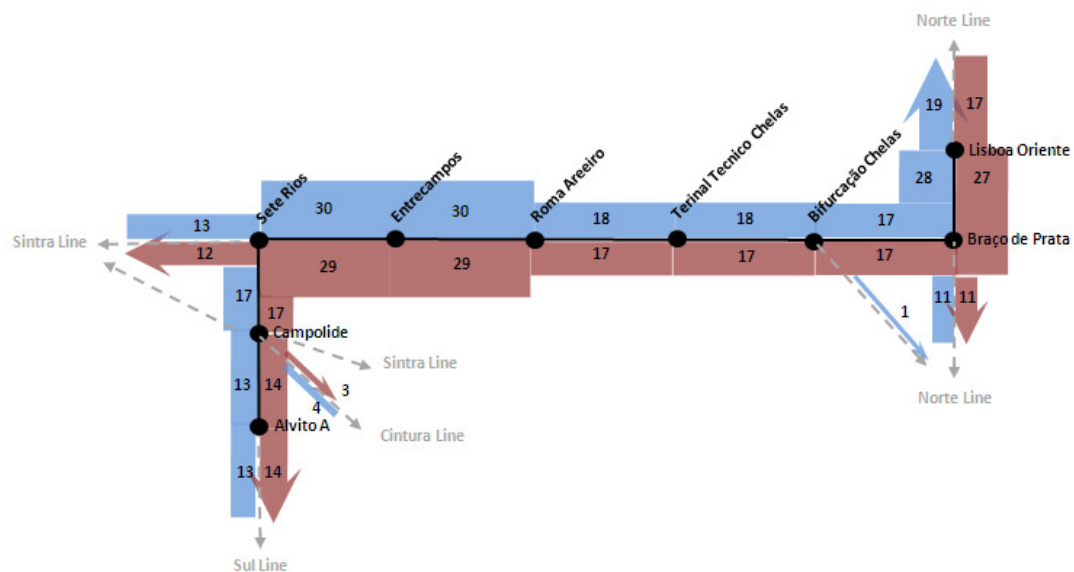


Figure 6.3 – Traffic Patterns in the Critical Section

From the traffic patterns shown above it can be inferred that the most loaded sections are *Sete Rios* (SRI)/*Roma-Areeiro* (RAR) and *Lisboa Oriente* (ORI)/*Braço de Prata* (BPR) with approximately 30 trains.

It is also noticeable the interactions between trains that run between ORI and *Alvito A* (ALT) with trains running in other PRNO sections, namely in *Norte Line*, *Sintra Line*, *Cintura Line* and *Sul Line*.

There are some train movements that conflict with each others. To ensure that the train paths are compatible, it is needed to guarantee a safety distance spacing, which consumes capacity.

Taking into account the itineraries between each station/junction/terminal and the traffic patterns, there are train paths with an impact on capacity consumption between ORI and BPR, TTC and *Bifurcação de Chelas* (BCH), RAR and *Entrecampos* (ETC), ETC and SRI. Those train paths and its impacts are identified below:

- **Lisboa Oriente/Braço de Prata**

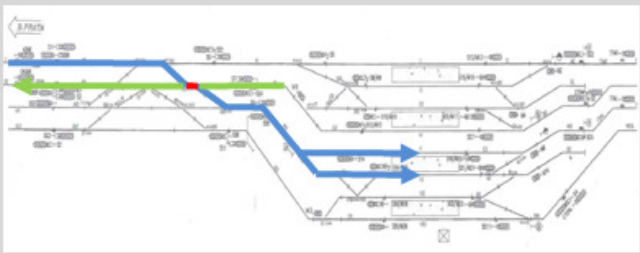
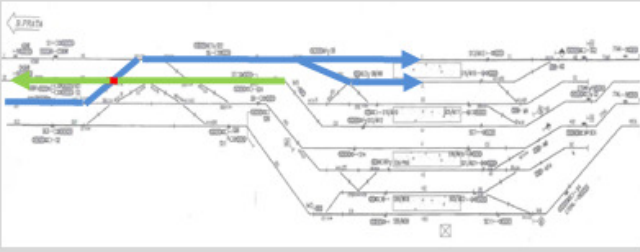
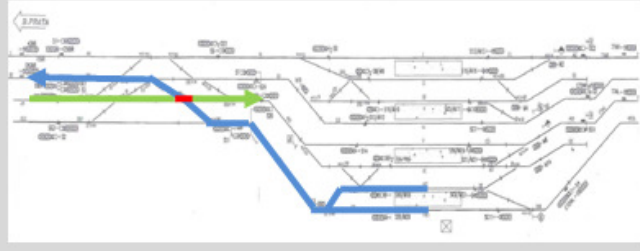
From		To		Diagram
Name	Track	Name	Track	
Braço de Prata	I	Lisboa Oriente	V/VI	
	III		I/II	
Lisboa Oriente	III/IV	Braço de Prata	IV	
	VII/VIII		II	

Table 6.2 – Train Path Conflicts, ORI/BPR

In Table 6.2, the arrows represent train paths and the conflicts between train paths are highlighted in red. The main train path conflicts in ORI/BPR section are due to train movements between and from ORI heading to or coming from the Cintura line and from *Lisboa Santa Apolónia* (LSA), which cannot be performed simultaneously.

The train path possibilities and its conflicts between ORI and BPR are summarized in the train path matrix presented in Table 6.3.

		TO							
		BPR				ORI			
		I	II	III	IV	I/II	III/IV	V/VI	VII/VIII
FROM	BPR	I						D2	
		II							
		III							
		IV							
	ORI	I/II							
		III/IV							
		V/VI							
		VII/VIII							

Train path without conflict

X

Train path in conflict with track X

Train path not allowed

Table 6.3 – Train Path Matrix, ORI/BPR

• **Terminal Técnico de Chelas/Bifurcação de Chelas**

From		To		Diagram
Name	Track	Name	Track	
Terminal Técnico de Chelas	AN/AS	Bifurcação de Chelas	C	

Table 6.4 – Train Path Conflicts, BCH/TTC

From Table 6.4 it is possible to observe that the only train path conflict in TTC/BCH section occurs when trains are going to the *Norte* line trough the *Xabregas* line.

The train path possibilities and its conflicts between BCH and TTC are summarized in the train path matrix presented in Table 6.5.

			TO											
			BCH			TTC								
			AS	DS	C	AN	DN	AS	DS	IT	IIT	IIIT	IVT	
FROM	BCH	AS												
		DS					AS							
		C					AS							
	TTC	AN			DS									
		DN												
		AS			DS									
		DS												
		IT												
		IIT												
		IIIT												
		IVT												

Train path without conflict
 X Train path in conflict with track X
 Train path not allowed

Table 6.5 – Train Path Matrix, BCH/TTC

• **Roma Areeiro/Entrecampos**

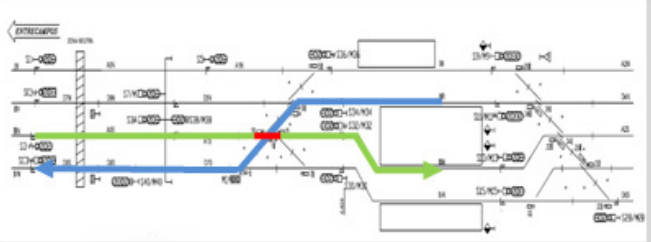
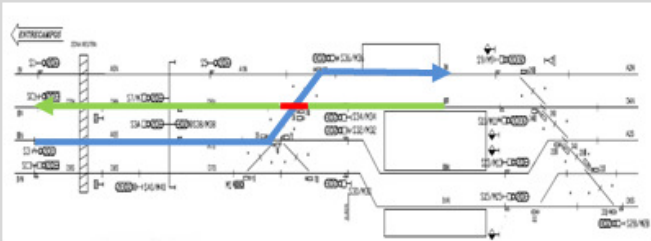
From		To		Diagram
Name	Track	Name	Track	
Roma Areeiro	II	Entrecampos	IV	
Entrecampos	III	Roma Areeiro	I	

Table 6.6 – Train Path Conflicts, RAR/ETC

From Table 6.6 it is possible to observe that train path conflicts are due to train movements between lines II and IV and between lines III and I.

The train path possibilities and its conflicts between RAR and ETC are summarized in the train path matrix presented in Table 6.7.

		TO							
		RAR				ETC			
		I	II	III	IV	I	II	III	IV
FROM	RAR	I							
		II							AS
		III							
		IV							
	ETC	I							
		II							
		III	DN						
		IV							

Train path without conflict

X

Train path in conflict with track X

Train path not allowed

Table 6.7 – Train Path Matrix, RAR/ETC

- Entrecampos/Sete Rios**

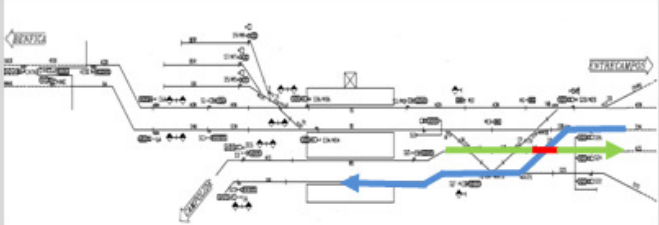
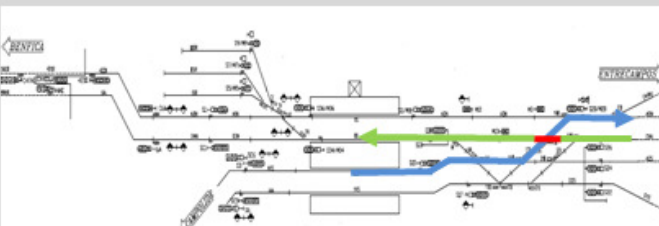
From		To		Diagram
Name	Track	Name	Track	
Entrecampos	II	Sete Rios	IV	
Sete Rios	III	Entrecampos	I	

Table 6.8 – Train Path Conflicts, ETC/SRI

From Table 6.8 it is possible to observe that train path conflicts are due to train movements between lines II and IV and between lines III and I.

The train path possibilities and its conflicts between ETC and SRI are summarized in the train path matrix presented in Table 6.9.

		TO											
		ETC				SRI							
		I	II	III	IV	I	II	III	IV				
FROM	ETC	I											
		II											
		III											
		IV											
	SRI	I											
		II											
		III											
		IV											

Train path without conflict

X

Train path in conflict with track X

Train path not allowed

Table 6.9 – Train Path Matrix, ETC/SRI

6.3 Scenarios Definition for Incremental Capacity Improvements

In order to study the relief of the bottlenecked sections in a gradual way, a sequential upgrade of the infrastructure is defined. This sequential upgrade comprises three infrastructure scenarios: infrastructure scenarios I, II and III. The infrastructure improvements increase from scenario I to III.

Each infrastructure scenario will be tested with 3 timetable Scenarios: timetable scenarios A, B and C. Each timetable scenario differs from each other by the number of High-Speed trains. Timetable scenario A comprises the least number of High-Speed trains, whereas timetable scenario C has the higher number of High-Speed trains.

The studied scenarios are summarized in Table 6.10.

