東京大学
THE UNIVERSITY OF TOKYO

Master's Thesis
修士論文

COMPARATIVE ANALYSIS OF THE LIFE CYCLE COST OF HIGH SPEED RAIL SYSTEMS
高速鉄道システムのライフサイクルコストに関する比較分析

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August 2012

ACKNOWLEDGMENT

I would like to express my sincere gratitude to my supervisor, Assistant Professor Hironori Kato for his stimulating guidance, for his time and patience, and for the pressure he put when necessary, but never in excess. His high expectations are matched by his careful attention, his friendliness and the confidence he puts in his students.

My thanks also go to other professors in the International Projects Laboratory, Professor Hideyuki Horii and Professor Riki Honda for their valuable advice. IP Lab offers a stimulating and open environment, and I wish to thank all its members, in particular Shunsaku Komatsuzaki for his support to students, as well as the former and current students of the “K-team”.

I would like to express my thanks to my co-advisor Hitoshi Ieda who is without a doubt one of the greatest teachers and professors, with a contagious passion to share and learn.

This thesis was made possible thanks to the interviewees both in Japan and in Europe who have accepted to give me some of their time and knowledge. In particular, I wish to express my special thanks to Laurent Bouillaut for providing me advice and contacts, and to Olivier Cazier for his continuous support, and the interesting discussions we had both in France and in Japan.

This work also concludes two wonderful years spent in Japan and Tokyo in particular. This experience cannot be shared in only a few words; I can only recommend discovering this fabulous country. I wish to thank all the people I have shared this time with, in particular those I have been living with. My stay here would never have been possible without the people who have made this happen, both at Todai and at Ecole des Ponts, in particular Louis Sato.

Last but not least, I wish to thank all the people who supported me from France. As always, my most devoted supporters are my family, and my closest friends. My thoughts particularly go to the person who has accepted to let me go and return to Japan even after experiencing the Great Tohoku Earthquake with me in Tokyo, and who continues to support me when I should be the one supporting her.

ABSTRACT

There is an increasing trend to consider high speed rail as a vertically separated industry in order to introduce more competition and better interoperability. A first consequence is a standardisation of rolling stock designs and the development of cost optimisation and decision support tools to increase the competitiveness of infrastructure management, which both aim at improving high speed rail services. However, high speed rail is an integrated system and this loss of integrated approach is not optimal from an engineering perspective. Engineering choices were historically guided by the local contexts of each country or region, and the many potential markets should have the opportunity to develop a system that is adapted to their own context. For these reasons, a life cycle cost model is proposed to optimise the choice of high speed rail systems under a given context.

This simple yet versatile model highlights the trade-offs between train design, infrastructure design, and operating constraints. It reveals that the manufacturers could consider larger capacity train designs. More importantly, it illustrates that a non-integrated approach such as a vertical separation without coordination leads to significant cost increases. Since higher costs would eventually be borne by the users or by the society, the regulatory authorities of the numerous high speed rail projects that are being implemented must not only coordinate the stakeholders but also ensure that their propositions and choices have a positive impact with adequate decision support tools.

Keywords: high speed rail; life cycle cost; TGV; Shinkansen;

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ABBREVIATIONS

HSR: High speed rail

ICE: German high speed train and network, stands for “InterCity Express”

JNR: Japan National Railways, former Japanese public railway operator.

JR: Japan Railway company, designates one of the six companies formed after the privatization of Japan National Railways: JR East, JR Central, JR West, JR Kyushu, JR Shikoku and JR Hokkaido. Only the first four JR companies operate Shinkansen.

LGV: name of French high speed lines, stands for “Ligne à Grande Vitesse”

LCC: Life cycle cost

MLIT: Japanese Ministry of Land, Infrastructure, Transport and Tourism

RAMS: Reliability, availability, maintainability and safety

RFF: French railway network manager, stands for “Réseau Ferré de France”

SNCF: French railway operator, stands for “Société Nationale des Chemins de fer Français”

TGV: French high speed trains, stands for “Train à Grande Vitesse”

UIC: International Union of Railways, stands for “Union Internationale des Chemins de fer”

1. OBJECTIVES, SCOPE AND OUTLINE

1.1. Objectives

The purpose of this study is to develop a new tool to calculate and optimise the life cycle cost of high speed rail. The output of the model should follow the following points:

- To estimate the costs of a new high speed rail system
- To assist in the selection of the best design options under specific local constraints
- To assist in the decision making process and allow a discussion among stakeholders.

1.2. Outline of report

The reasons underlying the necessity to develop this new tool are organized along three main axes.

Firstly, the history and development of high speed rail are reviewed to understand the contexts in which high speed rail was developed, and how those contexts evolved. It shows a convergence of philosophy in countries with an existing network, while new countries with different contexts have an increasing interest in high speed rail.

Secondly, a technical description of high speed rail systems highlights the very close relationships between rolling stock and infrastructure, and the pertinence to consider high speed rail as a whole.

Lastly, the different types of existing cost studies are reviewed, showing a specialisation in different fields and along different approaches, but lacking a comprehensive, integrated approach.

The life cycle cost tool is then described, explaining the boundaries, choices of models and data used. Next, the tool is applied to show how it can fulfil its objectives and which the outcomes are.

In conclusion, a summary of the content of the report is followed by an analysis of the results from the application, and the scope for future work is suggested.

1.3. Scope of research: definitions of high speed rail

High speed rail systems exist for almost fifty years now. Although the image of “bullet train” is very popular, one can wonder what makes it so different than conventional rail. In addition, the proper definitions of the high speed rail concept actually vary from one region to another, and depend on what is considered as high speed rail system.

1.3.1. A matter of speed

High speed rail is considered as a different mode than conventional rail, yet the main concept is the same since the beginning of railways: the contact of a steel wheel on a steel track. The distinction is actually based on the fact that above a certain speed, railways behave in a very different way.

The main problem of the speed increase is the visibility of the tracks and their surroundings. At high speed, drivers can neither see the lateral signalization, nor react in time if there is an intrusion on the tracks. Thus all the necessary information must be displayed in the cabin, and the tracks must be separated from the surroundings.

The design of the train has to be adapted as well. For instance, its aerodynamics must be good enough to reduce the aerodynamic drag, the suspensions must absorb the vibrations from the tracks, and the cabin must be air tight to avoid air flowing through it.

From an engineering perspective, the tracks play a critical role in the feasibility of high speed operation. Track geometry must be extremely well designed to avoid vibrations or even derailment. High speed rolling stock has a low axle load compared to conventional or freight trains, but lateral accelerations are very important at high speed and the track must endure them.[1] Maintenance of the infrastructure is thus very critical as well; a small default may have catastrophic consequences if not detected and taken care of. These engineering problematic will be explained with more details in chapter 3.

Nevertheless, higher speeds bring the advantage of time savings, and high speed rail has a very different target market than conventional rail. The figure below is an illustration of the competitive advantage brought by high speed rail in terms of travel time. According to this chart, high speed rail is more interesting for distances between 100km and 500km.

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[1] (Cazier, La Voie, 2012)

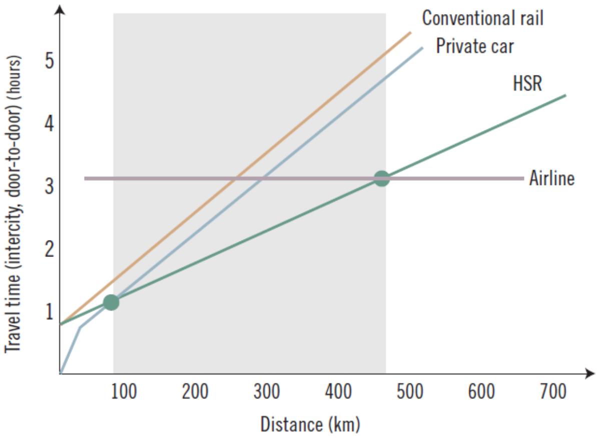

Figure 1 - Illustration of the competitiveness of HSR (de Rus, et al., 2009)

In fact, high speed rail market share can reach further distances. Figure 2 shows an example in North-East Japan, where JR East operates a part of the Shinkansen network. Even for distances up to 600km (Tokyo – Shin-Aomori), the use of Shinkansen is far more important, although travel time from Tokyo to Shin-Aomori is slightly shorter by air travel than by Shinkansen according to JR East estimations[2].

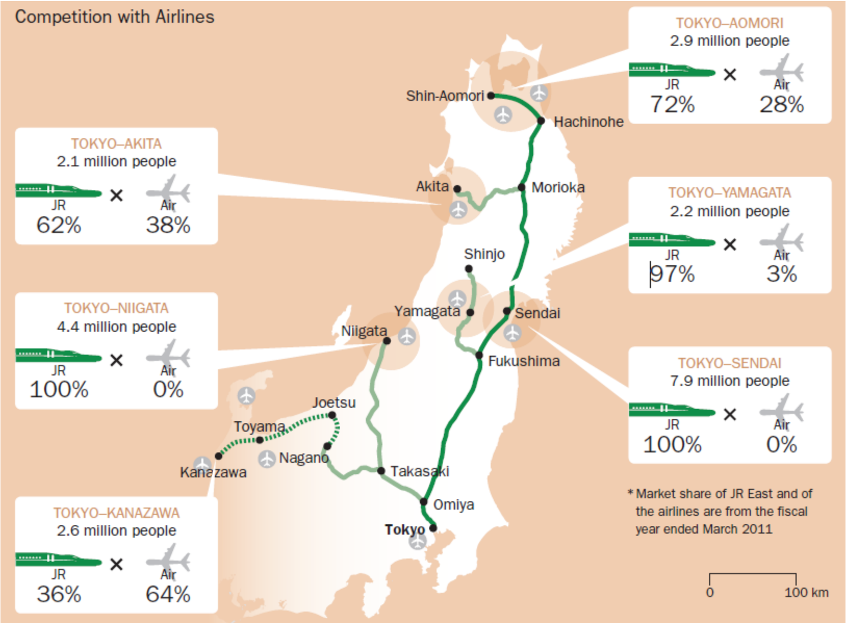

Figure 2 - Market share of Shinkansen versus airlines in North-East Japan in FY2010 (East Japan Railway Company, 2011)

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[2] (East Japan Railway Company, 2011)

1.3.2. Regional definitions

Each region where high speed rail is operated has its own definition of the system. The International Union of Railways (UIC) quotes three main definitions for Japan, United States and European Union.[3]

In Japan, the Shinkansen (literally "new trunk line") is defined by the government as "an artery railway that is capable of operating at the speed of two hundred kilometres per hour (200km/h) or more in its predominating section."[4]

The Federal Railroad Administration of the United States[5] defines High speed rail from the operational point of view, and distinguishes two cases:

- **HSR – Express.** Frequent, express service between major population centres 200–600 miles apart, with few intermediate stops. Top speeds of at least 150 mph on completely grade-separated, dedicated rights-of-way (with the possible exception of some shared track in terminal areas). Intended to relieve air and high-way capacity constraints.
- **HSR – Regional.** Relatively frequent service between major and moderate population centres 100–500 miles apart, with some intermediate stops. Top speeds of 110–150 mph, grade-separated, with some dedicated and some shared track (using positive train control technology). Intended to relieve highway and, to some extent, air capacity constraints.

The European Union has a more comprehensive definition that was published in the appendix of the Directive 96/48/EC[6]. This document defines the Technical Specifications for Interoperability on the European railway network. The definition considers both the infrastructure and the rolling stock:

- Infrastructure

  The infrastructure of the trans-European High Speed system shall be that of the lines of the trans- European transport network identified in Article 129C of the Treaty:
  - those built specially for High Speed travel,

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[3] (Yanase, 2010)

[4] (MLIT, 2010)

[5] (Federal Railroad Administration, 2009)

[6] (European Commission, 1996)

- those specially upgraded for High Speed travel. They may include connecting lines, in particular junctions of new lines upgraded for High Speed with town centre stations located on them, on which speeds must take account of local conditions.

High Speed lines shall comprise:

- Specially built High Speed lines equipped for speeds generally equal to or greater than 250 km/h,
- Specially upgraded High Speed lines equipped for speeds of the order of 200 km/h, specially upgraded High Speed lines which have special features as a result of topographical, relief or town-planning constraints, on which the speed must be adapted to each case.

