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

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.

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

1. Introduction

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.

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 has 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.

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 accomplish this, the following methodology is applied:

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.

2. Capacity Consumption Analysis of the Selected Study Area

2.1 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 Portuguese Railway Network in Operation (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, *Poceirão* Line and *Sines* Line.

Figure 2.1 - Study Area

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.

2.2 Capacity Consumption

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.

The **analytical methods** are the simplest methods for determining railway capacity. They usually obtain Theoretical Capacity though 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).

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).

The **simulation methods** are reproductions of the real world operations that are used to test solutions (Abril el al., 2008).

To measure the railway capacity consumption in the study area, the UIC leaflet 406 methodology is applied. 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. 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.

The Figure 2.2 summarizes the described methodology.

Figure 2.2 – UIC 406 Capacity Consumption Methodology

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 2.1 – Capacity Consumption, UIC Leaflet

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%.

Table 2.1 and Figure 2.3 present the capacity consumption evaluation for the entire study area performed in for the time window 7h to 9h on 27th June of 2012.

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.

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 2.1 – Study Area Capacity Consumption Evaluation

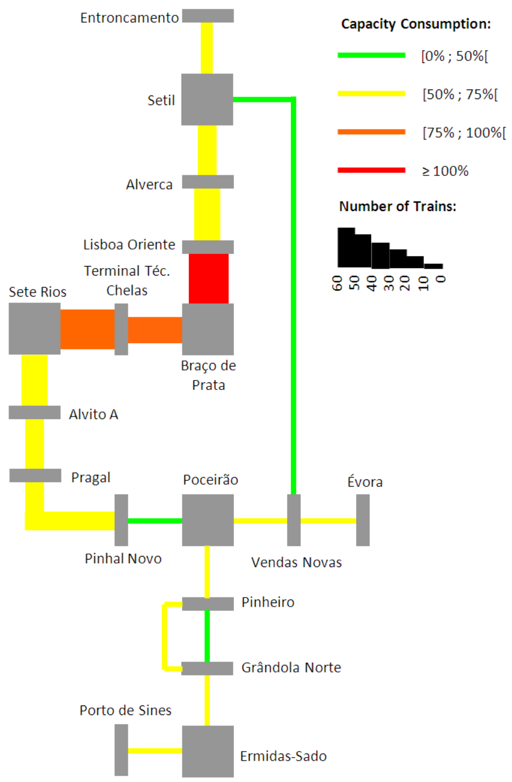

Figure 2.3 – Study Area Capacity Consumption Diagram

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

3.1 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 – *Poceirão* 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 €.

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.

3.2 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. This is summarized in Table 3.1.

Number of Trains (- → +)

Infrastructure Improvements (- → +)

	Timetable Scenarios		
Infrastructure 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 3.1 – Scenarios Considered in the Study

The infrastructure and timetable adopted in each scenario are presented in Table 3.2.

3.3 Measures of Performance

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

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 3.1.

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

Equation 3.1 – 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

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.

	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 *Lisboa Oriente/Braço de Prata* section	1 High Speed Train every 2 hours in each way
Scenario II-B	Improvement in the *Lisboa Oriente/Braço de Prata* section	1 High Speed Train every hour in each way
Scenario II-C	Improvement in the *Lisboa Oriente/Braço de Prata* section	2 High Speed Trains every hour in each way
Scenario III-A	Improvement in the *Lisboa Oriente/Braço de Prata* and Terminal Técnico Chelas/Braço de Prata sections	1 High Speed Train every 2 hours in each way
Scenario III-B	Improvement in the *Lisboa Oriente/Braço de Prata* and Terminal Técnico Chelas/Braço de Prata sections	1 High Speed Train every hour in each way
Scenario III-C	Improvement in the *Lisboa Oriente/Braço de Prata* and Terminal Técnico Chelas/Braço de Prata sections	2 High Speed Trains every hour in each way

Table 3.2 – Scenarios Summary

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.

3.4 Scenarios Simulation

3.4.1 Model Construction

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.

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 and stations are placed in nodes in OPENTRACK. The last stage in the generation of the railway network is the definition of train itineraries.

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.

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.

The global calibration of the model in OPENTRACK is carried out by adjusting the trains performance. 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 3.2 – 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 3.3.

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

Table 3.3 – Calibration Indicators

From Table 3.3 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.

3.4.2 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: *Lisboa Oriente, Braço de Prata, Roma Areeiro, Entrecampos, Sete Rios and Campolide* stations. For all scenarios the performance measures are calculated in each evaluation point.

The global assessment of the simulation results for each scenario is presented in Table 3.4.

		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 3.4 –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,

3.5 Capacity and Performance Evaluation

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.

The performance and capacity evaluation can be summarized in Table 3.5, 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 3.5 – Performance Thresholds Summary

Table 3.5 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. It is also noticeable that infrastructure scenario I does not achieve a performance higher than 80%.

Infrastructure scenario II enables to enhance the global performance in all timetable scenarios, when compared to infrastructure scenario I. The infrastructure scenario III enables to achieve a performance goal of 90% in all timetable scenarios.

From the performance and capacity evaluation performed 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 3.6.

		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 3.6 – 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 3.7.

		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 3.7 – 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 3.8.

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

4. 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 results of the simulation allowed to fulfill 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 no 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, thus, the economical and financial feasibility of the project should be re-evaluated.

5. References

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