		Number of Trains			
Infrastructure Improvements + ↓	Infrastructure Scenarios	Timetable Scenarios			
		Scenario A	Scenario B	Scenario C	
		Scenario I	Scenario I-A	Scenario I-B	Scenario I-C
		Scenario II	Scenario II-A	Scenario II-B	Scenario II-B
		Scenario III	Scenario III-A	Scenario III-B	Scenario III-C

Table 6.10 – Scenarios Considered in the Study

6.3.1 Infrastructure Scenarios

The infrastructure scenarios will focus the upgrade of ORI/BPR and BRP/TTC sections, since those are the sections with the highest capacity consumption values.

6.3.1.1 Infrastructure Scenario I

The infrastructure scenario I represent the current infrastructure, and it is presented in Figure 6.4. With this scenario it is intended to explore the capacity boundaries of the current infrastructure.

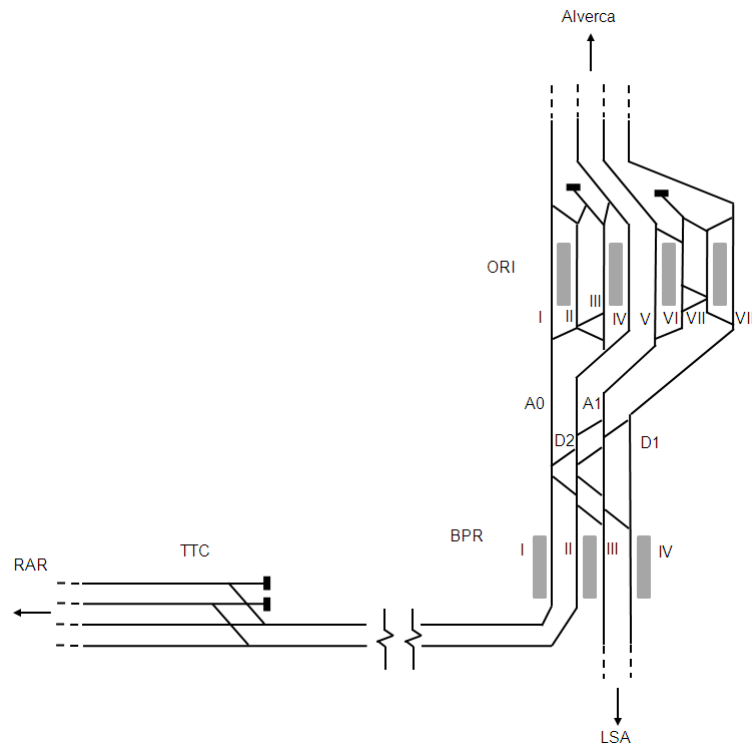


Figure 6.4 – Scenario I, ORI/RAR sections

According to the capacity consumption evaluation, the main problems with this scenario are expected to occur in the BPR/ORI section, which is already saturated.

6.3.1.2 Infrastructure Scenario II

Scenario II presents an upgrade in BPR/ORI section. The capacity consumption evaluation has showed that this is the most critical section of the study area, with a consumed capacity of 110%. Therefore the first infrastructure upgrade scenario will focus this section.

As analyzed before, there are several train path conflicts which have an impact on capacity consumption in BPR/ORI section. Thus, the strategy followed to increase its capacity is to eliminate some of the train path conflicts.

Taking into account the proposed strategy, the improvement of the critical section ORI/BPR comprises 2 unlevelled tracks which allow decrease the number of train path conflicts between ORI and BPR. This scenario enables train paths from track I of BPR to track V and VI of ORI, without affecting train movements in line D2. In the same way, scenario II enables train paths from track VII and VIII of ORI to track II of BPR without disturbing train movements in line A1.

The infrastructure scenario II is presented in Figure 6.5 and the improvements are highlighted in green.

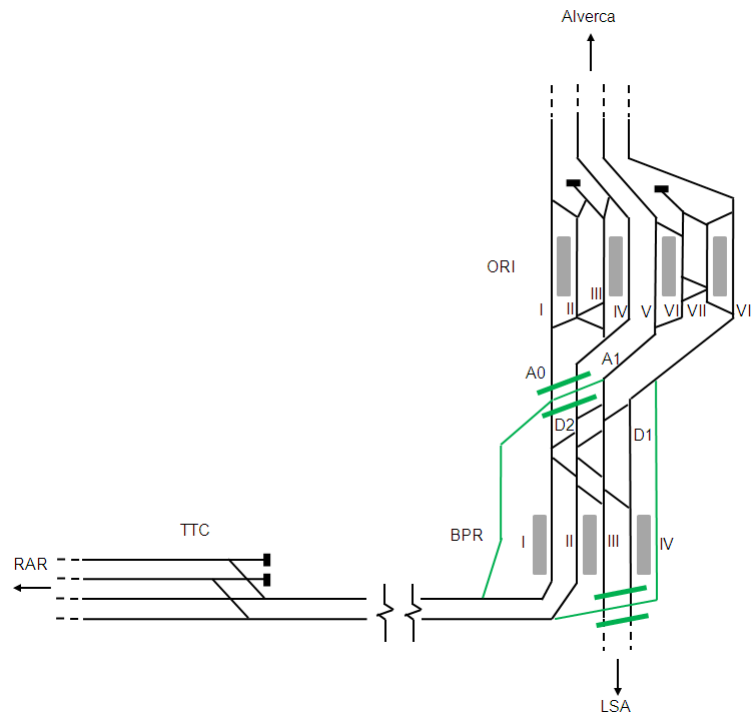


Figure 6.5 – Scenario II, ORI/RAR sections

The train path matrixes comparison for infrastructure scenarios I and II is presented in Figure 6.6, and it is possible to see the reduction of the train path conflicts.

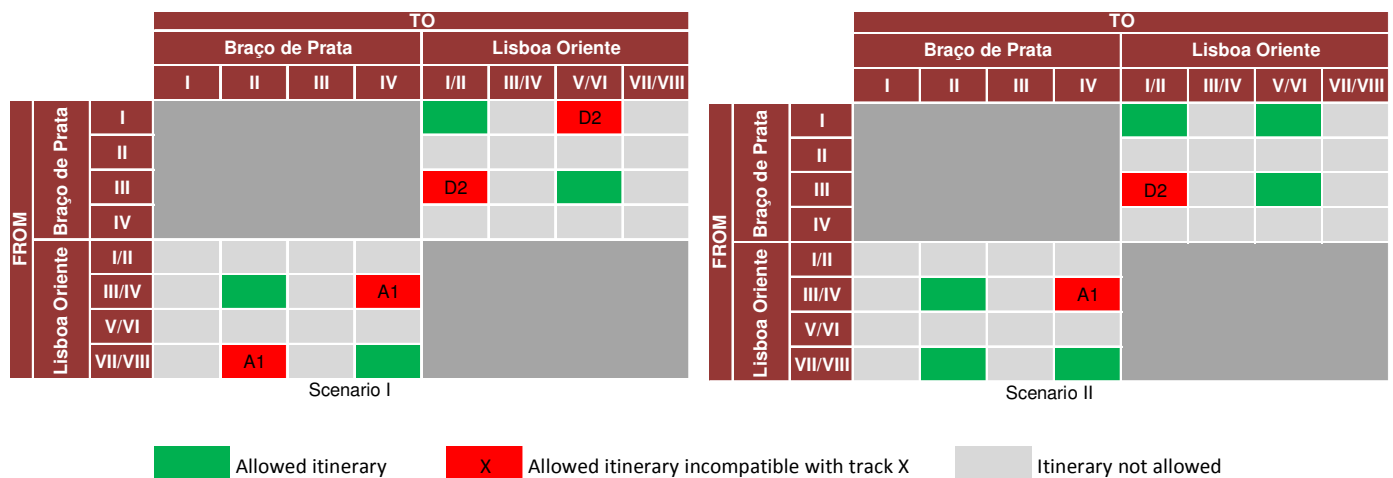


Figure 6.6 – Trains Path Matrix, Infrastructure Scenarios I and II

6.3.1.3 Infrastructure Scenario III

The scenario III is an upgrade of scenario II, and aims the improvement of the capacity in TTC/BPR section, the second critical section according to the capacity consumption evaluation.

Unlikely the BPR/ORI section, the capacity constraints in TTC/BPR section are not caused by train path conflicts. This can be concluded since there is only one train path conflict, which occurs between TTC and BCH, and it is performed by only one train in the selected time window for the capacity consumption

evaluation. Therefore, instead of eliminate train path conflicts, the proposed infrastructure improvements in this scenario are the construction of two additional tracks between BPR and TTC.

The infrastructure scenario III is presented in Figure 6.7 and the improvements are highlighted in blue.

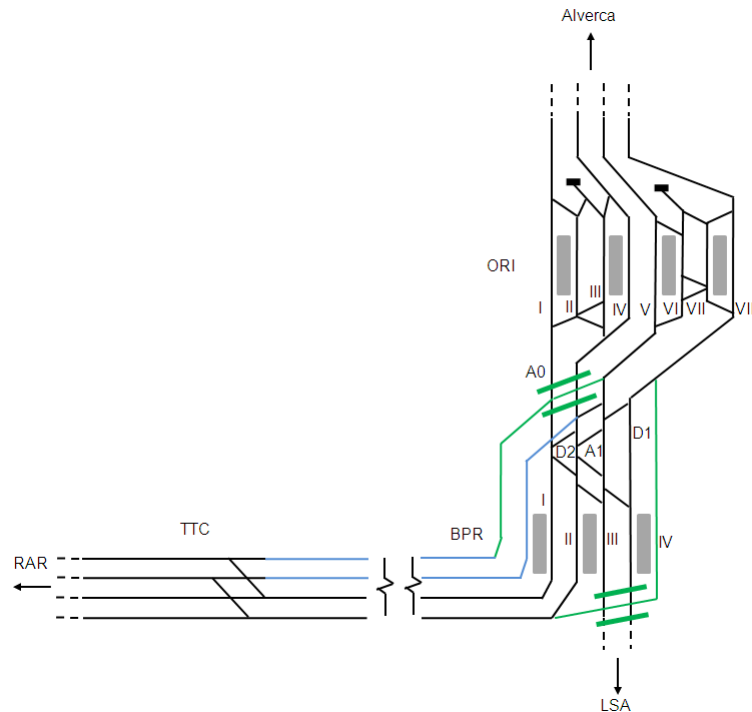


Figure 6.7 – Scenario III, ORI/RAR sections

6.3.2 Timetable Scenarios

All timetable scenarios comprise the current timetable of the conventional trains. Timetable A can be seen as an early stage of the High-Speed train service, with low demand, which progressively increases to timetable B and C, with higher number of trains.

Timetable scenario A has one High-Speed train every two hours in each way, while in timetable scenario B the number of High-Speed trains increases to one every hour in each way. In timetable scenario C, the number of High-Speed trains is two every hour in each way.

The timetable scenarios are presented in Appendix 2 – Timetable Scenarios.

The infrastructure and timetable adopted in each scenario are summarized in Table 6.11.