- Rolling stock

  The High Speed advanced-technology trains shall be designed in such a way as to guarantee safe, uninterrupted travel:

  - at a speed of at least 250 km/h on lines specially built for High Speed, while enabling speeds of over 300 km/h to be reached in appropriate circumstances,
  - at a speed of the order of 200 km/h on existing lines which have been or are specially upgraded,
  - at the highest possible speed on other lines.

The latter definition shows that High speed rail should be considered as a whole system, which includes the infrastructure and the rolling stock. In addition to these two elements, the International Union of Railways (UIC) proposes a list of elements that form together the high speed rail system[7]:

- Infrastructure
- Station emplacement
- Rolling stock
- Operation rules
- Signalling systems
- Marketing
- Maintenance systems
- Financing
- Management

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[7] (UIC, 2010)

- Legal aspects

The UIC also highlights that High speed rail characteristics may differ among different countries and situation, so that it is very difficult to give a precise definition of high speed rail.

1.3.3. Operational definition: variability of high speed rail

One of the possible approaches is to consider the operational viewpoint in comparison with conventional rail to show the variability of high speed rail system. In that case, the UIC distinguishes four cases:

- Exclusive operation: in that case, high speed and conventional operations are completely separated and both have their own infrastructure. This is the case of the Japanese Shinkansen.
- Mixed high speed: although both systems have their own infrastructure, high speed rail may operate on (upgraded) conventional infrastructure with some limitations, allowing reductions in building costs. This is the case of the French TGV.
- Mixed conventional: some conventional trains may use the high speed infrastructure. This is the case of the Spanish railway network, which was first designed with a narrow gauge. The high speed network uses standard gauge and conventional trains with adaptive gauge systems may use the high speed infrastructure. Yet this flexible system reduces the overall capacity of high speed operations.
- Fully mixed: both high speed and conventional trains can use both infrastructures. This is the case in Germany and Italy where high speed rail uses some upgraded conventional lines, and freight services use spare capacity on high speed lines during the night.[8]

1.3.4. Definition for this study

In this master thesis, a high speed rail system satisfying both following conditions is considered:

- Infrastructure and rolling stock are designed to allow a maximum speed of 300km/h or more,
- Operations are exclusive, for passengers only.

The first hypothesis means that current rolling stock may need to be upgraded to improve the aerodynamics or the power output for instance. This hypothesis is not unrealistic given that

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[8] (Campos & de Rus, 2009)

some trains can already achieve a speed of 360km/h as it will be shown further on, and that speed records have been set above 500km/h twenty years ago. The second hypothesis allows the high speed line to be used at its maximum efficiency since the high speed trains are not slowed down by slower trains or conventional infrastructure. Those elements will be detailed in the following chapters.

Furthermore, the magnetic levitation technology is not considered as high speed rail. That is because although it is also a very high speed guided transportation system, it does not use the same technology as rail, which is steel wheel on rail. In addition, this technology has not been used as an intercity transportation system yet, and the current project of Maglev Chuo Shinkansen in Japan is still at a very early stage[9]

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[9] (Central Japan Railway Company, 2011)

2. HISTORY AND DEVELOPMENT OF HIGH SPEED RAIL: A REVIEW

High speed rail will soon celebrate its fiftieth birthday, and is rapidly growing and expanding. This chapter aims to explain the different context and motivations of its development, which not only show the different uses of a high speed system but also the reasons of its diversity. Then a few current high speed rail projects are presented, showing new local contexts, and rolling stock developments are described, highlighting a convergence in high speed train design.

2.1. Japanese Shinkansen: a step forward

On October 1, 1964, the Shinkansen was inaugurated; becoming the first operated high speed rail system in the world, and the only one until 1981. Since then, it has expanded and has always showed very high performances. This part is a summary of how this ground-breaking system has been created and how it evolved.

2.1.1. Purpose and design

Being the first high speed rail in the world, the Shinkansen had no other examples to be inspired from. It was a completely new railway system and came from the specific needs of the Japanese railway market. The development of the Shinkansen began in the 1950s. At that time, both private railway companies and Japan National Railway (JNR) coexisted, the latter being the largest railway company in Japan.[10]

The Japanese railway network suffered from extended damage after World War II, and its rolling stock was obsolete and unsafe. It appeared to JNR that they needed to implement new technologies in order to renew and regenerate their railways. Because of the 1,027mm narrow gauge in use all over the country with many steep grades and tight curves, the weight per axle of the trains had to be limited, and JNR chose to implement distributed motorization instead to replace steam locomotives. Since electric railcars were already in use, the choice was to electrify major existing lines and to develop electric multiple unit (EMU) motorization for the trains.

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[10] (Aoki, Imashiro, Kato, & Wakuda, 2000)

That technology also provides higher capacity due to shorter turnarounds at terminals. The first train using this technology was the "Shonan Densha" on the Tokaido line from Tokyo to Osaka, which was fully electrified in autumn 1956. The success was tremendous: regular tickets used to be sold out within ten minutes after being sold one month in advance.[11]

With its 556km length, that is 3% of the JNR network, the Tokaido line accounted for 24% of JNR passenger traffic (and 23% of freight traffic), with an impressive 7.6% annual growth. It was clear that the line would reach its capacity soon. Three solutions were proposed to tackle this issue:

- Double the Tokaido line capacity with a parallel double-track, narrow gauge line
- Build a double-track, narrow gauge line on a different route
- Build a new standard-gauge line

The idea to introduce the standard gauge was not very popular because it meant that the whole line should be built before the operation could start. If a financial problem occurred before the completion, the investment would prove useless. A parallel narrow-gauge line could be built in several steps, each of them improving a section of the existing line until the capacity is doubled on the entire line. But the JNR direction, embodied by Hideo Shima, chief Engineer and Shinji Sogo, president, realized that with the rising competitiveness of both car and air travel, higher level of service should be granted in order to keep up the pace. Moreover, a new standard gauge line would be used for express passenger service while the existing narrow-gauge line would carry freight and local passenger services. A more direct line with fewer stops and grades, and no tight curves nor grade crossing would furthermore allow high speed operation.

Regarding the rolling stock, it was decided to keep the EMU distributed power system that had been improved to allow more comfortable and safer travel (electric braking), as well as a light axle load. To power the train, West Japan commercial frequency of 25kV/60Hz was used as a standard, with conversion substations where 50Hz is used. In comparison, other electrified narrow-gauge lines used 1,5kV DC input.[12]

In December 1958, the decision was taken to build the new separate standard-gauge trunk line. The cost was estimated at 195 billion yen for a five-year construction period, in order to open the line for the 1964 Olympics. The funding was partly granted by a loan to the World Bank not

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[11] (Smith, 2003)

[12] (Mochizuki, 2011)

only to gather all the money, but also to make sure that changes in the political sphere would not impact the completion of the project, as it is required by the World Bank. The construction was completed in due time, and the first high speed rail system began its commercial operation on October 1st, 1964. The Tokaido Shinkansen proved to be both a technological and commercial success: within three years after inauguration, the revenue had already exceeded the initial costs.[13]

2.1.2. The Nationwide Shinkansen Railway Development Law

In 1970 the Japanese government enacted the Nationwide Shinkansen Railway Development Law to support the creation of a more than 7000km Shinkansen network to acknowledge the political pressures to cover the rest of the country.[14]

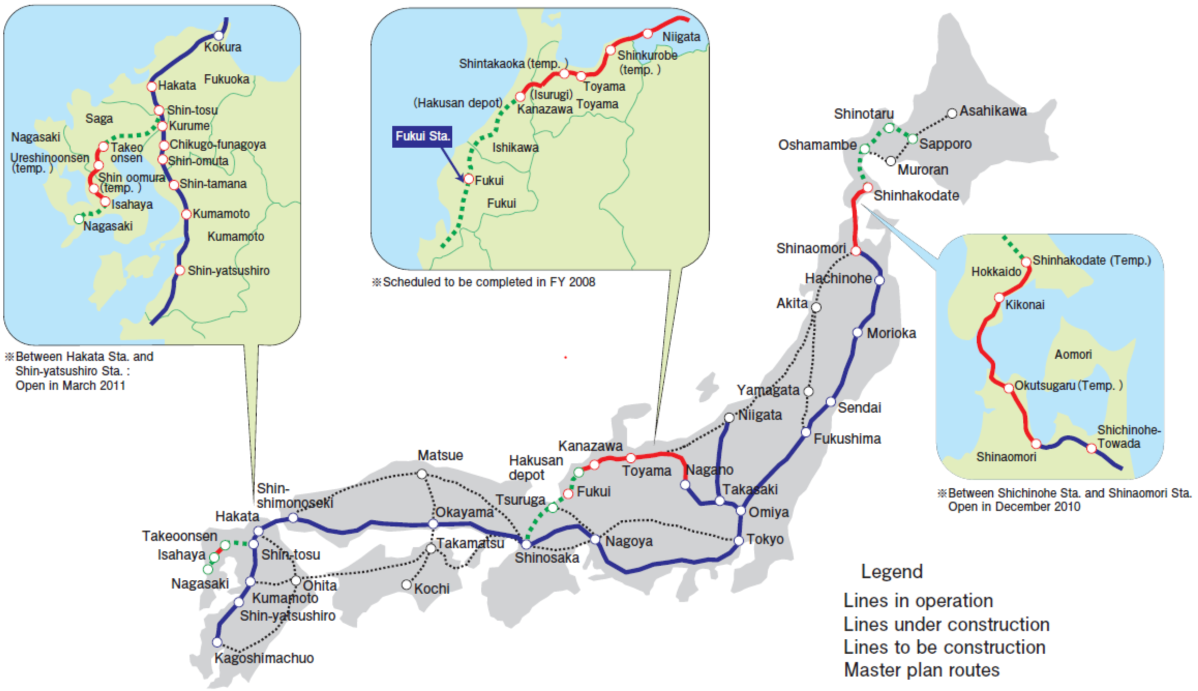

Figure 3 - Current status of Shinkansen network development (JRTT, 2012)

This master plan, as shown on Figure 3, projected to link the northern city of Asahikawa in Hokkaido Island to Kagoshima on southern Kyushu Island, not only through a simple corridor on Pacific coast of the main Honshu Island, but also crossing the central mountains to reach the Sea of Japan coast, as well as Shikoku Island.

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[13] (Aoki, Imashiro, Kato, & Wakuda, 2000)

[14] (Takatsu, 2007)

Nowadays, the existing network spreads from northern Aomori prefecture in northern Honshu to southern Kyushu, with a few branches spreading to the western coast. It is divided into four parts, each of which is operated by one of the six JR companies. The table below shows the list of existing Shinkansen lines, their origin and destination, length, year of opening and operator. It also includes the upgraded conventional lines called mini-Shinkansen, which need adapted trains that can run both trough Shinkansen and mini-Shinkansen lines.

Table 1 - Existing Shinkansen lines, adapted from (JRTT, 2012; Hood, 2006)

Section name	From	To	Length (km)	Year opened	Operator
Tokaido	Tokyo	Shin-Osaka	553	1964	JR Central
Sanyo	Shin-Osaka	Hakata	554	1972-1975	JR West
Joetsu	Omiya	Niigata	300	1982-1985	JR East
Tohoku	Tokyo	Shin-Aomori	675	1985-2010	JR East
Hokuriku	Takasaki	Nagano	117	1997	JR East
Kyushu	Hakata	Kagoshima-Chuo	257	2004-2010	JR Kyushu
Yamagata*	Fukushima	Shinjo	149	1992-1999	JR East
Akita*	Morioka	Akita	127	1997	JR East

**mini-Shinkansen lines*

2.1.3. Fifty years of high performances

Since 1964 many improvements have been made to the original Shinkansen design. In fact, for each new line, a new train set has been developed, in addition to the renewal of existing train sets.

2.1.3.1. Evolution of train set technology

If all the Shinkansen have a similar non-articulated EMU design, there have been several improvements in terms of aerodynamics capacity, axle load reduction, commercial speed, and riding comfort for instance.

There are many different types of Shinkansen, as Figure 4 shows, but some have two or more different structures. The 0 Series was the first Shinkansen, operated on the Tokaido line from 1964 to 2008. It was a 16-car train but was later reduced to 6-car for local services. 100 Series were introduced on Sanyo Shinkansen (Osaka-Fukuoka) in 1985 and will retire in 2012. They brought higher speed from 220km/h to 230km/h. They also have been shortened to 4-car and 6-car configurations. Other Series have also undergone such refurbishment (500, and E2). Some Series have had a very short life expectancy, such as 400 Series, replaced after 8 years of operation.

Figure 4 – Past, present and future Shinkansen rolling stock (Ishizuka, 2012)

Interestingly, the characteristics of the different Series show a wide range of variability. For instance the acceleration and axle load of the N700 and 800 Series are better than other Series although E5 and E6 are more recent. These high performances are required on the highly travelled Tokaido Shinkansen to reduce the distance between consecutive trains, and on the Kyushu Shinkansen that has steeper gradients. There are also different train structures, from 16-car design to 6-car design; some Series have a double-deck (E1 and E4) for an increased capacity aiming to provide a commuting operation pattern. Finally, the latest rolling stock has introduced a tilting mechanism to increase passenger comfort in curves and raise the speed on the Tokaido line, where the curves are tighter. Another particularity is the mini-Shinkansen, which is the name given to the narrow-gauge lines converted to standard gauge, allowing through-service for narrower cross-section Shinkansen trains at a slower speed of only 130km/h. Only 400, E2 and future E6 series are adapted to mini-Shinkansen tracks.[15] All those different characteristics highlight the fact that the different Shinkansen train sets are designed to be adapted to the section where they are operated: a double-decker train for commuting operations, a very light, tilting train for very high frequency despite tighter curves, powerful motors where the gradient is steeper. This is a particularity of the Shinkansen network: dedicated trains but low interoperability.

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[15] (Japanese Overseas Rolling Stock Association, 2004; UIC, 2011)

2.1.3.2. Exported Shinkansen

In addition to the local Shinkansen, two Shinkansen-based rolling stock models have been exported in Taiwan and China respectively. The distinction between Shinkansen and Shinkansen-based train is important since exported trains have been integrated with other foreign systems such as different signalization, and s such cannot be considered as Shinkansen systems.

The Taiwanese 700T is a 12 cars high speed train derived from the 700 Series Shinkansen, with a slightly shorter nose. Its maximum operating speed is 300km/h.[16]

The Chinese CHR2 is also derived from the Japanese Shinkansen.[17]

2.1.3.3. Strong points of Shinkansen operation

Since it was inaugurated, the Shinkansen has always had an image of very high quality and level of service, especially regarding the following points[18]:

- Safety record: up to now, and including the Great Tohoku Earthquake, there has never been any fatality during Shinkansen operation.
- High capacity: 341 trains are now operated every day only on the Tokaido Shinkansen, which represents around 138 million passengers per year. During the morning peak hour, up to 11 trains per hour depart from Tokyo, with a three-minute minimum interval.
- Average delay: with such a large amount of trains, the punctuality is a key issue, and JR Central has achieved an average delay of less than one minute per train. In comparison, around 25% of the French TGV are more than five minutes late.[19]

These strong points have been achieved thanks to high-end communication and signalization technologies, as well a fully separated infrastructure with earthquake-proof systems. These technical elements will be detailed in paragraph 3.2.4.3.

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[16] (Japanese Overseas Rolling Stock Association, 2009)

[17] (UIC, 2011)

[18] (Central Japan Railway Company, 2011)

[19] (RFF, 2011)

2.2. High speed rail in Europe: from specific needs to a European network

Although the European Union can be considered as a homogenous region to some extent, many differences between countries still exist. Regarding high speed rail development, a long way had to be achieved before a European high speed railway could emerge. This part focuses on three main points: the beginning of high speed rail in Europe, the technical developments that occurred, and then the creation of the emerging European high speed railway.

Initially, high speed rail was introduced separately in the European countries, and they were designed and built according to the specific needs of the countries. This is why there are several types of high speed trains in Europe and why they slightly differ in terms of infrastructure and rolling stock.[20]

2.2.1. French TGV

2.2.1.1. Purpose and design

After the Shinkansen was introduced in Japan, the French government started to investigate in order to implement a similar technology. The market share of the train was decreasing and the French operator, SNCF, wanted to address this problem by raising the speed to confront both car and airlines. The studies started in 1966, and a first prototype was unveiled in 1971. In this first version, the TGV was propelled by diesel turbines, and reached the speed of 318km/h, which is still the record for this kind of propulsion.[21]

One of the main characteristic of the TGV was already introduced: the Jacobs bogie. Instead of having separate cars, with two bogies at each side, the TGV was designed with shared bogies. Two cars stand on each side of one bogie but can still have a relative movement, which reduces the number of bogies, gives the train a harder structure and a lower gravity centre to reduce the risks of derailment, and allows tighter curves.[22] The Jacobs bogie has always been used on TGV designs, even up to now for the next-generation AGV that is described in the next part.

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[20] (Givoni, 2006)

[21] (Picard & Beltran, 1994; Klein, 2001)

[22] (Brabie, 2007; Fourniau, 2011)

The prototype helped the SNCF to understand more efficiently the behaviour of a high speed train: how to dissipate the kinetic energy during braking, how to improve the signalization that has to be displayed inside the driver's cabin because the train is too fast for conventional signalization, etc. But because of the oil crisis in 1973, and also for political reasons, it was eventually decided to change the power supply from turbines to electricity, using pantographs for the alimentation.[23] This important difference led to new research and development, which started in 1974. In the same time the development for a high speed line also began.

The new TGV Sud-Est (South-East) had a similar design to the prototype: two power cars and eight articulated cars joined with Jacobs bogies. The power was delivered by twelve 535kW DC motors with a 0.8 power factor, and can be alimented in both 1.5kV DC and 25kV AC. The cars were divided into two categories: 1st and 2nd class with 2+1 and 2+2 seats respectively, for a total of 368 seats and 345 today after two renovations. In the middle of a train is located a bar-restaurant car, which is still the case today. Two TGV can be coupled to provide higher capacity. Initially orange, the exterior was changed to blue and metallic silver like the other TGV.

The first line to be opened is Paris-Lyon , also called LGV Sud-Est, in three stages from 1981 to 1983, where the capacity is very limited due to mixed traffic (local, express and freight trains). SNCF actually had two options; one was to double the existing line which would have two lines in each directions, the other was to design and build a new infrastructure in a parallel course. The second option was chosen. Indeed, the cost-benefit evaluation showed that it was better to design a new and more direct line to decrease the total length, and to allow higher speed as there are less curves. In addition, the TGV is lighter than conventional trains, thus the cost of the infrastructure is actually lower than conventional line, despite the great precision required.

Moreover, the new high speed line was designed to be compatible with the existing conventional lines. The compatibility allows lower construction costs as it is not necessary to build a dedicated line until the city centre where there is hardly enough space for this. Moreover, the TGV can also go to more remote regions where the demand is not high enough to justify the creation of a High speed line.

2.2.1.2. Evolution of TGV rolling stock

There have been several iterations of the TGV. The TGV Atlantique was a first upgrade of the TGV SE. It introduced a more aerodynamic shape, more power with synchronous motors, 10

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[23] (Picard & Beltran, 1994)

passenger cars instead of 8, and the top speed is increased to 300km/h. They can also be coupled but only together.

In 1992, the TGV Réseau ("Network") was launched on the North High speed line from Paris to Lille, but is also operated on other lines of the network. They are some improvement from the TGV Atlantique such as the introduction of air tight cabin. A three-current version has also been launched to allow the train to circulate in Belgium and in Italy. The Thalys (1995, from the name of the operator), which links Paris, Brussels, Amsterdam and the German network, is a TGV Réseau with two different purple outlooks, compatible signalization and different interior design. Thalys can be coupled together or with a TGV Réseau.

In 1994 was inaugurated the Eurostar train, its original name being TGV TMST (TransManche Super Train). It is operated through the Channel Tunnel between France and Great Britain, linking Paris to London. The Eurostar has several differences in comparison with the other TGV. First, it has a different nose design and slightly smaller cross-section to fit in the British loading gauge. The train sets can be split in their middle and each part pulled in case of emergency. For this reason, the two halves are articulated like a regular TGV but not at the junction. And although they are too long to fit along a platform if coupled, this is possible if the train needs to be pulled by an emergency locomotive. It also introduced an asynchronous motor to increase the power output.

The TGV Duplex, first introduced in 1995, was a major evolution with its double-decker design. In its two locomotives, seven passenger cars and one restaurant car, the capacity is about 550 seats. Because of the double-decker design, the weight of the train had to be reduced to fit the loading gauge of 17 tons per axle that is the standard for French and European high speed network. There are several generations of Duplex, the latest being the EuroDuplex.

The TGV POS (Paris - Ostfrankreich – Süddeutschland: Paris – Eastern France – Southern Germany) has been designed for the LGV Est high speed line from Paris to Eastern France in 2006. It is a refurbished TGV Réseau with a new, more powerful locomotive with a design similar to Thalys and Duplex. The commercial speed has been increased to 320km/h and it is the first TGV to include the European traffic management standard by default, as well as signalization systems from France, Germany and Swiss. The new asynchronous motors allow the TGV POS to run at full speed in Germany despite a different current input. It is also equipped with electromagnetic brakes for the German network.[24] TGV POS was a specific order by SNCF

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[24] (Railway Gazette International, 2006)

for the LGV Est. The decision was made to replace the passenger cars of single-decker trains by Duplex cars on lines where the demand was high, and to use the new, more powerful, multi-systems locomotives with refurbished single-decker cars for the LGV Est.

In comparison with the Japanese strategy of rolling stock specialization, French operator SNCF prefers to have a standard train design that is operable on any line of the network.

2.2.1.3. Exportation of TGV technologies

The TGV has been a commercial success in France but also in a few countries where the technology was adapted to local market, in addition to the Eurostar and Thalys.

The AVE S-100, launched in 1988, is a modified TGV Atlantique with 10 passenger cars instead of 8, adapted current input and signalization, better air cooling to adapt to local conditions, better pressure reduction for the passengers, and different interior design with audio and video equipment. Despite the wider gauge used in Spain, the AVE S100 is designed for the standard gauge.

In the United States, a heavier version of the TGV has been launched between Boston and Washington in 2000. The Acela Express has two power cars and 6 passenger cars. It has been designed by Bombardier and Alstom to circulate on the existing network at 240km/h, and uses a tilting technology to reduce the discomfort in tight curves.

In Korea, the KTX inaugurated in 2004 is a modified TGV Réseau with two power cars, 1 motorized passenger cars at each extremity and 16 regular passenger cars, and reaches a maximum speed of 305km/h. Alstom won a bid against Siemens (ICE) and Mitsubishi (Shinkansen).

2.2.2. German ICE

2.2.2.1. Purpose, design and evolution

A few years after the TGV was first introduced, Germany launched their Inter-City Express, or ICE. In 1985, a prototype was launched and beat the world record at 406km/h in 1988.

The ICE began commercial operation in 1991 on two new lines, from Hamburg to Mannheim and from Stuttgart to Munich. The ICE has two power cars and 10 non-articulated cars, among which a restaurant car slightly higher than passenger cars. The ICE is also larger than the recommended loading gauge that would allow international circulation, in order to provide a higher comfort inside the cars. The top speed was 280km/h and the capacity 743 seats, more than a TGV, but ICE could not be coupled.

In comparison with the French TGV, the German ICE system was designed to overcome slow sections on the network.[25] Thus there was no debate on the necessity to build a new infrastructure, but the discussions were focused on the use of the new lines. The Deutsche Bahn (DB) decided that it would be better to allow mixed traffic so that they would all take advantage of the shorter trips. But this eventually became a drawback because the fast ICE was slowed by the slower freight trains. Another difference is that, while new TGV were introduced in the same time of the opening of new lines, this schedule was not the same in Germany. Thus when the third line opened there were not enough trains to provide regular service, and the DB had to wait several months.

The second version of ICE, ICE2, was launched in 1997 to provide smaller trains set on the line with lower demand. It has a similar shape but have only one power car, six passenger cars and a cab car with passenger seats, for a capacity of 391 seats.