	Infrastructure	Timetable
Scenario I-A	Current Infrastructure	1 High Speed Train every 2 hours in each way
Scenario I-B	Current Infrastructure	1 High Speed Train every hour in each way
Scenario I-C	Current Infrastructure	2 High Speed Trains every hour in each way
Scenario II-A	Improvement in the ORI/BPR section	1 High Speed Train every 2 hours in each way
Scenario II-B	Improvement in the ORI/BPR section	1 High Speed Train every hour in each way
Scenario II-C	Improvement in the ORI/BPR section	2 High Speed Trains every hour in each way
Scenario III-A	Improvement in the ORI/BPR and TTC/BPR sections	1 High Speed Train every 2 hours in each way
Scenario III-B	Improvement in the ORI/BPR and TTC/BPR sections	1 High Speed Train every hour in each way
Scenario III-C	Improvement in the ORI/BPR and TTC/BPR sections	2 High Speed Trains every hour in each way

Table 6.11 – Scenarios Summary

6.4 Measures of Performance

For the performance evaluation of the scenarios, the performance measures used are the mean delay and punctuality.

6.4.1 Mean Delay

Train delay is the deviation of a train from the timetable at a specific evaluation point. It can be measured at the train departure in the origin station, at the train arrival in the destination station or at the train arrival or departure in any intermediate station.

The mean delay is the average train delays on a specific evaluation point, and is given by Equation 6.1.

$$\bar{x}_i = \frac{\sum_j^n x_{ij}}{n}$$

Equation 6.1 – Mean Delay

Where,

- $\bar{x}_i$ is the mean delay at evaluation point i
- x_{ij} is the delay of train j at evaluation point i
- n is the number of trains measured at evaluation point i

6.4.2 Punctuality

Punctuality is the percentage of trains that arrive/depart at a specific evaluation point with a delay less or equal than a certain threshold. For the purpose of this project, it is established the punctuality threshold in 1 minute.

As the mean delay, punctuality can be measured at the train departure in the origin station, at the train arrival in the destination station or at the train arrival or departure in any intermediate station.

6.5 Scenarios Simulation

6.5.1 Simulation tool – OPENTRACK

The performance evaluation of the proposed scenarios is performed through simulation.

The simulation has been carried out using OPENTRACK simulation tool. It is a user-friendly railroad network simulation program, which allows modeling rail system operations based on user defined infrastructure, train and timetable data.

The railway network should be modeled in OPENTRACK according to track layouts. All signs, switches and stopping locations should be included in the model. For this purpose, the rail network should be divided into elementary sections, which have the same values of maximum speed, gradient and curve radius.

As train data inputs, OPENTRACK needs the definition of the rolling stock, such as train length and load, braking capability, traction power, maximum speed, etc.

The arrival and departure times in all stations for the simulated trains is also a data input used by OPENTRACK.

After the input definition, the simulation can be carried out and OPENTRACK generates multiple outputs data, such as diagrams, trains graphs, statistics, among others.

The OPENTRACK process is illustrated in Figure 6.8.

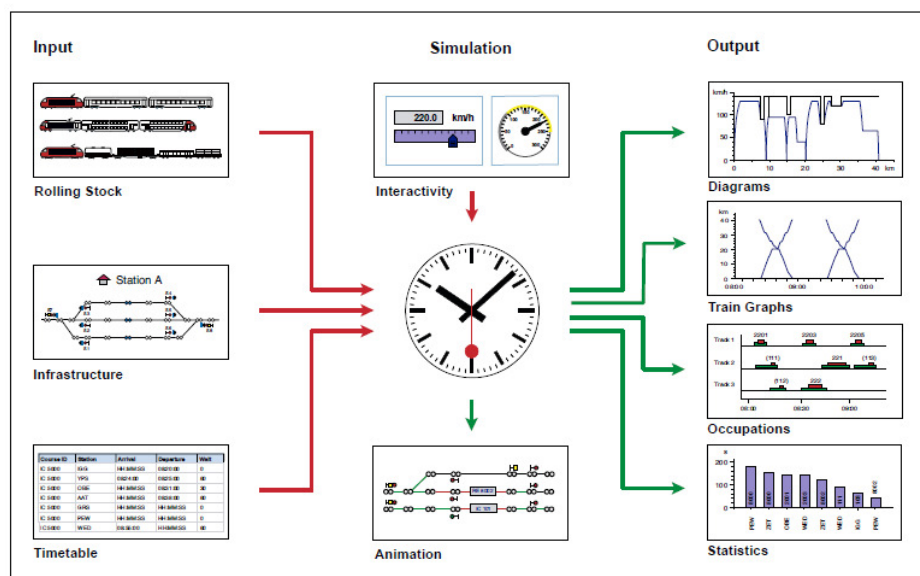


Figure 6.8 – OPENTRACK Process: Input/Simulation/Output (Huerlimann et al., 2003)

6.5.2 Model Construction

In OPENTRACK the construction of a railway system model needs the detailed generation of a rail infrastructure, the definition of the rolling stock and the timetable data.

The first step to build the model is to generate the rail network. The rail network was generated by reproducing the track layouts, which comprises information regarding the tracks, the signals, the stations and the trains itineraries.

In OPENTRACK the railway track is modeled through edges and nodes. All boundaries for maximum speed, gradients and curve radius are represented in a node. Nodes are connected to each other by edges. Every edge has several attributes such as length, maximum speed, curve radius and gradient.

Signals are placed in the nodes and OPENTRACK uses two different types of signals: signals with changing information and halt position indicators. The first type of signals controls the train movements and can be divided into main signals, distant signals and shunting signals. The halt position indicators define the stopping location of a train in a station.

Stations are modeled in OPENTRACK as station areas. Station areas include the station node, which represent the station location, station tracks, entrance and exit signals and halting points.

Figure 6.9, Figure 6.10 and Figure 6.11 illustrates the modeled area. The section LSA/*Bobadela Sul* (BNS) is represented in Figure 6.9, which includes LSA, BPR, ORI, *Moscavide* (MOE), *Sacavém* (SAC) and BNS.

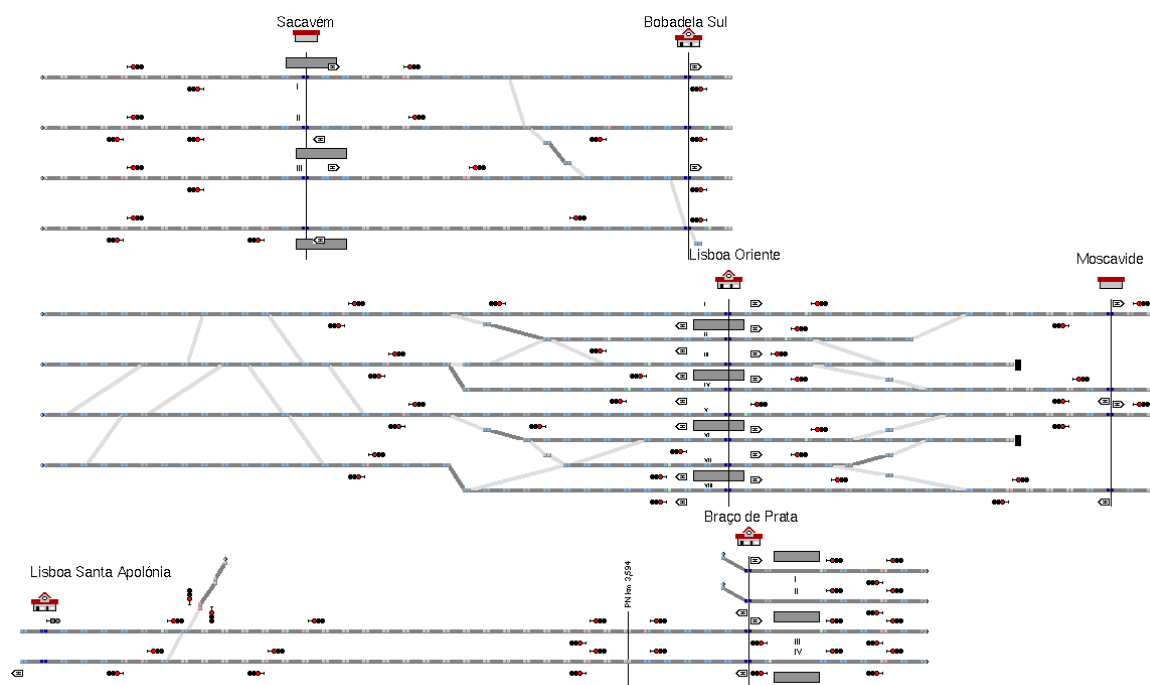


Figure 6.9 – Model, LSA/BNS Section – Scenario I

Figure 6.10 shows BPR/RAR section, which includes *Marvila* (MVA), *Chelas* (CHE) and RAR.

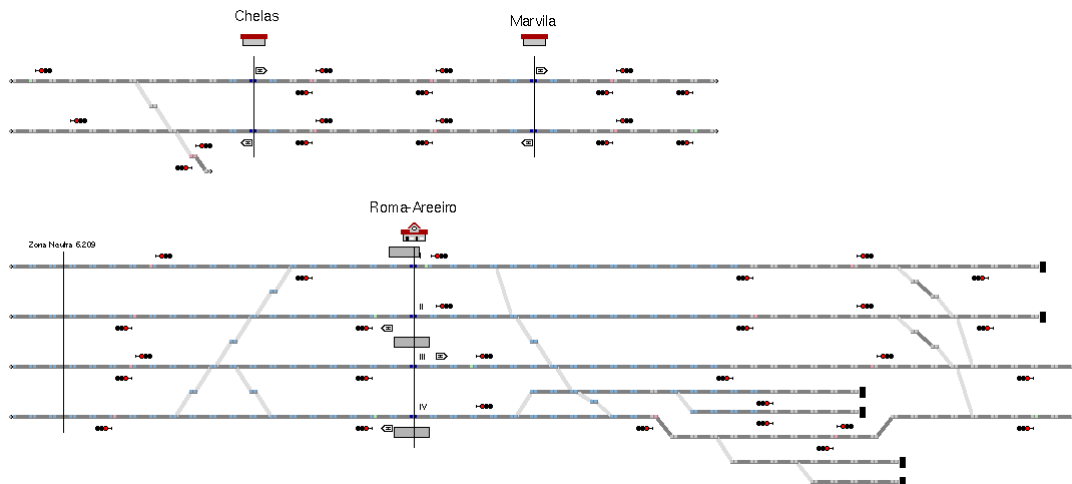


Figure 6.10 – Model, BPR/RAR Section – Scenario I

Figure 6.11 represents RAR/ALT section, which includes ETC, *Entrecampos Poente* (EPO), SRI, *Campolide* (CDA) and ALT.