The ICE3 introduces important changes: it is now powered by EMU distributed traction and integrates some interoperability measures to allow cross-border transit. The ICE3 is based on a Siemens Valero, which is briefly described in part 2.4.22.3.

Like SNCF, German operator Deutsche Bahn shows a preference for a standard train set to be operated on any line of its network, and eventually on the emerging European network. Through service to Paris on the French LGV Est are already operated.

2.2.2.2. Eschede disaster

Although high-speed rail has a well-earned reputation of being very safe, there was a very dramatic accident in Germany, which remains the deadliest high speed train accident in the world. It happened on June 3rd, 1998 near the village of Eschede in Germany, on the line between Munich and Hamburg.[26]

The steel tire of a wheel of the second car (first passenger car) broke, punctured the train floor and stayed embedded. When the train came to a track switch further, the broken part eventually caused following cars to take the wrong direction, leading the train to be slammed against the piers of a highway bridge. The bridge then collapsed on the train, eventually killing a total of 101 people passed away and injuring more than 100 people.

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[25] (Givoni, 2006)

[26] (Kieselbach, Esslinger, Koller, & Weisse, 2004)

The accident was actually caused by a modification of the wheel design. Indeed, to reduce the vibration and noise inside the cabin, a rubber ring was installed between the tire and the body of the monobloc wheels. The rubber got eventually used, deformed, and lead to cracks. The design was not fully tested at high speed but endured several years before the accident.

This was the deadliest accident in the history of high speed rail but has not slowed down the development of high speed rail in Europe, partly because the wheel design modification affected only the German ICE. Yet this accident highlights the importance of testing every component of the system before commercial operation.

2.2.3. European network and interoperability

For more than one and a half century, railways were developed according to national schemes, like TGV and ICE mentioned in the previous paragraphs. Each company had its own technical standards and operation rules, obeying national requirements. Each network had, and still has its own specific signalization and communication systems. Thus it was very difficult and costly to cross the borders through railway, for both freight and passenger traffics. This part shows first the various incompatibilities that exist over Europe, and then briefly explains the decisions made at the European level to eventually create an interoperable railway network.

2.2.3.1. Incompatibilities between countries

Across Europe, many different technical standards are coexisting on the conventional and high speed railway networks:

- 17 signalization and communication systems
- 6 loading gauges
- 4 different electric current voltages and frequencies
- 4 rail gauge: 1.435m (standard gauge), 1.67m (Spain), 1.6m (Ireland) and 1.524m (Finland and ex-USSR members)

This situation is still a source of complication and cost for trans-border traffic and leads to a fragmented railway market. In spite of many efforts to integrate those railway systems, the national segmentation is still a main issue that slows the development of European services. And as long as those shared services cannot emerge, the Union will not be allowed to implement a real common market.

But those problems are not recent, and several attempts were made to find solutions. In 1882, several European governments have met to establish a Technical Unity that every railway company should follow. Among those standards, the normal width for the gauge was defined

(1435mm), but a few countries such as Spain, Finland or Russia kept their own width (especially to avoid an invasion through railway in case of war). Moreover these agreements were not enough to create real railway integration in Europe.

In 1922, the UIC (International Union of Railway) was created to gather railway companies. Thus the companies were discussing directly with few direct interference from the governments. The UIC established the main characteristics of the modern railway networks. Actually, there were many small differences from a country to another, but the UIC determined several standards that were integrated in prescriptions. Although those prescriptions are not mandatory, the companies had more benefit to apply them and to be able to share services with their neighbours. During the following decades, other agreements were made to ease the interoperability of passenger and freight railway cars. Step by step, the companies began to apply similar standards.

Nonetheless those standards were only focused on railway cars and not on the power cars or motorization units. The companies failed to agree on signalization and alimentation standards, and thus limited border crossing to cases when agreements between two countries could be found. But actually the length of the administrative process to find these agreements was far more inconvenient than changing the power car and drivers.

To illustrate the difficulties of border crossing, here are some statistics from the French operator, SNCF. In 2005, SNCF had 29 power cars compatible with three current types (25kV, 15kV and 1.5kV) so that they can circulate on the network of France, Belgium, Luxembourg, Italy, Germany and Swiss. But the two latters have different signalization systems, thus SNCF must work with the operators from both countries to design interoperable power cars.

2.2.3.2. European transport policy

During the 1980s, the European Commission launches the first debates about the creation of a European transport policy. This decision was based on two assessments:

- The raising debts in the railway industry
- The decreasing traffics and market shares of railway

To overcome this situation, the Council of Ministers asked the Commission to initiate a European transport policy. New rules were proposed to modify the operation of State Members' railways to ease their efficiency and their adaptation to fit the requirements of the European market.

The European directive 91-440 (1991) requires the State Members to implement the four following rules before 1993:

- Independence of railway companies from the governments
- Infrastructure management and railway operation should be separated at least from the viewpoint of accountability
- Better financial situation for railway companies
- Guarantee of access and transit allowance for railway companies for both international freight and passenger (with specific restrictions and conditions on the latter)

With this directive, the European railway market is now theoretically opened, but it took more time to implement this law into each State Member's legal framework, and even more to create a common system to physically allow the trains to easily transit from a country to another.

In addition, to avoid that high speed railway undergoes the same interoperability difficulties of conventional railway the Commission considered the two networks independently. The first debates about high speed railway were launched in the early 1990s. A discussion group was created, gathering State Members' governments, operators and railway industries. They examined every aspects of the railway system such has the operability, technical standards, compatibility, and so on.

2.2.3.3. New European standards for interoperability

In 1996, the ministries of UE, based on the results from the Commission, defined in the directive 96/48 the interoperability for high speed rail as the aptitude from the European system to allow a safe transit without changes of train and according to the specified performances. This aptitude is based on a wide range of legal, technical, operational conditions that need to be fulfilled and certified. In addition, the directive requires that high speed lines follow interoperability technical specifications introducing several new standards for interoperability.

One of the main one is related to the traffic management. On the new lines (and upgraded ones) will be implemented the European Railway Traffic Management System (ERTMS) that is a unified communication and signalization system.

Another point aims to reduce the alimentation issue by considering only two operational currents: 25kV 50Hz and 15kV 16 2/3 Hz.

Although those standards were defined 15 years ago, it takes a long time and a lot of money to implement them. Moreover, the governments gave the priority to freight transit which is in a more urgent situation.

The new rules given by the European Union also induce some political problems because of the opening of the European market. Indeed, as the infrastructure and the rolling stock are separated in two independent structures in each country, a toll has been introduced by the infrastructure managers. The toll amount is the focus of many debates in France for example. Another point is the repartition of the train paths. Before 2001, they were given according to the "grandfather right", that is to the company that had those paths without any debate. But another European directive fixed this issue and they are now reallocated every year.

Finally, in order to coordinate, advise and propose new rules to the European Union, the European Rail Agency has been created. It aims to be in the centre of the decision-making regarding the evolution of the European railway network.

The figure below shows the current European high speed network and its many projects. Many high speed interconnections between countries are still lacking but should be built by 2025.[27]

Figure 5 - European high speed rail network (UIC, 2012)

2.2.4. Other European high speed trains

High speed rail spread across Europe over the last decades. As mentioned above, each country developed its own technology, yet only France and Germany only use their own technology.

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[27] (UIC, 2012)

Here is a description of the Italian and Spanish cases, which have both developed a local technology and imported foreign rolling stock.

2.2.4.1. Italian Pendolino and tilting trains

The Pendolino is an Italian high speed tilting train (ETR450) that was first introduced in Italy in 1989 between Rome and Milan. The first ETR 450 reached 250km/h in an eight-car configuration but was than improved and modernized and was followed by several EMU powered Pendolino. The maximum tilt of the ETR 450 was 13° but was reduced on newer iterations. The New Pendolino, Pendolino's latest iteration, is now operated in several other countries and manufactured by Alstom Ferroviera, subsidy of French manufacturer Alstom.[28]

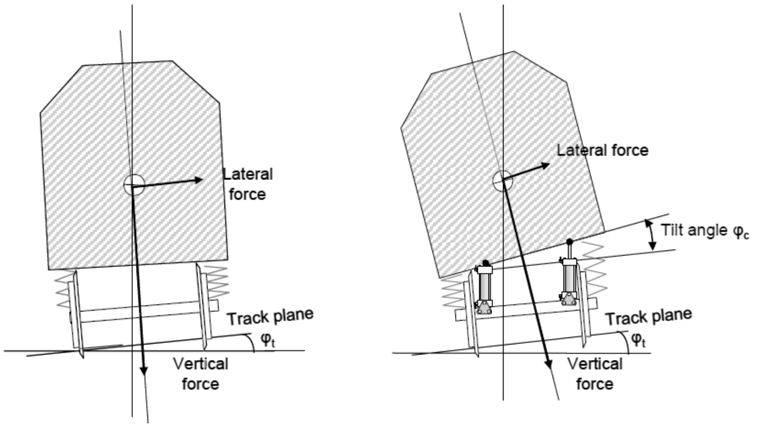

Figure 6 – Tilting train principle (Persson, 2008)

As shown on Figure 6, the principle of the tilting train is to allow the cabin to tilt while the train takes a curve so that the centrifugal force does not impact on the comfort of the passenger. The advantage of tilting trains is that it can run at higher speed on conventional network. But there are several issues that make it difficult to implement a tilting system, such as motion sickness and technical constraints.[29]

Nowadays, the new Italian operator NTV does not operate tilting trains but the new Alstom AGV described in paragraph 2.4.1, while historical operator TrenItalia ordered Bombardier Zefiro train sets, described in paragraph 2.4.3.

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[28] (Alstom, 2012)

[29] (Kim, 2006; Persson, 2008)

2.2.4.2. Spanish Talgo: variable gauge and articulated structure

Spain currently has the largest high-speed network in Europe[30] with the particularity of having both broad and standard gauge. Because of that, the manufacturer Talgo has provided some trains with a gauge-changing mechanism to operate through the whole Spanish high speed network. More interestingly, all Talgo trains use of single axle articulated bogies for the high speed trains, with very short wagons. The wheels are independent and the axles permanently steered to keep the wheels parallels to the tracks in curves.[31]

Other trains are operated on the Spanish network by the Spanish only operator RENFE. Some are derived from a single-decker TGV, few of them being operated on the Spanish gauge. More recent trains are Siemens Velaro as described in paragraph 2.4.2 and Talgo trains.

As a conclusion, both Italian and Spanish networks are operated with different types of trains, which is a different strategy than the French and German one. The diversity of trains operated on the different parts of the European network and the various signalization systems makes it difficult to have smooth through services, but the technical standards for interoperability and European legislation aim to unify the signalization and communication system throughout the countries. This situation is very different than the Japanese one, where each JR Company has a local monopoly.

2.3. Other networks and projects

This paragraphs briefly describes the current status of high speed rail around the world, and then describes a few examples of high speed rail projects in China, California, Australia and India.

2.3.1. Existing lines and projects

The number of countries where high speed rail is operated has slowly increased up to now, but as the map below shows, many countries are now considering to introduce a high speed rail system. Note that countries that run higher speed trains on conventional infrastructure only are not included; this is the case of Sweden, for instance. Table 2 shows that the demand is growing

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[30] (UIC, 2011)

[31] (Talgo, 2012)

especially in Europe and Asia, and also that more lines will be built in fifteen years than in the past fifty years.