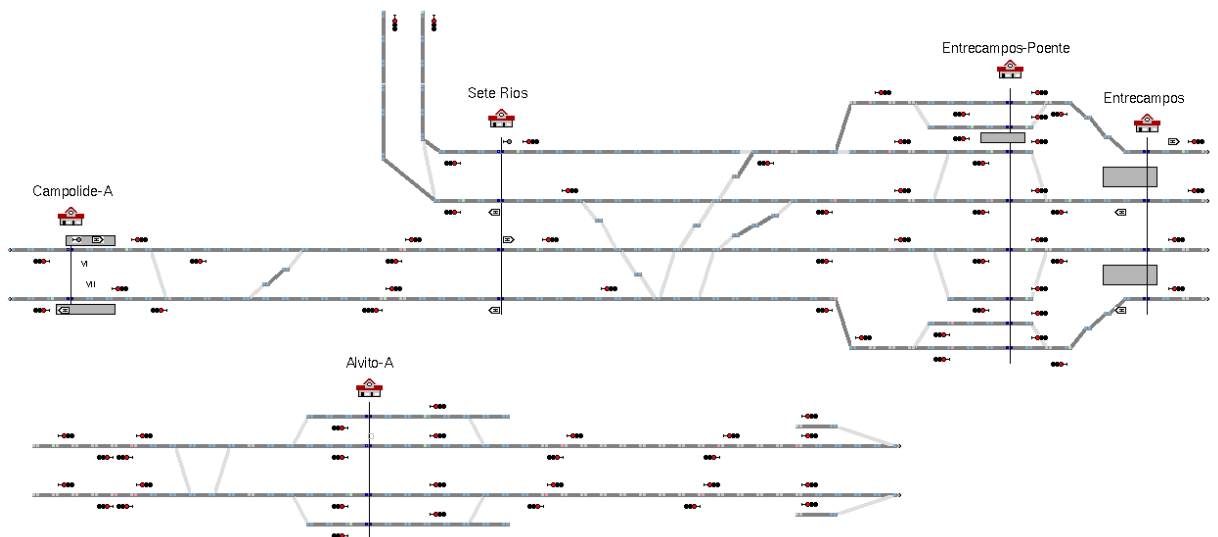


Figure 6.11 – Model, RAR/ALT Section – Scenario I

The last stage in the generation of the railway network is the definition of train itineraries. Itineraries are trips between two main points of the network, such as two stations. Before generating itineraries, it is necessary to define routes. A route is a set of vertices in one direction of travel between two signals. After the definition of routes, it is necessary to create the paths. A path is a set of routes in one direction of travel that is often used by several trains, such as the routes between two exit signals of two successive stations. Finally the itineraries can be generated as a composition of several successive paths. Figure 6.12 presents an example of an itinerary in OPENTRACK.

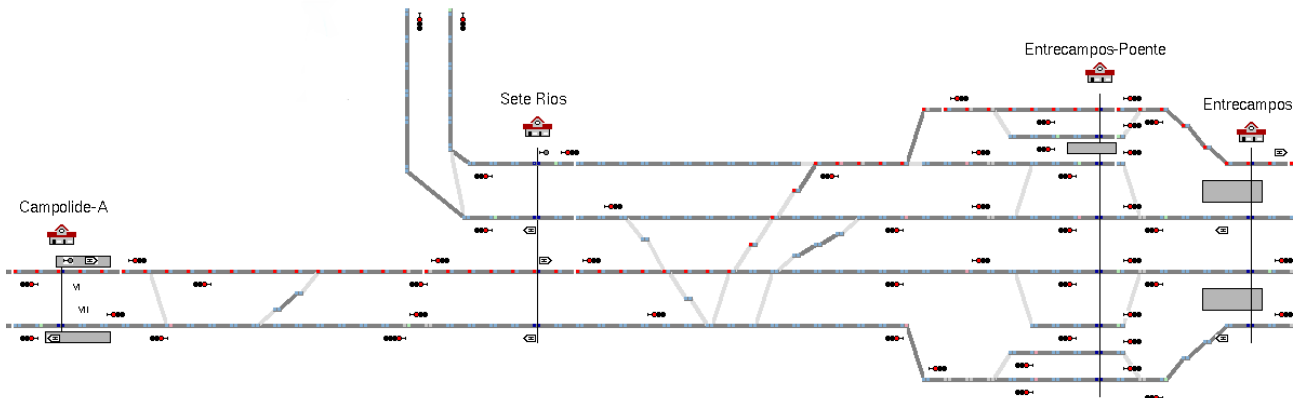


Figure 6.12 – Itinerary

The modeled area involved a total of 91,045 km of tracks.

The second step in the model construction is the rolling stock data definition. Six type of engines were defined, each of them with specific parameters for maximum speed, train length, train load, maximum tractive effort, tractive effort/speed diagram, air resistance coefficients, maximum acceleration, braked weight percentage, etc.

Figure 6.13 and Figure 6.14 presents an example of an engine type and the respective tractive effort diagram.

Figure 6.13 – Engines

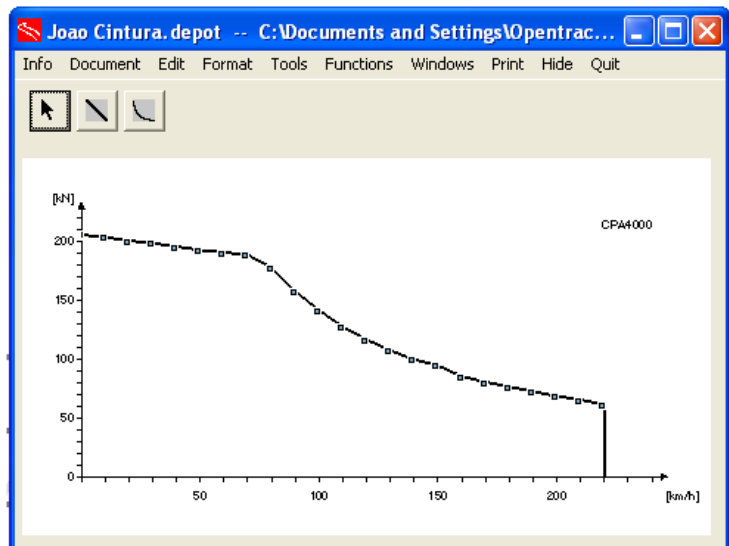


Figure 6.14 – Tractive Effort Diagram

The third and last input for the model construction is the timetable data. The timetable data of approximately 600 trains were loaded, which included international trains, long distance trains, regional trains, urban trains, freight trains, passenger and freight empty trains and High-Speed trains. Figure 6.15 and Figure 6.16 presents the services and timetable views in OPENTRACK.

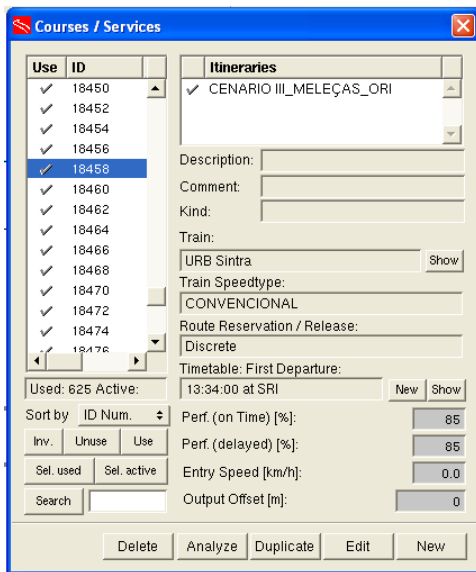


Figure 6.15 – Courses/Services

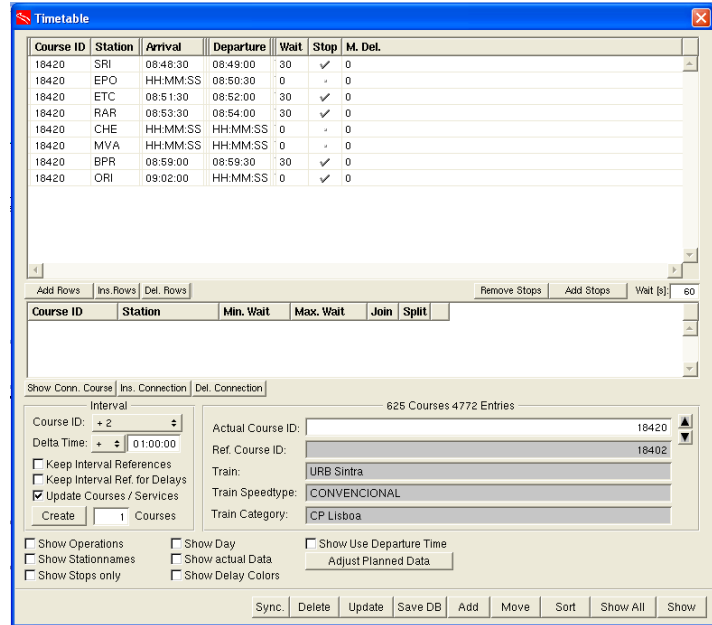


Figure 6.16 – Timetable

As mentioned in chapter 2 *Railway Infrastructure and Operations Planning*, timetables are designed considering an additional time margin, the recovery time, which prevents delays caused by random factors. Since OPENTRACK simulation does not consider those causes, trains are systematically running before the planned timetable. This can be prevented by calibrating the model. The calibration in OPENTRACK can be carried out by adjusting the trains performance.

After adjusting the performance of each train, the global calibration of the model should be checked. The verification of the model calibration is performed by computing it's adhesion to the trains planned timetable. The global model adhesion to the planned timetable is given by a calibration indicator, which can be obtained by:

$$C_x = \frac{m_x}{M}$$

Equation 6.2 – Model Calibration Indicator

where,

- C_x is the calibration indicator for a delay threshold of x seconds
- m_x is the number of measurements with a delay deviation higher or lower than a threshold of x seconds
- M is the total number of measurements

The calibration indicators for delay thresholds of 30, 60, 90 and 120 seconds are presented in Table 6.12.

C_{30}	C_{60}	C_{90}	C_{120}
83,7%	92,0%	94,4%	95,5%

Table 6.12 – Calibration Indicators

From Table 6.12 it can be inferred that more than 90% of the measurements in the model are according to the planned timetable, for deviation thresholds above or equal to 60 seconds.

With the model calibrated, the simulation can be performed. Figure 6.17 and Figure 6.18 presents a snapshot of a simulation and a planned/simulated train diagram.

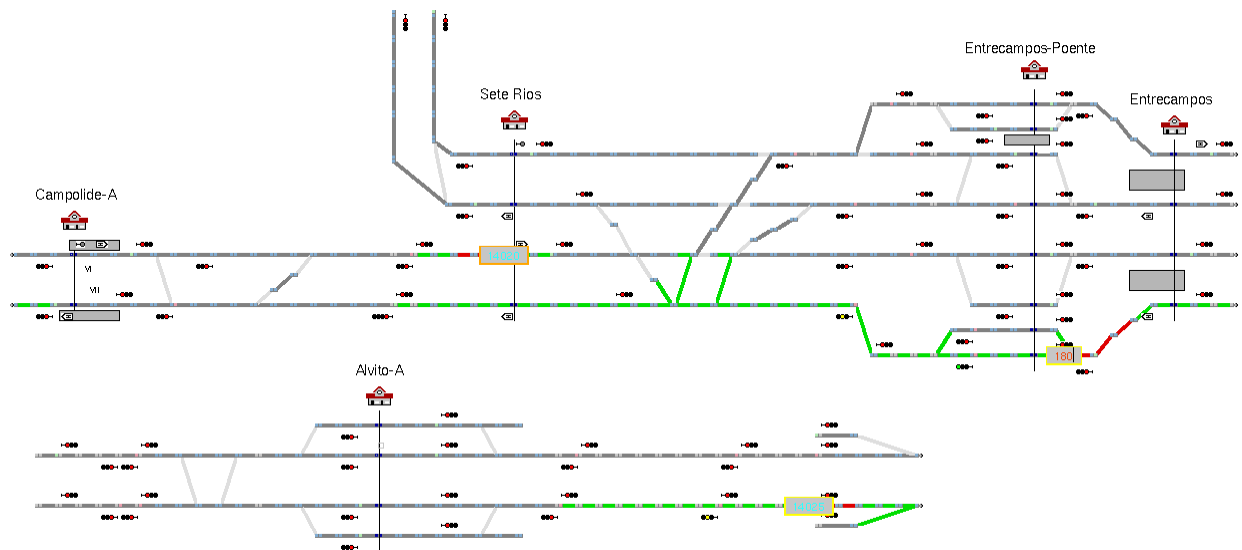


Figure 6.17 – Simulation

Alvito-A - Bobadela Sul

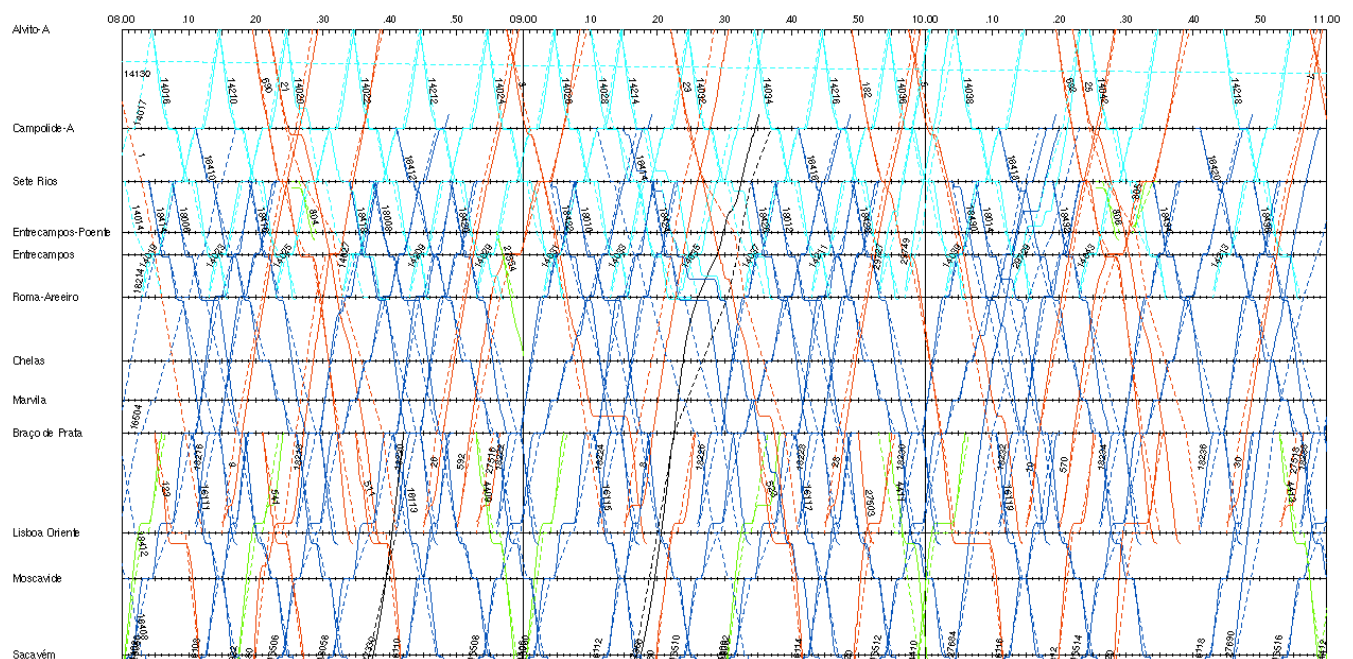


Figure 6.18 – Planned/Simulated Time Train Diagram

6.5.3 Analysis of Results for Punctuality and Mean Delays of Each Scenario

The simulation is carried out in the time band [6h-12h]. The performance of the scenarios is evaluated in six selected points: ORI, BPR, RAR, ETC, SRI and CDA. For all scenarios the performance measures are calculated in each evaluation point.

6.5.3.1 Infrastructure Scenario I

Figure 6.19 presents the punctualities for infrastructure scenario I and for the current situation in all evaluation points.

The preliminary capacity consumption evaluation performed confirms the simulation results, since ORI is the critical station with the lowest punctualities of all evaluation points. Also in line with the capacity consumption analysis, RAR is the second critical point.

As observed in Figure 6.19, ORI, RAR and CDA are the most sensitive points to the increase number of trains. It is also noticeable the system performance worsen in RAR, ETC, SRI and CDA when compared to the current situation results. From Figure 6.19 it is also noticeable that punctuality in BPR increases in timetable scenario C. This might be explained due to network effects generated by the global worsening performance in the remaining evaluation points.

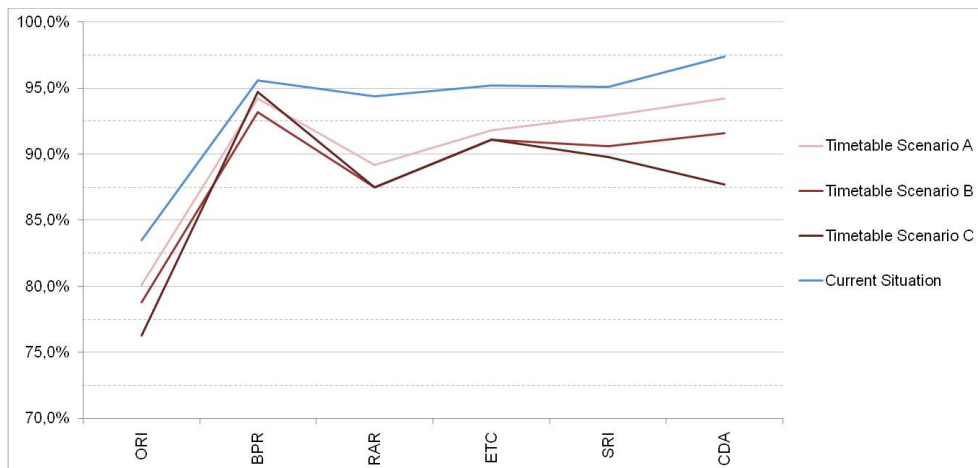


Figure 6.19 – Punctualities - Infrastructure Scenario I

Figure 6.20 show the mean delays for infrastructure scenario I in all evaluation points.

It can be observed that ORI and RAR are the evaluation points with higher mean delays.

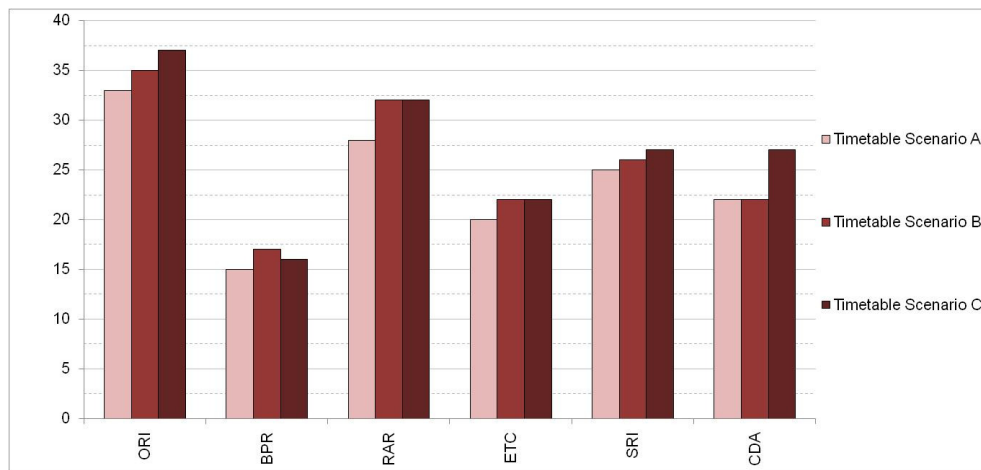


Figure 6.20 – Mean Delays - Infrastructure Scenario I

6.5.3.2 Infrastructure Scenario II

The punctualities for infrastructure scenario II in all evaluation points are presented in Figure 6.21.

When compared to infrastructure scenario I, it can be noted that there is a generalized performance improvement in infrastructure scenario II. The main performance change in infrastructure scenario II is observed in ORI, where the punctuality increases approximately 10% in all timetable scenarios, reflecting the infrastructure improvement in ORI/BPR section.

Despite the improved performance in infrastructure scenario I, the critical points remain ORI and RAR. In timetable scenario C there is a punctuality worsening in CDA, adding this station to the critical evaluation points. For this timetable scenario, CDA presents the lowest punctuality values of all evaluation points.

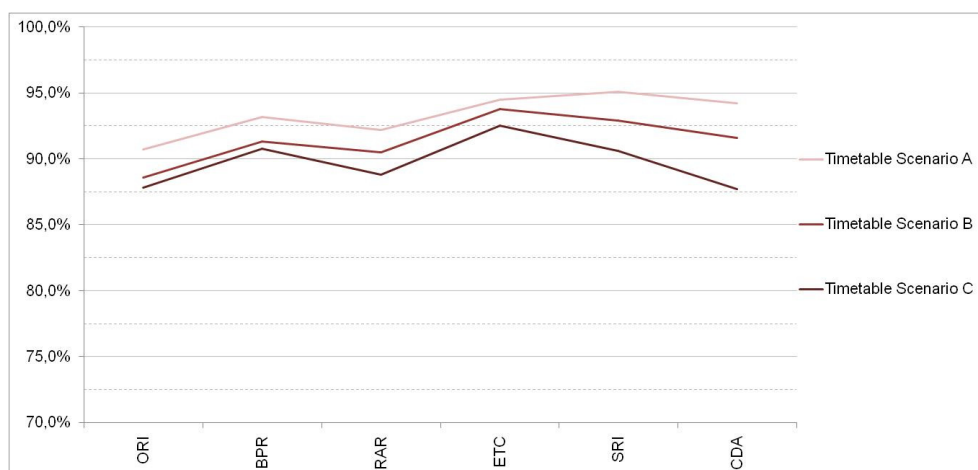


Figure 6.21 – Punctualities - Infrastructure Scenario II

Figure 6.22 presents the mean delays for infrastructure scenario II, where it can be observed that RAR has the highest mean delays.

The infrastructure upgrade generates a reduction of approximately 50% in the ORI mean delay.

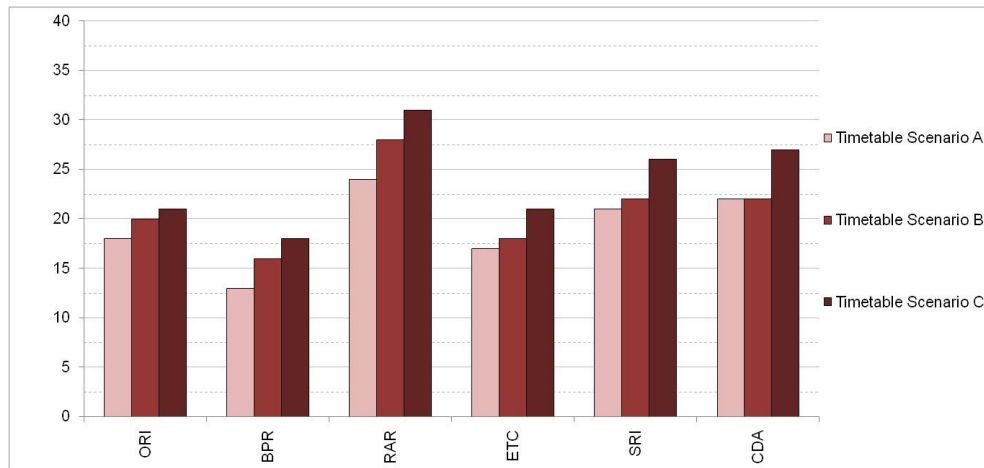


Figure 6.22 – Mean Delays - Infrastructure Scenario II

6.5.3.3 Infrastructure Scenario III

The punctualities for infrastructure scenario III in all evaluation points are presented in Figure 6.23.