Table 2 - Length of HSR networks with speed above 250lm/h as of November 2011, adapted from (UIC, 2011)

Region	Length in operation	Length under construction	Length planned for 2025
Europe	6,637 km	2,427 km	8,705 km
Asia	10,167 km	6,211 km	5,722 km
Other countries	362 km	200 km	1,891 km
Total world	**17,166 km**	**8,838 km**	**16,318 km**

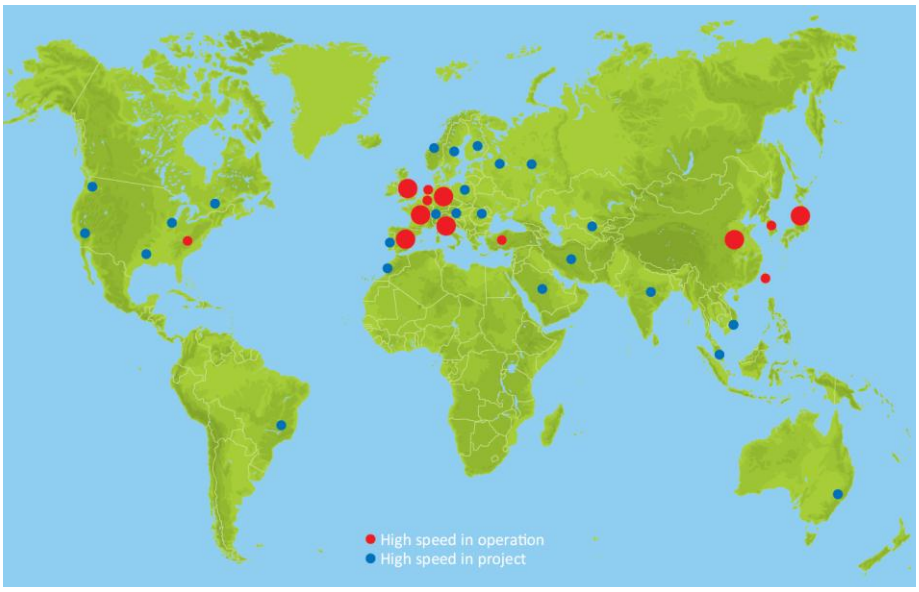

Figure 7 - High speed lines around the world (UIC, 2012)

2.3.2. China

Although the Chinese high speed rail network is very recent, its development has been extremely fast. First announced in 2004 as a mid-term plan, the high speed network project has soon become a reality with approximately 13,000km of operated high speed line[32]. Figure 8 shows the network completion in 2010, with only 4,900km completed at that time[33].

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[32] (Morgan Stanley Research Global, 2011)

[33] (Takagi K. , 2011)

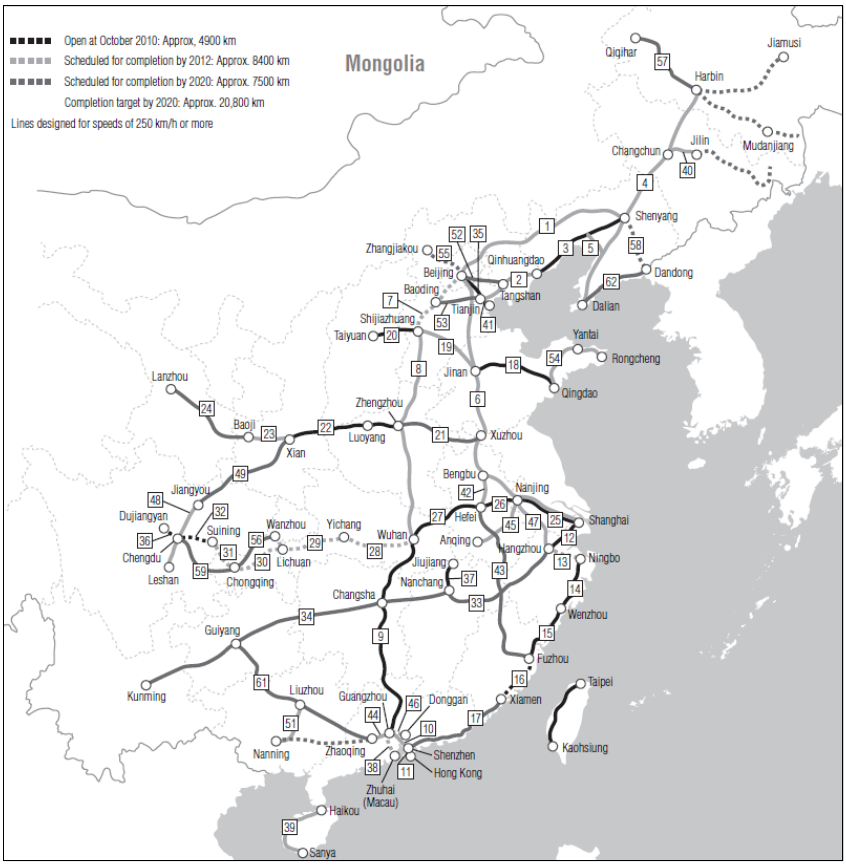

Figure 8 – Map of the Chinese and Taiwanese high speed rail network (Takagi K. , 2011)

With such a growth, China has ordered various different train sets from existing manufacturers, creating joint ventures and developing its own high speed rail rolling stock. However, the Wenzhou accident last year raised many concerns about the growth rate of the network and the impact on its quality and safety[34]. This accident is a proof that HST system integration is very important and the design for speed, security, signalization and communication should be prioritized before the growth of the network.

Yet high speed rail is a key factor for China's economic growth as it links major economic centres and increases the mobility of the population as an analysis by Morgan Stanley[35] shows.

2.3.3. California

The discussions about building a high speed rail network in the United States of America, and in California in particular, started many years ago. In 1991, the Intermodal Surface Transportation

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[34] (Areddy & Jie, 2011) (Railway Gazette International, 2012)

[35] (Morgan Stanley Research Global, 2011)

Efficiency Act was the first move from the Federal Government to promote high speed rail, with a program to fund safety improvements on specific railway corridors, designated as “high speed corridors”[36] and shown in Figure 9. Yet those are only upgraded railway corridors, with no further focus on proper high speed rail. Today, several barriers still slow the development of a proper high speed network, as mentioned by the Federal Railroad Administration:

- Lack of expertise and resources,
- Lack of high speed rail safety standards,
- Poor fiscal conditions in many States after the recent economic downturn,
- Need for coordination between States for interstate lines.

To overcome those difficulties, the Federal Railroad Administration has enacted a succession of acts to improve passenger rail safety and planning, to prepare the necessary legal framework for high speed rail at the federal level, and to participate in the funding of selected projects.

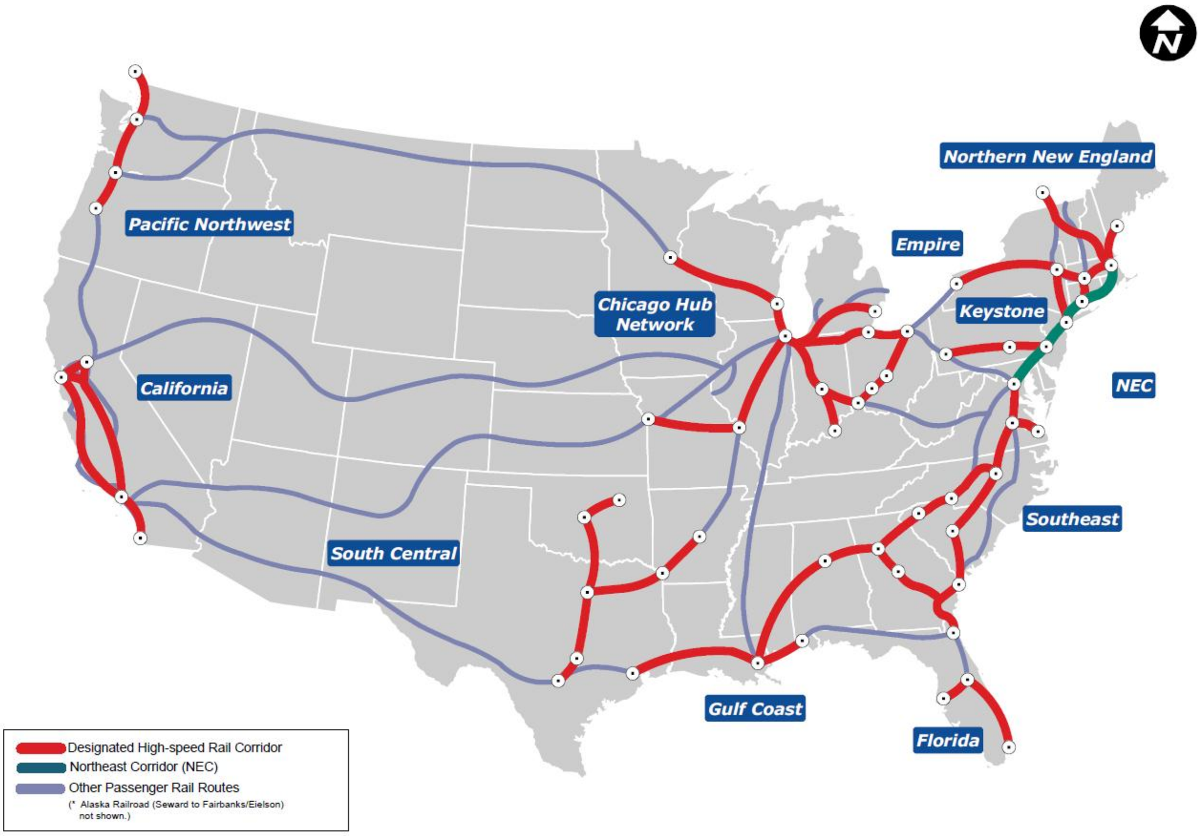

Figure 9 – Designated high speed rail corridors in the United States of America

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[36] (Federal Railroad Administration, 2009)

Under those new conditions, the California High Speed Rail Authority has proposed a business plan for a high speed rail network in 2008, revised several times until last april.[37] They justify the need for high speed rail in California with economic, environmental and economic benefits, among which:

- Creation of direct and indirect jobs
- Improved mobility
- Congestion relief of both freeways and airports
- Decrease in pollution, greenhouse gas and dependency on foreign oil
- Revitalisation and economic development around the new stations

In this revised version of the business plan, they plan to build a high speed network from San Diego to Los Angeles and Sacramento as Figure 10 shows. To reduce the cost, the project will be built in several phases. The first will link San Francisco to Los Angeles with a dedicated infrastructure between San Jose and Los Angeles, and through service on upgraded existing tracks between San Jose and San Francisco. This first phase will be completed by 2029 for a total cost of 68 billion dollars and a total length of 520 miles, or 840km. The construction of the first part of phase one, the “Initial Operation Section” in the middle of the State, should start next year. The schedule of the second phase, expanding the dedicated high speed tracks north to Sacramento and Los Angeles, and south to San Diego, has not been announced yet.

Ridership and revenues from the first phase have been estimated to reach 21.4 million passengers after phase one is completed, to 29.1 million passengers thirty years later.

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[37] (California High-Speed Rail Authority, 2012)

Figure 10 – California high speed rail alignment

2.3.4. Australia

The Australian Department of Infrastructure and Transport has recently published the first part of a feasibility study[38] for high speed rail development in the Eastern coast, linking Brisbane, Sydney, Canberra and Melbourne with a 1650km long line, to be completed in 2036 for a total cost estimation ranging from 61 to 108 billion Australian dollars. The shortlisted boundary of shortlisted corridors is shown in Figure 11.

Discussions about high speed rail in Australia have begun in the late 1990s with several projects covering a part or the totality of the current projected line.

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[38] (AECOM Australia Pty Ltd, 2011)

The study assumes a high speed rail system on ballasted track designed for up to 400km/h, with operations limited at 350km/h. Rolling stock is considered to have eight to ten cars, without further precisions on its design, and the stations would be designed to allow up to sixteen cars.

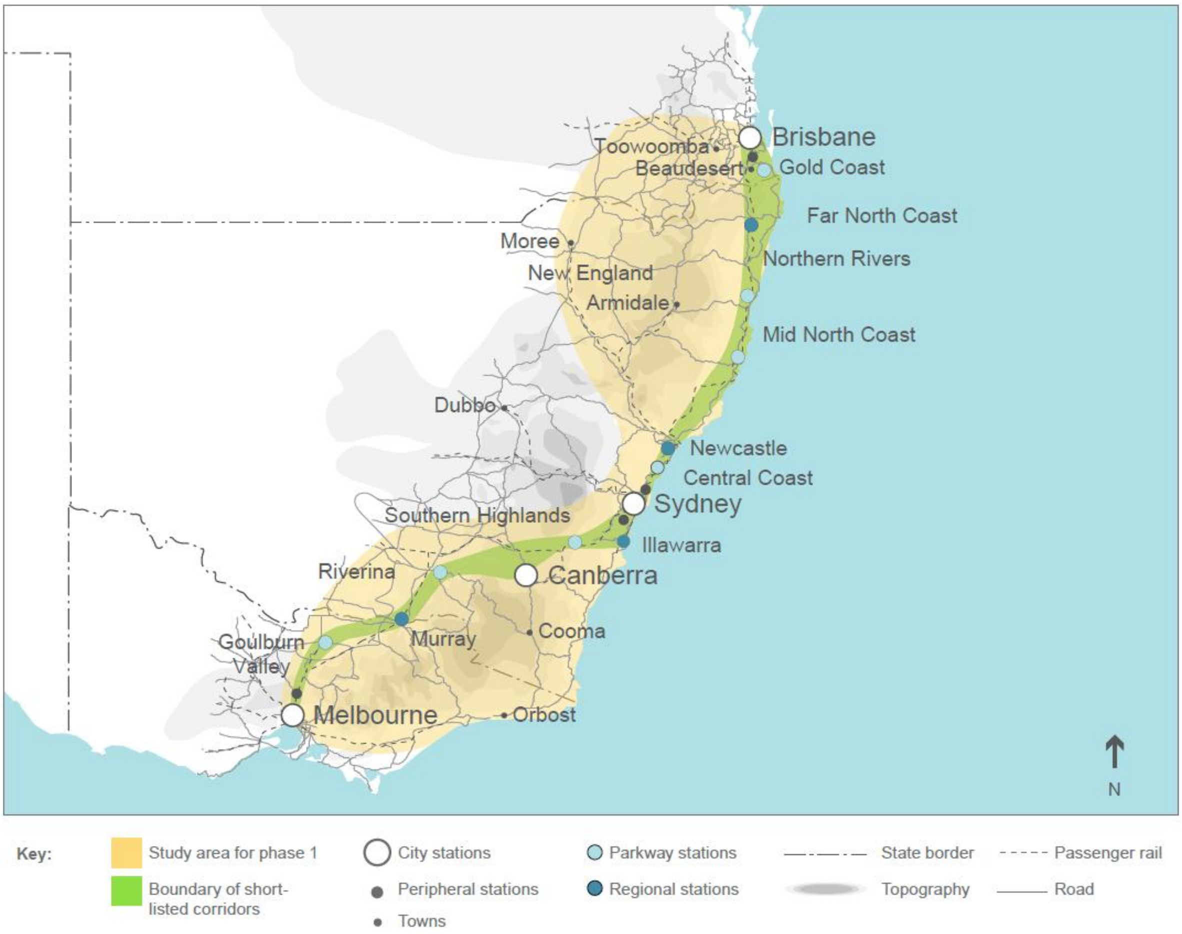

Figure 11 – Boundary of shortlisted corridors of the Australian high speed rail project

They also give some general yet valuable lessons learned from past experience in other countries about the development of high speed rail, focusing on five points:

- Integration: high speed rail must support complementary transport services
- Support for regional land use goals: high speed rail can stimulate regional development
- De-congestion of existing transport systems: planners must optimise infrastructure performance
- Importance of stations: early station planning
- Capital costs are unlikely to be recovered

The first, third and fifth lessons are important in the context of this thesis: high speed rail is designed to be integrated with other modes and as such, its performance should be set before a cost assessment or a cost-benefit analysis. Finally, cost estimation should include the comparison of several options, with a wide scope, in order to identify solutions that are feasible and can significantly reduce the cost. For instance, the Department of Transportation does not mention the reasons why only a ballasted track is considered in the infrastructure design, thus it is unknown why other designs have been omitted and if this decision could ultimately lead to biased cost estimation.

2.3.5. India

As mentioned in paragraph 2.3.1, several developing countries are planning to introduce high speed rail in the future, among which India. With its rapidly growing economy and industry, this large country is willing to develop a high speed rail network to sustain its growth. There are six different lines[39] and the Press Information Bureau of the Government of India[40] has listed the progress of the prefeasibility studies and it is presented in Table 3.

Table 3 – Status of the prefeasibility studies of Indian high speed rail projects, adapted from (Press Information Bureau, Government of India, 2012)

Line	Prefeasibility study status
Pune-Mumbai-Ahmedabad	Completed
Delhi-Chandigarh-Amritsar	Technical evaluation of the offers has been completed and financial bid is under finalization
Delhi-Agra-Lucknow-Varanasi-Patna	In progress
Howrah-Haldia	In progress
Hyderabad-Dornakal-Vijaywada-Chennai	In progress
Chennai-Bangalore-Coimbatore-Ernakulam-Thiruvananthapuram	Technical bids have been evaluated and financial bids are under evaluation

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[39] (Akiyama, 2011)

[40] (Press Information Bureau, Government of India, 2012)

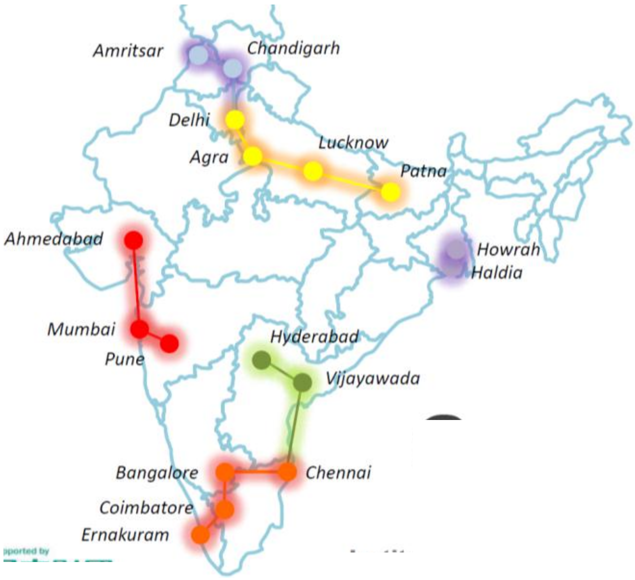

Figure 12 – Indian high speed rail network project (Takada, 2012)

2.4. Convergence of the next-generation rolling stock

The 2010 edition of Innotrans fair trade for railway transportation was the occasion for the manufacturers to reveal their latest designs. The trend for future rolling stock is to aim speed greater than 350km/h, which suppose a very hard work on the aerodynamics. Indeed, at speed greater than 300km/h the noise generated by the air flowing can be more important than the rolling noise, which may cause discomfort to passengers. Other critical problems such as the safety are reduced thanks to the implementation of ERTMS that provides better information to the driver. Regarding the environmental issues, the new products aim to reduce their footprint, making high speed train even more environmentally acceptable in comparison to other modes.[41] This chapter reviews the latest rolling stock developments around the world, showing an increasing competition and convergence of train design.

2.4.1. Alstom AGV

The AGV (Automotrice à Grande Vitesse) is the little brother of the famous French TGV. But in comparison to the TGV, it is not powered by power cars but by an EMU distributed traction. Yet it has kept the Jacobs bogie for the train structure. The AGV motorization was the key of 2007's world record at 575km/h, mixed with two TGV POS power cars. The AGV also has a quad-voltage power system (that is more than required by the European standards as it is not fully

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[41] (Railway Technology, 2011)

implemented), permanent-magnet rotors, better electric components, and regenerative breaking, allowing the train to reach 360km/h for a consumption reduced by 15% compared to the latest TGV Duplex. The EMU also allows increasing the number of passenger by 20%. Finally, according to Alstom, the maintenance cost is 30% less important. The interior design features 350 to 650 seats in 7 or 14 cars configurations.[42] The AGV began commercial services not in France but in Italy in late 2011, with the company NTV.

2.4.2. Siemens Velaro

The Velaro is the latest German train, and has already conquered several markets including Germany (ICE3) Spain, forthcoming new Eurostar, and even China. The Velaro also has EMU traction. There are several models of Velaro, reaching maximum commercial speed of 320km/h (ICE3) to 380km/h (Chinese CHRC3C), making it the fastest train on commercial services. The Velaro train sets can be operated with both wide or narrow body, and different numbers of cars.[43] Siemens also won the bid to replace the Eurostar train sets with its Velaro E320.[44]

2.4.3. Bombardier Zefiro

Like the Velaro, the Zefiro is a family of EMU powered trains that aim to seduce several markets. The Zefiro 250, for its top speed of 250km/h, has been exported to China and the Zefiro 380 should join it. The Zefiro 300 has been ordered by TrenItalia. The capacity of the different models is approximately the same: 600 seats in an 8-car configuration and 1200 in 16-car configuration. The Zefiro 250 is also available in sleeper configuration, with a total of 496 beds and 122 seats.[45]

2.4.4. Shinkansen developments

Although actual Shinkansen and trains derived from Shinkansen still have a maximum operating speed below 320km/h, Japanese railway engineers have developed the latest E5 Series Shinkansen by designing two 360km/h prototypes, with similar structure but different

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[42] (Alstom, 2012; Railway Gazette International, 2007)

[43] (Siemens Mobility, 2011)

[44] (Railway Gazette International, 2010)

[45] (Bombardier Transportation, 2011)

nose.[46] Current exported Shinkansen derived from former E2 and 700 Series, but current and future effort will surely use the latest developments to compete with other manufacturers.

2.4.5. Korean next-generation KTX

Korean manufacturer Hyundai Rotem recently unveiled an experimental prototype that could reach 430km/h. Interestingly its design is very different than the former KTX train sets, which derived from the French TGV. The new HEMU-430X features a distributed traction, a non-articulated design, and a single-decker, narrow body.[47]

2.4.6. Chinese developments

As mentioned above, China has imported foreign rolling stock but also tried to develop its own technology. This strategy proved successful when CSR Qingdao Sifang revealed a prototype that could reach up to 500km/h to study its behaviour at such very high speeds. Although it is only a prototype, it shows the ambitions of the country to propose a competitive high speed train as well. Again, this train has a non-articulated structure and is propelled with distributed motorization.[48]

2.4.7. Convergence of the rolling stock design

The convergence of shapes, propulsion and design of the latest rolling stock is obvious, as Table 4 shows: every manufacturer has introduced single-decker trains with distributed propulsion with wide or narrow body, aiming at speeds above 350 km/h.

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[46] (Japanese Overseas Rolling Stock Association, 2004)

[47] (Railway Gazette International, 2012)

[48] (Railway Gazette International, 2012)

Table 4 - Current and future rolling stock

	TGV Duplex	AGV	Velaro	Zefiro	Shinkansen*	KTX*	Chinese HSR*
Manufacturer	Alstom		Siemens	Bombardier	Kawasaki, Hitachi	Hyundai Rotem	CSR Sifang
EMU propulsion		Yes	Yes	Yes	Yes	Yes	Yes
Non-articulated structure			Yes	Yes	Yes	Yes	Yes
Double-deck	Yes						
Maximum speed	320	360	380	380	360	>380	>380
Narrow body	Yes	Yes	Yes			Yes	
Wide body			Yes	Yes	Yes		Yes

**Prototype*

First developments of high speed rail rolling stock were an extension of the conventional trains, with locomotive propelled trains in France and Germany, and EMU trains in Japan. Then those designs were kept while the performances were improved to raise speed and comfort, decrease the train weight and incorporate better signalization and communication systems. Only Japanese and French manufacturers explored the double-decker high speed trains. Yet nowadays, whether it has been pushed by interoperability rules, continuous improvements, technical constraints or the willingness to amortize years of research and development, the result is that most of the manufacturers seem to commit to the same design. By increasing the competitiveness and complying with interoperability standards, this convergence is a very good opportunity for existing markets. However, it does not necessarily provide the best options for new markets where the contexts are different and the requirements can be adapted.

3. HIGH SPEED RAILWAY SYSTEM ANALYSIS

In order to understand the problematic of high speed rail, it is important to know which the components of the system are, how they differ among the existing technologies. To illustrate these differences, examples from French TGV and Japanese Shinkansen are mostly used, as well as some other existing high speed rail systems. This chapter first examines the rolling stock and operational considerations, then the infrastructure, and the signalization.

3.1. Rolling stock design

The rolling stock is designed to accommodate the expected demand with the lowest operating and maintenance cost. However, existing HSR systems show that there are different options to design a train. The followings are the options:

- Train length and coupling
- Classes configurations
- Narrow or wide body and seat layout
- Single or double-deck
- Locomotive or distributed motorization
- Articulated or non-articulated structure

After describing the train design options, their impact on the train aerodynamics and on the timetable is discussed, since they are very critical factors for high speed operation. Finally, potential designs are compared with existing designs.