Infrastructure scenario III generates more stable results, which are less sensitive to timetable changes. The exception occurs in CDA, where the results show a punctuality reduction in timetable Scenarios B and C.

Despite the performance improvement of infrastructure scenario III, when compared to scenario II, in all timetable scenarios, the results show that the biggest performance enhancements occurs for timetable Scenarios B and C.

The critical evaluation points in infrastructure scenario III are ORI and RAR, since the lowest punctuality values occur in those stations.

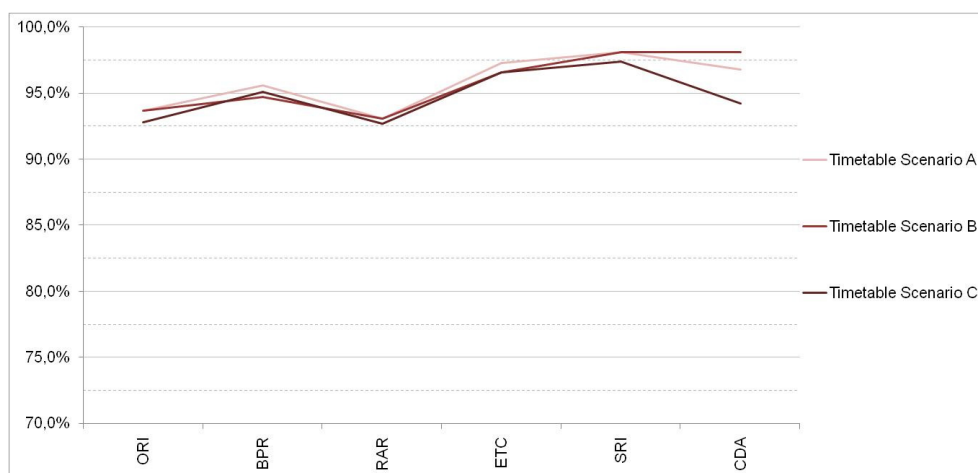


Figure 6.23 – Punctualities - Infrastructure Scenario III

Figure 6.24 presents the mean delays for infrastructure scenario III, where it can be observed that RAR has the highest mean delay.

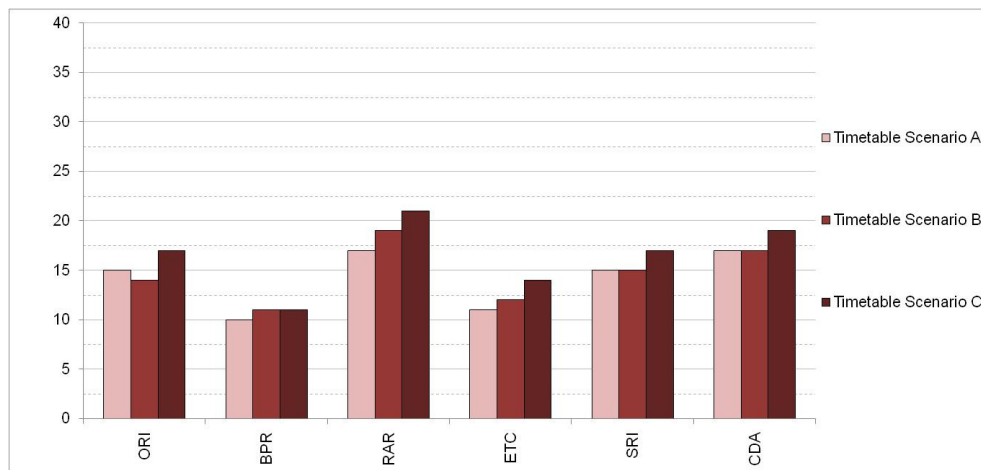


Figure 6.24 – Mean Delays - Infrastructure Scenario III

6.5.3.4 Global Assessment

The global assessment of the simulation results for each scenario is presented in Table 6.13. For the current infrastructure and current timetable, the aggregated results of the model for the average delays and punctuality are 19 seconds and 93,9%, respectively.

		Timetable Scenarios							
		Current Situation		Scenario A		Scenario B		Scenario C	
		Average Delays [s]	Punctuality	Average Delays [s]	Punctuality	Average Delays [s]	Punctuality	Average Delays [s]	Punctuality
Infrastructure Scenarios	Scenario I	19	93,4%	24	90,2%	26	88,7%	27	87,9%
	Scenario II	-	-	19	93,4%	21	91,6%	24	89,9%
	Scenario III	-	-	14	95,8%	15	95,7%	16	95,0%

Table 6.13 –Simulation Results, Global Assessment

As expected, it can be observed that performance levels decrease when the number of trains increases, and performance levels increase with infrastructure improvements. It is also noticeable that in scenario I-A the average delays increases 5s and the punctuality reduces approximately 3%, when compared to the current timetable and infrastructure.

From the aggregated results it is noted a performance improvement from infrastructure scenario I to infrastructure scenario II with timetable scenario A. The infrastructure improvement generates an increase of 3,2% in the aggregate punctuality for timetable scenario A. For timetable Scenarios B and C the infrastructure improvement generates performance progressively less significant when compared to scenario A.

The infrastructure scenario III generates more stable results, which are less sensitive to timetable changes, revealing higher capacity than the remaining infrastructure scenarios,

Table 6.14 presents the improvements in the performance measures achieved by each infrastructure enhancement.

		Timetable Scenarios					
		Scenario A		Scenario B		Scenario C	
		Average Delays [s]	Punctuality	Average Delays [s]	Punctuality	Average Delays [s]	Punctuality
Infrastructure Scenarios	Scenario I → Scenario II	-5	3,2%	-5	2,9%	-3	2,0%
	Scenario II → Scenario III	-5	2,4%	-6	4,1%	-8	5,1%

Table 6.14 –Performance Improvements by each Infrastructure Enhancement

6.6 Capacity and Performance Evaluation

6.6.1 Accomplishment of Performance Goals and Capacity Evaluation of Each Scenario

As discussed in chapter 4 *Railway Capacity Evaluation*, it is difficult to state capacity in a straightforward way. Capacity is directly linked with the level of performance required for the railway system.

In this study, the capacity in each scenario is evaluated for four performance levels goals: punctualities of 80%, 85%, 90% and 95 %. Therefore, if a scenario has punctuality above the performance goal in all evaluation points, it is said that that it is feasible. This means that the scenario capacity is not exceeded.

If in any evaluation point the punctuality is below the performance goal, the scenario is considered as unfeasible. This means that the scenario has capacity shortage.

Figure 6.25 presents the punctualities for infrastructure scenario I with performance thresholds of 80%, 85%, 90% and 95%.

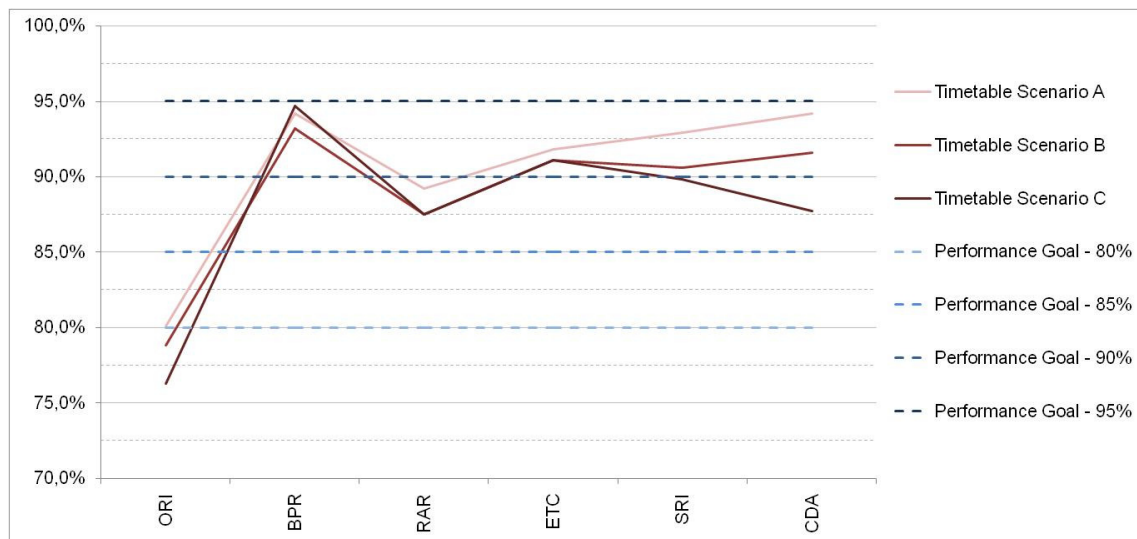


Figure 6.25 – Accomplishment of Performance Goals – Infrastructure Scenario I

From Figure 6.25 it can be observed that scenario I-B and scenario I-C do not fulfill the required performance level in ORI in any established performance goals, and therefore are considered to be unfeasible.

It can also be observed that timetable scenario A is the only timetable scenario that can obtain the required performance levels in all evaluation points for a performance goal of 80%. Thus, this is the only feasible timetable scenario for infrastructure scenario I.

Figure 6.26 presents the punctualities for infrastructure scenario II with performance thresholds of 80%, 85%, 90% and 95%.

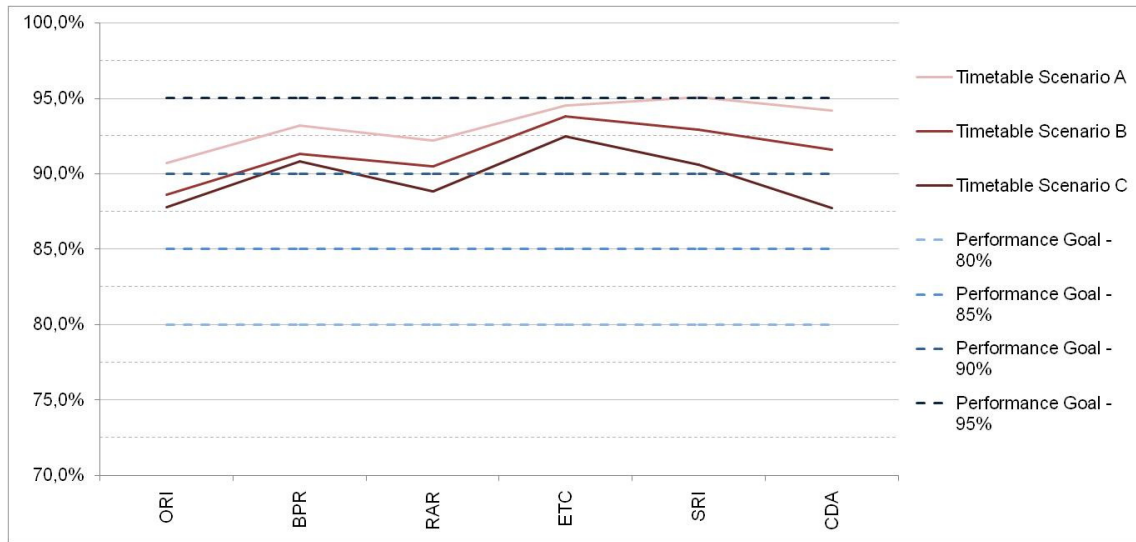


Figure 6.26 – Accomplishment of Performance Goals – Infrastructure Scenario II

The upgrade in ORI/BPR section enables the feasibility of scenarios B and C, which are attainable with performance goals of 80% and 85%. The infrastructure improvements enable also to improve the exploitation of timetable scenario A at a performance level of 90%.