3.1.1. Train length and coupling

Operators try to limit the length of the trains to avoid too long platforms in station and too long walk before seating, which would impact passenger comfort and time spend in station. Both in Japan and in Europe, maximum train length is 400m, and train sets typically range from 200m to 400m long.[49]

In addition, many operators run coupled trains, or multiple units, to double the capacity or to allow the two units to separate in an intermediary station and reach two different destinations,

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[49] (Yanase, 2010)

hence grouping two services in one and saving network capacity. Since it doubles the train length, trains above 200 meters are usually not coupled. Shorter trains may allow triple units; however it requires more space for the noses or locomotives and as a consequence reduces overall train capacity compared with a double or single unit with the same total length.

3.1.2. Classes configuration

High speed rail operators usually propose only two classes to their clients, with different names. French SNCF and German Deutsche Bahn, for instance, simply call them "first" and "second" class, but in Japan, first class is called "Green Class". The classes mainly determine the change in comfort and services. Regarding capacity, a higher pitch and larger seat means a smaller capacity. The capacity of 1st class is assumed to be 60% of the second class, as it is the case on French single-deck TGV and Japanese E2 Series. Figure 13 shows an important variability especially for Shinkansen, from 32% on JR West N700 to 77% on JR Central N700[50], but the average value is close to 60%. Superior classes such as the "GranClass" of the newly introduced E5 Series Shinkansen on the Tohoku line, or as the "Best Seats" Class on some Chinese high speed trains are considered marginal for the time being.

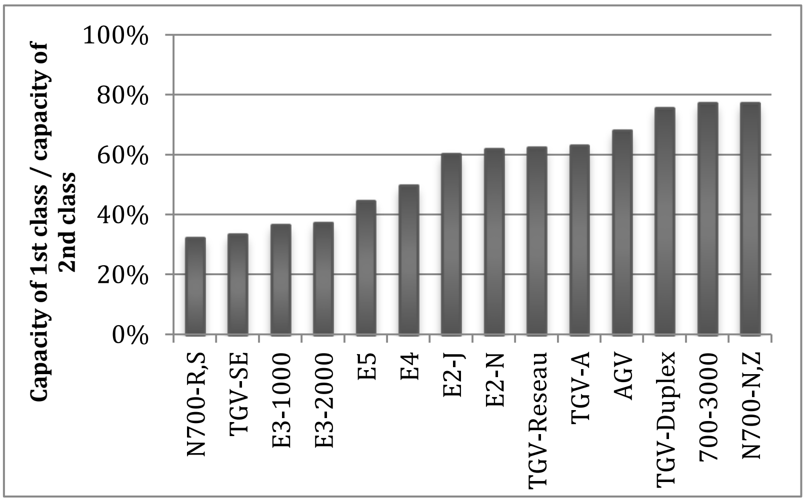

Figure 13 - Ratio of capacity of 1st class and 2nd class for TGV and Shinkansen

3.1.3. Narrow or wide body

Although Shinkansen and European HSR use the same standard track gauge, the width of Shinkansen is more important. This allows one more seat per row as shown in Table 5. Japanese

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[50] (Brisou, 2011)

and Chinese HSR prototypes show that a wider body does not limit the maximum speed. Indeed, the Japanese Fastech360 prototype reached 360km/h[51], while Chinese CHR380 rolling stock family can be operated at up to 380km/h[52] and a prototype targeting 500km/h has been recently unveiled[53]. Regarding narrow body, French V150 speed record train set allowed French railway engineers to test the behaviour of Alstom's TGV and AGV at more than 570km/h.[54]

Table 5 – Width and seat layout of Shinkansen and TGV

	Shinkansen	TGV
Width	3.38m	2.91m
Seat layout (2nd Class)	2+3	2+2
Seat layout (1st Class)	2+2	2+1

Thus both designs are considered in the model. The impact of a wide body on the capacity is an additional 20% for second class. A wider body also induces a larger train section, which has an impact on the infrastructure and is described in paragraph 3.1.1.

3.1.4. Single or double-deck

To increase the capacity with a lower impact on the operating schedule, HST with a second deck may be introduced, such as the E1 and E4 Series Shinkansen in North-East Japan, or the TGV Duplex in France.

The capacity increase provided by a second deck is easily evaluated by comparing double-decker to single-decker HST, both in France and in Japan. Table 6 shows that a second deck increases the capacity by approximately 40% for both TGV and Shinkansen.

Table 6 - Capacity increase of a second deck

	Shinkansen	TGV
Average capacity for single-decker trains	75	48
Average capacity for double-decker trains	102	68
Capacity increase of double-decker train	40%	42%

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[51] (Japanese Overseas Rolling Stock Association, 2004)

[52] (UIC, 2011)

[53] (Railway Gazette International, 2012)

[54] (Alstom, 2012)

Despite the capacity increase, double-decker trains impose a constraint to the operators in term of accessibility. Indeed, both TGV Duplex and double-decker Shinkansen have steps that some people cannot climb, or not easily. Thus double-decker trains should have some seats and space for handicapped people at the platform level, or have the lower platforms to have the lower deck at platform level. The latter solution would require existing lines to perform some works in stations, and may not be feasible on the lines where both single-decker and double-decker trains are used.

3.1.5. Motorization

There are two types of motorization: distributed traction and locomotive. The first consists in having smaller motors installed on several bogies along the train instead of bigger motors in the locomotives. Shinkansen was designed with distributed electric traction or electric multiple unit (EMU), while European engineers first introduced the locomotive type traction. As shown on Table 7, EMU is more efficient since it provides a larger power output, higher acceleration performance with less slipping risk, more seats in first and last cars, and a flexible train length by adding as much motorized bogies as necessary. It also provides a better acceleration performance, which helps reducing the headway and thus increases the capacity of the line.[55]

Table 7 - Comparison of EMU and locomotive motorizations, adapted from (Yanase, 2010)

	EMU	**Locomotive**
Propulsion system	Lower power, large number	Higher power, small number
Maximum axle load	Lighter	Heavier
Passenger capacity	Full except driver cab and nose	2 cars occupied by locomotive, driver cab and nose
Noise in cabin	Larger	Smaller
Maintenance cost related to the number of traction motors	Larger	Smaller
Acceleration performance	Better	Worse

These reasons may explain the changes to EMU technology in Germany, Spain, and Korea. German operator Deutshe Bahn first introduced ICE with a locomotive traction and Spanish operator RENFE a TGV, but both operators have been ordering Siemens Velaro train, an EMU,

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[55] (Emery, 2011)

non-articulated train.[56] In Korea, TGV was also first introduced, but Korean manufacturer recently unveiled an EMU prototype.[57]

3.1.6. Articulated or non-articulated structure

One of the major differences between TGV and affiliated trains from the other trains is its articulated structure. Instead of having two bogies per car as usual, the bogies are located between two cars in TGV. This structure allegedly provides a stronger link between the cars that would allow the train to keep its integrity in case of derailment.[58] The reduced number of bogies induces a higher weight per axle, which increases the track deterioration, yet the maintenance of the train should be cheaper with less bogies.

With an articulated structure, it is observed that the cars are shorter on French TGV (18.7m) and AGV (18m) than those on non-articulated trains (25m). This is because they avoid a too long span between two bogies. A longer span would increase the weight per axle, or require a larger gap between two tracks in curves to avoid collisions. TGV also has another particularity: because of their heavy weight, the locomotives do not share a bogie with their following car. Thus the first and last passenger cars are slightly longer to keep the same span between bogies. AGV has a slightly shorter span than TGV because motorized bogies are heavier, hence the cars are made shorter to compensate with the weight increase. In addition, articulated bogies have a longer wheelbase: 3.0m for TGV, 2.5m for non-articulated trains[59]. Figure 14 summarizes the differences between non-articulated and articulated structures, as well as the particularity of TGV.

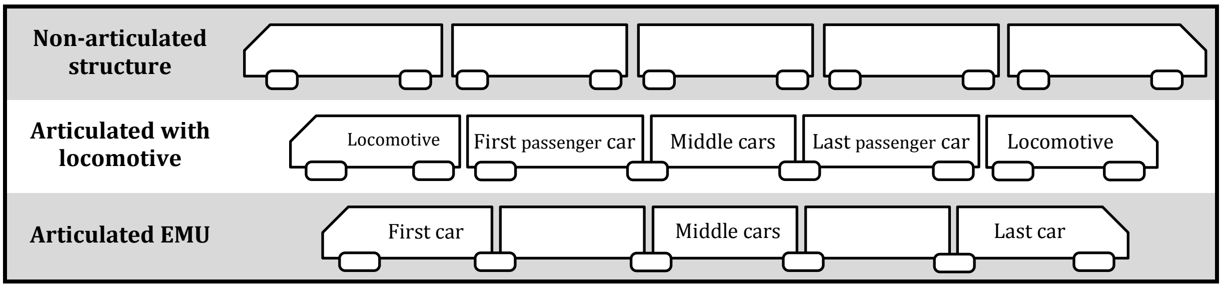

Figure 14 - Difference between non-articulated structure (top), locomotive articulated structure (middle) and EMU articulated structure (bottom)

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[56] (Siemens Mobility, 2010)

[57] (Railway Gazette International, 2012)

[58] (Brabie, 2007)

[59] (Antoni, SNCF: Asset maganement and Safety, 2012)

3.1.1. Train design and aerodynamics

The choice of the train design has a high impact on the aerodynamics, and aerodynamic drag impacts the train performance, energy consumption, noise, and comfort significantly.[60] At high speed, 80% of the resistance is caused by aerodynamics forces.[61]

High speed train aerodynamics is a complex problem of fluid dynamics, but the impact of the train design and shape is a well-known issue for manufacturers. Nowadays train noses are shaped using three dimensional fluid mechanics software and tested in wind tunnels. The Shinkansen trains are the best examples of the continuous improvement of train aerodynamics. While the section of the Shinkansen has been reduced, the nose has been much lengthened. The evolution of the nose shape from the round, bullet-shaped nose of the first 0 Series Shinkansen and the long, streamlined nose of the 700 Series is striking as Figure 15 shows.

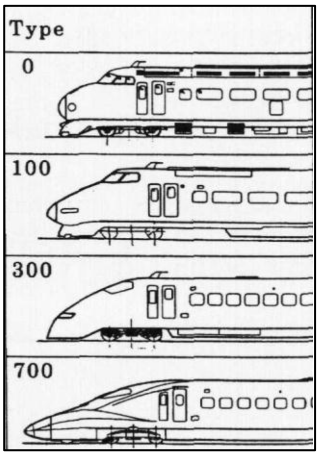

Figure 15 – Nose shape of different Shinkansen trains (Ito, 2000)

Many studies by researchers in the field of fluid mechanics have analysed the aerodynamics of high speed rail and highlight not only the impact of the nose shape, but various factors. Ito[62] focuses on the improvements made to the Shinkansen: reducing the train section, covering the car body and between the cars, and redesigning the pantographs. These elements impact the aerodynamic drag that creates the aerodynamic resistance.

The total resistance to motion R can be written[63] as a second degree polynomial relationship with the train speed V:

$$R = a + b * S + c * S^2 \tag{1}$$

Where a and b represent the mechanical resistance and C the aerodynamic drag. It can be expressed as:

$$c = \frac{1}{2} * \rho * A_{train} * C_D \tag{2}$$

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[60] (Raghunathan, Kim, & Setoguchi, 2002)

[61] (Shetz, 2001)

[62] (Ito, 2000)

[63] (Raghunathan, Kim, & Setoguchi, 2002) (Shetz, 2001)

Here ρ is the air density, A_{train} the frontal section of the train and C_D the drag coefficient, which depends on the train characteristics such as the shape of the nose, the length of the train, and the friction coefficient of the body, including bogies, wheels, and pantographs. Raghunathan[64] shows that a significant reduction of the drag is achieved by improving the underneath structure of the train in particular, and by sharpening and lengthening the nose.