A performance level of 95% is not possible to achieve with infrastructure scenario II in any timetable scenario.

Figure 6.27 presents the punctualities for infrastructure scenario III with performance thresholds of 80%, 85%, 90% and 95%.

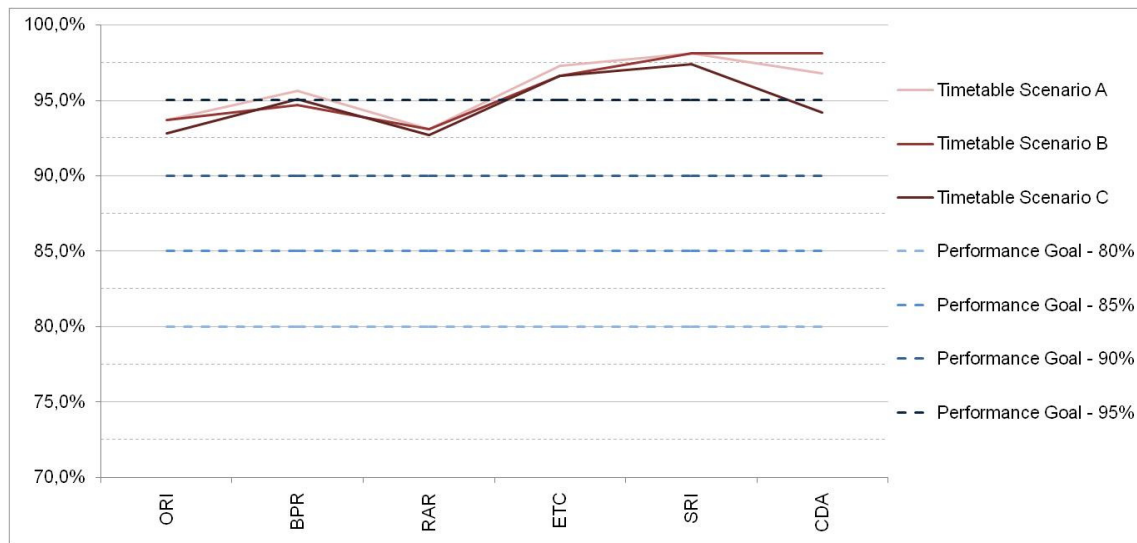


Figure 6.27 – Accomplishment of Performance Goals – Infrastructure Scenario III

From Figure 6.27 it is possible to notice that infrastructure scenario III improve the performance of timetable scenario B and C, enabling the exploitation of those scenarios at a performance level of 90%.

Despite the overall improvements observed in infrastructure scenario III, it is not possible to achieve a performance level of 95% in timetable scenario A.

The feasibility of the studied scenarios, for a performance goal of 80%, is summarized in Table 6.15.

		Timetable Scenarios		
		Scenario A	Scenario B	Scenario C
Infrastructure Scenarios	Scenario I	✓	✗	✗
	Scenario II	✓	✓	✓
	Scenario III	✓	✓	✓

Table 6.15 – Scenarios Feasibility, Performance Goal of 80%

Table 6.15 shows that all scenarios are considered to be feasible at a performance level of 80%, with the exception of scenarios I-B and I-C.

The feasibility of the studied scenarios, for a performance goal of 85%, is summarized in Table 6.16.

		Timetable Scenarios		
		Scenario A	Scenario B	Scenario C
Infrastructure Scenarios	Scenario I	✗	✗	✗
	Scenario II	✓	✓	✓
	Scenario III	✓	✓	✓

Table 6.16 – Scenarios Feasibility, Performance Goal of 85%

Table 6.16 shows that scenario I is unfeasible for all timetable scenarios, whereas infrastructure scenarios II and III remain feasible in all timetable scenarios.

The feasibility of the studied scenarios, for a performance goal of 90%, is summarized in Table 6.15.

		Timetable Scenarios		
		Scenario A	Scenario B	Scenario C
Infrastructure Scenarios	Scenario I	✗	✗	✗
	Scenario II	✓	✗	✗
	Scenario III	✓	✓	✓

Table 6.17 – Scenarios Feasibility, Performance Goal of 90%

It is possible to observe in Table 6.17 that infrastructure scenario II becomes unfeasible in timetable scenarios B and C for a performance goal of 90%. Infrastructure Scenario III achieves the performance goal in all timetable scenarios.

The feasibility of the studied scenarios, for a performance goal of 95%, is summarized in Table 6.18.

		Timetable Scenarios		
		Scenario A	Scenario B	Scenario C
Infrastructure Scenarios	Scenario I	✗	✗	✗
	Scenario II	✗	✗	✗
	Scenario III	✗	✗	✗

Table 6.18 – Scenarios Feasibility, Performance Goal of 95%

Table 6.18 shows that it is not possible to operate at a performance level of 95% in all the 9 scenarios under analysis, and, therefore they are considered to be unfeasible for that performance goal.

6.6.2 Inferences on the Feasibility of Each Scenario

The performance and capacity evaluation can be summarized in Table 6.19, which presents the operations performances thresholds for each scenario.

		Timetable Scenarios		
		Scenario A	Scenario B	Scenario C
Infrastructure Scenarios	Scenario I	80%	<80%	<80%
	Scenario II	90%	85%	85%
	Scenario III	90%	90%	90%

Table 6.19 – Performance Thresholds Summary

From this table it is possible to identify the infrastructure investments overtime needed to fulfill the required railway system performance levels. The infrastructure scenarios to operate each timetable for different strategies of operation (performance levels of 80%, 85% and 90%) are presented below.

- **Strategy: Operate at a performance level of 80%**

If the strategy is to operate at a performance level of 80%, the system can start the operations without an initial investment, since scenario I-A guarantees a performance level of 80%. When demand requires the implementation of timetable scenario B, it is necessary to upgrade the infrastructure to scenario II in order to assure the required performance levels. For this level of performance it is not needed another infrastructure improvement since scenario II-C accomplishes the required performance level.

In this way, if the chosen strategy is to operate a performance level of 80%, there is 1 infrastructure investment to make when demand requires timetable scenario B, as presented in Table 6.20.

		Timetable Scenarios		
		Scenario A	Scenario B	Scenario C
Infrastructure Scenarios	Scenario I	80%	<80%	<80%
	Scenario II	90%	85%	85%
	Scenario III	90%	90%	90%

Table 6.20 – Infrastructure Investments Decision Matrix – Operation at a performance level of 80%

- **Strategy: Operate at a performance level of 85%**

If the strategy is to operate at a performance level of 85%, an improvement in the infrastructure is needed in the beginning of the operations, since scenario I-A does not accomplishes the required performance level. Thus, this strategy requires an early infrastructure investment. When demand requires the implementation of timetable scenarios B and C, the infrastructure scenario II fulfills the performance levels, therefore the infrastructure does not need further improvements. This can be observed in Table 6.21.

		Timetable Scenarios		
		Scenario A	Scenario B	Scenario C
Infrastructure Scenarios	Scenario I	80%	<80%	<80%
	Scenario II	90%	85%	85%
	Scenario III	90%	90%	90%

Table 6.21 – Infrastructure Investments Decision Matrix – Operation at a performance level of 85%

- **Strategy: Operate at a performance level of 90%**

Similarly to the previous strategy, if the chosen strategy is to operate at a performance level of 90%, the infrastructure should be improved to scenario II in the beginning of the operations. When demand requires the implementation of timetable scenario B, the infrastructure should be improved to scenario III since scenario II-B does not accomplish required performance level for this strategy. For the higher demand scenario (timetable scenario C), infrastructure scenario III fulfill the required performance level.

In this way, if the chosen strategy is to operate a performance level of 90%, two infrastructure investments are needed: the first improvement (infrastructure scenario II) should be done in the beginning of the operations, and the second investment should be done when demand requires the implementation of timetable scenario B. This can be observed in Table 6.22.

		Timetable Scenarios		
		Scenario A	Scenario B	Scenario C
Infrastructure Scenarios	Scenario I	80%	<80%	<80%
	Scenario II	90%	85%	85%
	Scenario III	90%	90%	90%

Table 6.22 – Infrastructure Investments Decision Matrix – Operation at a performance level of 90%

7. Conclusions and Further Developments

The main objective of this dissertation was the development and evaluation of intermediate scenarios for incremental capacity improvements for the case study of the Portuguese part of the Lisbon – Madrid High-Speed rail corridor.

On this regard, a preliminary evaluation of the capacity consumption on the selected study area was performed using the UIC leaflet 406 methodology, which allowed the identification of the bottleneck sections for the traffic increase. This analysis discussed and quantified the current capacity constraints in the PRNO, which are located in the Lisbon metropolitan area. A set of scenarios for incremental capacity improvements were developed and evaluated in multiple exploitation environments, through simulation, together with 3 timetable (demand) scenarios.

The simulation results allowed to perform a performance and capacity evaluation of each scenario, and to establish a set of different strategies for the infrastructure development as demand for High-Speed services increases. The simulation methodology proved to be a powerful and needed tool for the strategic planning of a complex transportation system, such as the selected case study.

The incremental capacity design methodology can be a useful approach to deal with uncertainty in future demand and to deal with budget constraints, providing flexibility to the project by giving the option to defer part of the investments. This gives the possibility to obtain more information about uncertain variables.

This study allowed to understand the impacts of each infrastructure improvements in the punctuality and mean delay for each timetable scenario. With this information, a decision matrix for the timing of the infrastructure investments was developed, depending on the system performance level goal. It is to be noted that it was not possible to achieve performance levels of 95% in any infrastructure scenario. This leads to conclude that, for the case study under analysis, the operation of High-Speed services in conventional railway infrastructure is not feasible if the pursued performance levels are too high.

As for further research, a timetable optimization concerning capacity maximization can be analyzed and evaluated. A more efficient timetable can improve infrastructure capacity.

Finally, as stated previously, one should bear in mind that this study is focused on the supply perspective, and does not consider the effects on the demand due to operate conventional and High-Speed services in the same infrastructure. The operation of High-Speed services in conventional railway infrastructures, in part or in all route, have an impact in travel times, since speed constraints will be higher than if operated in a dedicated infrastructure. In fact, if the operation of the Lisbon – Madrid High-Speed train in the Poceirão – Lisbon section is carried through the conventional railway infrastructure, the travel times between Lisbon and Madrid should increase by around 1h, according to the simulation performed by RAVE. Since travel time is a highly valued attribute by High-Speed services passengers, the demand forecast for this service will definitely decrease and, thus, the economical and financial feasibility of the project should be re-evaluated. Thus, in a medium to long term perspective,

this High-Speed rail corridor should evolve to a solution with a dedicated infrastructure, in order to be a more competitive mode in relation to other transportation modes, being capable to generate and to attract demand.

8. References

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Appendix 1 – Detailed Features of the Study Area Infrastructure

Line	Section		Length [km]	Number of Tracks	Track Gauge	Safety and Signaling System	Electrification System	Maximum Load	Loading Gauges	Communication System
	Begin	End								
Norte	Braço de Prata	Alverca	17,818	Quadruple	Broad	Bi-directional automatic block signalling (EBICAB 700)	25 kV / 50 Hz	D4	CPb+	Rádio Solo-Comboio TTT CP N
	Alverca	Castanheira do Ribatejo	12,424	Triple	Broad	Bi-directional automatic block signalling (EBICAB 700)	25 kV / 50 Hz	D4	CPb+	Rádio Solo-Comboio TTT CP N
	Castanheira do Ribatejo	Santana-Cartaxo Resguardo	28,952	Double	Broad	Bi-directional automatic block signalling (EBICAB 700)	25 kV / 50 Hz	D4	CPb+	Rádio Solo-Comboio TTT CP N
	Santana-Cartaxo Resguardo	Entroncamento	43,116	Double	Broad	Single directional automatic block signalling (EBICAB 700)	25 kV / 50 Hz	D4	CPb+	Rádio Solo-Comboio TTT CP N
Cintura	Campolide A	Sete Rios	1,140	Double	Broad	Bi-directional automatic block signalling (EBICAB 700)	25 kV / 50 Hz	D4	CPb+	Rádio Solo-Comboio TTT CP N
	Sete Rios	Terminal Técnico de Chelas	3,650	Quadruple	Broad	Bi-directional automatic block signalling (EBICAB 700)	25 kV / 50 Hz	D4	CPb+	Rádio Solo-Comboio TTT CP N
	Terminal Técnico Chelas	Braço de Prata	2,836	Double	Broad	Bi-directional automatic block signalling (EBICAB 700)	25 kV / 50 Hz	D4	CPb+	Rádio Solo-Comboio TTT CP N
Sul	Campolide A	Alvito A	2,552	Double	Broad	Bi-directional automatic block signalling (EBICAB 700)	25 kV / 50 Hz	D4	CPb+	Rádio Solo-Comboio TTT CP N
	Alvito A	Pragal	5,100	Double	Broad	Bi-directional automatic block signalling (EBICAB 700)	25 kV / 50 Hz	(*)	CPb+	Rádio Solo-Comboio TTT CP N
	Pragal	Pinhal Novo	29,506	Double	Broad	Bi-directional automatic block signalling (EBICAB 700)	25 kV / 50 Hz	D4	CPb+	Rádio Solo-Comboio TTT CP N
	Bifurcação Águas Moura Sul	Ermidas-Sado	84,292	Single	Broad	Bi-directional automatic block signalling (EBICAB 700)	25 kV / 50 Hz	D4	CPb+	Rádio Solo-Comboio TTT CP N
Alentejo	Pinhal Novo	Poceirão	14,968	Double	Broad	Bi-directional automatic block signalling (EBICAB 700)	25 kV / 50 Hz	D4	CPb+	Rádio Solo-Comboio TTT CP N
	Poceirão	Vendas Novas	26,431	Single	Broad	Bi-directional automatic block signalling (EBICAB 700)	25 kV / 50 Hz	D4	CPb+	Rádio Solo-Comboio TTT CP N
	Vendas Novas	Casa Branca	33,568	Single	Broad	Bi-directional automatic block signalling (EBICAB 700)	25 kV / 50 Hz	D4	CPb	GSM-P
Évora	Casa Branca	Évora	26,049	Single	Broad	Bi-directional automatic block signalling (EBICAB 700)	25 kV / 50 Hz	D4	CPb+	GSM-P
Vendas Novas	Setil	Vendas Novas	69,609	Single	Broad	Bi-directional automatic block signalling (EBICAB 700)	25 kV / 50 Hz	D4	CPb+	Rádio Solo-Comboio TTT CP N
Poceirão	Bifurcação do Poceirão	Bifurcação Águas de Moura Norte	5,357	Double	Broad	Bi-directional automatic block signalling (EBICAB 700)	25 kV / 50 Hz	D4	CPb+	Rádio Solo-Comboio TTT CP N
	Bifurcação Águas de Moura Norte	Bifurcação Águas de Moura Sul	2,805	Single	Broad	Bi-directional automatic block signalling (EBICAB 700)	25 kV / 50 Hz	D4	CPb+	Rádio Solo-Comboio TTT CP N
Alcácer	Pinheiro	Grândola Norte	29,740	Single	Broad	Bi-directional automatic block signalling (EBICAB 700)	25 kV / 50 Hz	D4	CPb+	Rádio Solo-Comboio TTT CP N
Sines	Ermidas-Sado	Porto de Sines	50,539	Single	Broad	Bi-directional automatic block signalling (EBICAB 700)	25 kV / 50 Hz	D4	CPb+	Rádio Solo-Comboio TTT CP N

(*) 25 de Abril bridge maximum load constraints

Appendix 2 – Timetable Scenarios

High-Speed Trains Timetable, Madrid → Lisbon

Timetable Scenario A

	A	D		A	D		A	D	
Alvito A		05:57:30			07:57:30			09:57:30	
Campolide		06:01:00			08:01:00			10:01:00	
Sete Rios		06:03:00			08:03:00			10:03:00	
Entrecampos Poente		06:04:30			08:04:30			10:04:30	
Entrecampos		06:05:00			08:05:00			10:05:00	
Roma Areeiro		06:06:00			08:06:00			10:06:00	
Braço de Prata		06:09:30			08:09:30			10:09:30	
Oriente	06:12:00			08:12:00			10:12:00		

Timetable Scenario B

	A	D		A	D		A	D		A	D		A	D		A	D	
Alvito A		05:57:30			06:57:30			07:57:30			08:57:30			09:57:30			10:57:30	
Campolide		06:01:00			07:01:00			08:01:00			09:01:00			10:01:00			11:01:00	
Sete Rios		06:03:00			07:03:00			08:03:00			09:03:00			10:03:00			11:03:00	
Entrecampos Poente		06:04:30			07:04:30			08:04:30			09:04:30			10:04:30			11:04:30	
Entrecampos		06:05:00			07:05:00			08:05:00			09:05:00			10:05:00			11:05:00	
Roma Areeiro		06:06:00			07:06:00			08:06:00			09:06:00			10:06:00			11:06:00	
Braço de Prata		06:09:30			07:09:30			08:09:30			09:09:30			10:09:30			11:09:30	
Oriente	06:12:00			07:12:00			08:12:00			09:12:00			10:12:00			11:12:00		

Timetable Scenario C

	A	D	A	D	A	D	A	D	A	D	A	D	A	D	A	D	A	D	A	D	
Alvito A		05:57:30		06:22:00		06:57:30		07:22:00		07:57:30		08:22:00		08:57:30		09:22:00		09:57:30		10:22:00	
Campolide		06:01:00		06:24:30		07:01:00		07:24:30		08:01:00		08:24:30		09:01:00		09:24:30		10:01:00		10:24:30	
Sete Rios		06:03:00		06:27:00		07:03:00		07:27:00		08:03:00		08:27:00		09:03:00		09:27:00		10:03:00		10:27:00	
Entrecampos Poente		06:04:30		06:31:30		07:04:30		07:31:30		08:04:30		08:31:30		09:04:30		09:31:30		10:04:30		10:31:30	
Entrecampos		06:05:00		06:32:00		07:05:00		07:32:00		08:05:00		08:32:00		09:05:00		09:32:00		10:05:00		10:32:00	
Roma Areeiro		06:06:00		06:33:00		07:06:00		07:33:00		08:06:00		08:33:00		09:06:00		09:33:00		10:06:00		10:33:00	
Braço de Prata		06:09:30		06:39:00		07:09:30		07:39:00		08:09:30		08:39:00		09:09:30		09:39:00		10:09:30		10:39:00	
Oriente	06:12:00		06:41:00		07:12:00		07:41:00		08:12:00		08:41:00		09:12:00		09:41:00		10:12:00		10:41:00		11:12:00

A - Arrival Time
D - Departure Time

High-Speed Trains Timetable, Lisbon → Madrid

Timetable Scenario A

	A	D		A	D		A	D	
Oriente		06:15:00			08:15:00			10:15:00	
Braço de Prata		06:17:00			08:17:00			10:17:00	
Roma Areeiro		06:21:00			08:21:00			10:21:00	
Entrecampos		06:22:00			08:22:00			10:22:00	
Entrecampos Poente		06:22:30			08:22:30			10:22:30	
Sete Rios		06:24:00			08:24:00			10:24:00	
Campolide		06:26:00			08:26:00			10:26:00	
Alvito A		06:28:30			08:28:30			10:28:30	

Timetable Scenario B

	A	D		A	D		A	D		A	D		A	D		A	D	
Oriente		06:15:00			07:15:00			08:15:00			09:15:00			10:15:00			11:15:00	
Braço de Prata		06:17:00			07:17:00			08:17:00			09:17:00			10:17:00			11:17:00	
Roma Areeiro		06:21:00			07:21:00			08:21:00			09:21:00			10:21:00			11:21:00	
Entrecampos		06:22:00			07:22:00			08:22:00			09:22:00			10:22:00			11:22:00	
Entrecampos Poente		06:22:30			07:22:30			08:22:30			09:22:30			10:22:30			11:22:30	
Sete Rios		06:24:00			07:24:00			08:24:00			09:24:00			10:24:00			11:24:00	
Campolide		06:26:00			07:26:00			08:26:00			09:26:00			10:26:00			11:26:00	
Alvito A		06:28:30			07:28:30			08:28:30			09:28:30			10:28:30			11:28:30	

Timetable Scenario C

	A	D	A	D	A	D	A	D	A	D	A	D	A	D	A	D	A	D	A	D				
Oriente		06:15:00		06:45:00		07:15:00		07:45:00		08:15:00		08:45:00		09:15:00		09:45:00		10:15:00		10:45:00		11:15:00		11:45:00
Braço de Prata		06:17:00		06:47:00		07:17:00		07:47:00		08:17:00		08:47:00		09:17:00		09:47:00		10:17:00		10:47:00		11:17:00		11:47:00
Roma Areeiro		06:21:00		06:51:00		07:21:00		07:51:00		08:21:00		08:51:00		09:21:00		09:51:00		10:21:00		10:51:00		11:21:00		11:51:00
Entrecampos		06:22:00		06:52:00		07:22:00		07:52:00		08:22:00		08:52:00		09:22:00		09:52:00		10:22:00		10:52:00		11:22:00		11:52:00
Entrecampos Poente		06:22:30		06:52:30		07:22:30		07:52:30		08:22:30		08:52:30		09:22:30		09:52:30		10:22:30		10:52:30		11:22:30		11:52:30
Sete Rios		06:24:00		06:54:00		07:24:00		07:54:00		08:24:00		08:54:00		09:24:00		09:54:00		10:24:00		10:54:00		11:24:00		11:54:00
Campolide		06:26:00		06:56:00		07:26:00		07:56:00		08:26:00		08:56:00		09:26:00		09:56:00		10:26:00		10:56:00		11:26:00		11:56:00
Alvito A		06:28:30		06:58:30		07:28:30		07:58:30		08:28:30		08:58:30		09:28:30		09:58:30		10:28:30		10:58:30		11:28:30		11:58:30

A - Arrival Time

D - Departure Time