Running resistance and aerodynamic resistance in particular at high speed has evidently a large impact on the energy consumption of the train, which counterbalances the resistance to make the train move. Thus reducing the drag has a significant impact on the energy consumption and, as a consequence, on the emissions of pollutants and greenhouse gases from energy production.

Aerodynamics resistance is an important constraint, yet it can also be turned to an advantage. The two Japanese Fastech 360 prototypes have been designed with aerodynamic brakes: small plates that can be pushed up to increase air resistance, with a reduced emergency braking distance of 7% at 360km/h.[65] Results had a significant impact on the braking distance, yet this innovative braking system has not been installed on the E5 and E6 Series Shinkansen derived from one of the Fastech 360 prototypes.

Finally, a very important issue is the pressure waves generated when a train enters a tunnel at high speed. This point is described in paragraph 3.2.2.3.1.

3.1.1. Train design and timetable

When the number of passengers per car increases, it takes more time to alight and board the train and lengthens the dwelling time in station. Additional doors can be installed but it reduces the capacity especially with a double-decker design if a door is installed in the middle and at both ends of a car.

It is observed by looking at the timetables that the minimum time in station is 1 minute for Shinkansen and 3 minutes for TGV. The difference can be explained partly by the maximum number of passenger per door: TGV Duplex has up to 96 passengers in a wagon with one door, while E4 Series Shinkansen never has more than 133 passengers in a wagon with two doors, hence no more than 67 passengers per doors. Another part of the explanation is the cultural difference and the behaviour of the passengers. As Hood highlights in his book[66] about the

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[64] (Raghunathan, Kim, & Setoguchi, 2002)

[65] (Arai, Kanno, & Yanase, 2008)

[66] (Hood, 2006)

Shinkansen, Japanese culture is one the main reasons why Shinkansen operations can be so smooth and in particular require such a little time in stations.

Several studies have been focusing on improving alighting and boarding time by improving the interior train design. Heinz[67] has measured and compared different trains in Sweden to measure and model the service time in stations. She stresses the need to consider the time in station in operation models and timetable design. Rüger & Tuna[68] have studied in detail various interior arrangements to find the most critical problems affecting punctuality and dwell time. Evidently, larger doors and corridors, and doors at platform level induce a significant improvement, but they also examine the position of the doors, the seating configuration, and even the position of baggage racks. Their conclusion shows an important potential time reduction of 70%. The Scandinavian design concept of Green Train[69] considers the interior design to improve the reduction of the time in station, and one can expect the manufacturers to tackle this problematic when designing current or future trains.

3.1.1. Existing train designs

The following table shows a summary of the different train design options compared with existing high-speed rolling stock.

Table 8 - Train design options and existing rolling stock

	Motorization	**Narrow body**		**Wide body**	
Number of decks		**Single**	**Double**	**Single**	**Double**
Non-articulated structure	**Locomotive**	Former ICE			
	EMU	ICE3		Shinkansen	Shinkansen E4
Articulated structure	**Locomotive**	TGV, KTX	TGV Duplex		
	EMU	AGV			

There are very few different wide body designs and double-decker designs. An articulated structure is proposed only by a two manufacturers, Alstom and Talgo, which have not yet sold trains to operators in need of wide designs. Regarding double-decker design, there are several technical challenges to overcome when designing such trains: reducing of the weight to limit the weight per axle, keeping a low aerodynamic drag despite the larger section, granting

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[67] (Heinz, 2003)

[68] (Rüger & Tuna, 2008)

[69] (Fröidh, Green Train, Basis for a Scandinavian High-Speed Train Concept, 2012)

accessibility to handicapped persons, and taking into account the higher gravity centre that can affect the safety in curves or with strong lateral wind. Also, existing infrastructures cannot be upgraded to run wider or higher trains. Next paragraph will highlight the links between rolling stock and infrastructure.

3.2. Infrastructure

High speed rail infrastructure is similar to conventional infrastructure in its principle: two parallel steel on which the trains run. Yet the higher speed and lighter rolling stock induce different constraints in order to grant a safe operation. The following paragraph describe both Japanese and French railway infrastructure to show the specificities of high speed railways. The infrastructure can be divided into several elements that are successively observed: the track, the civil structures, the power supply systems, and the buildings and other structures.

3.2.1. Track

A railway track can be described by the type of rail it uses, the track structure it is made with, and the track geometry and alignment of the line.

3.2.1.1. Type of rail

The quality of a rail is very important to grant a very good contact with the train wheels, sustain years of operation with as few defects as possible. Both in Europe and in Japan, the rails used for high speed lines are flat-bottomed steel rails. They are very similar as Figure 16 shows. Rails are distinguished by their linear weight and alloy composition. Shinkansen first used 50kg/m rails but switched to 60kg/m rails[70], while European standards also recommend 60kg rails. Japanese high speed lines use a bainitic alloy, which allegedly provides a longer lifetime of 1,000 megatons (Mt) of train traffic against 700Mt for European rails.[71]

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[70] **Invalid source specified.**

[71] (Cazier, La Voie, 2012)

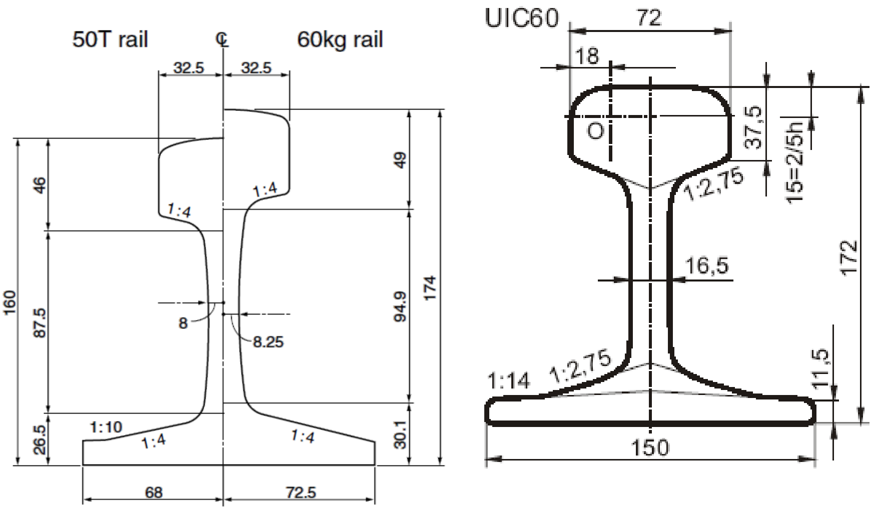

Figure 16 - Comparison of Shinkansen (left) and European (right) rails for high speed operation

Nowadays the rails are welded together to eliminate discontinuities. That is called continuously welded rails and is used both in Japan and in Europe.

3.2.1.2. Track structure

Although the types of rail are quite similar between different countries, track structures have more variability. There are two main categories of high speed track types: ballasted tracks and ballastless tracks. Both technologies have advantages and drawbacks for high speed operation.

3.2.1.2.1. Ballasted tracks

Ballasted tracks have been used for conventional rails for a very long time, and continuously upgraded. They have been used for the first high speed line, the Tokaido Shinkansen in Japan, and are still used in other countries such as France.

The rails linked together by large and short concrete sleepers and are laid in a layer of crushed rocks or gravel, called ballast. The sleepers distribute the weight of the train over the ballast, which in turn maintains the alignment of the rails by absorbing the vibrations and avoiding lateral movements. In curves, these movements are stopped either by a shoulder of ballast on the sides of the sleepers, or by a larger surface of ballast on the sides. Ballast thickness is between 20 and 30cm below the sleepers and between 30 and 35cm between sleepers.[72]

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[72] (Centro de Experimentación de las Obras Públicas, 2008)

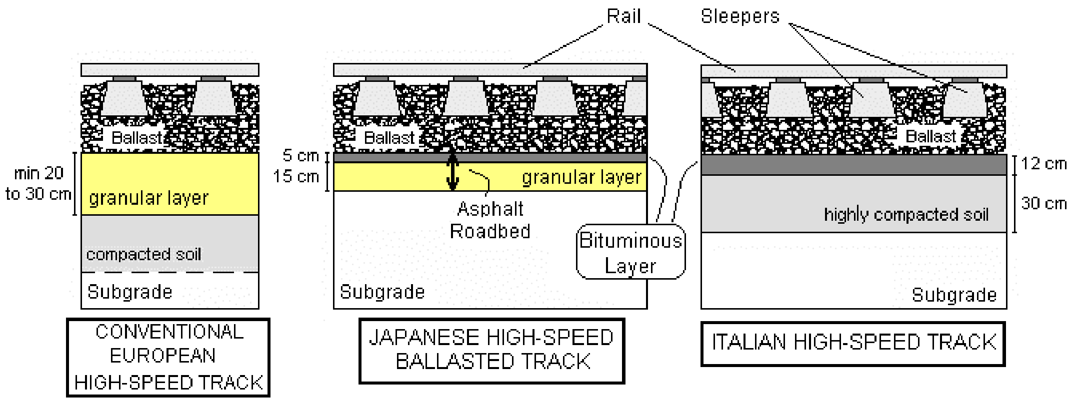

Figure 17 - Several types of ballasted high speed tracks (Teixeira, 2007)

There are several layers between the ballast and the ground; their role is to provide a high stiffness and to avoid subsidence. Their composition and thickness depends on the countries and lines. The Tokaido line introduced a 5cm bituminous layer on top of a 15cm asphalt roadbed, laid on the subgrade. Italian Direttisima line has a similar structure, with thicker layers and highly compacted soil in place of the asphalt roadbed.[73] The role of these layers is to protect the subgrade from erosion and ice, to drain rainwater, and to separate the layer of ballast from the subgrade.[74] Figure 17 shows the variation of ballasted tracks between conventional Japanese, Italian and European track, which is similar to the French track.

In France, a bituminous layer was introduced only in 2007 with the LGV Est line, and the following LGV Rhin-Rhône. Another improvement is the installation of rail pads between the rail and the sleepers to absorb the vibrations transmitted to the ballast, responsible for its degradation at high speed. Thus, given the very good behaviour at high speeds, French network manager RFF will keep on using ballasted track, although they are also working on slab track.[75]

3.2.1.2.2. Ballastless tracks

With slab tracks, rails are not laid on ballast, but fastened on a concrete sleeper embedded in a concrete slab or directly on a concrete slab for slab tracks. Since no ballast is used, the vibrations are absorbed by pads between the fastening and the sleeper. High speed tracks around the world mostly use German Rheda tracks in Germany and Asia, and Japanese slab tracks in Japan and Taiwan.

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[73] (Cazier, La Voie, 2012)

[74] (RFF, 2008)

[75] (Cazier, RFF Interview, 2012)

Japanese Shinkansen lines have been using slab tracks for 40 years, since it was introduced in 1972 for the Sanyo Shinkansen line.[76] It was designed to have greater lateral elasticity and vertical strength than ballasted tracks, with a limited impact on the cost. The concrete slabs have a rectangular shape, and are 5m long, 2.2m wide and around 20cm high. They have a slot at each end for a stopper to be inserted in order to avoid slab movement. Between the slab and the concrete infrastructure is laid a cement asphalt mortar, as shown in Figure 18. Japanese slabs are prefabricated. There are several types, in particular framed slabs that are used in tunnels. Those slabs have an empty rectangle in the middle. It reduces the cost of the tracks since less concrete is used.

German Rheda tracks use concrete sleepers embedded in a layer of concrete instead of ballast. The sleepers are prefabricated but the concrete layer is injected on the construction site.[77]

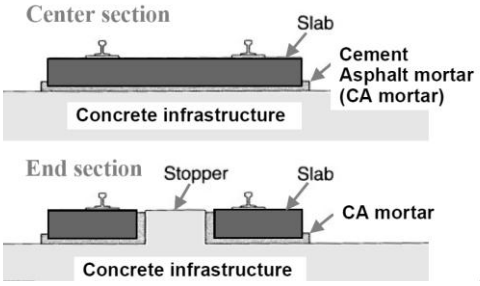

Figure 18 – Japanese slab track structure (Takai, 2007)

3.2.1.2.3. Comparison between ballasted and balastless tracks

Railway engineers and practitioners agree[78] on the fact that balastless track is more suitable for strong weather conditions such as snow and heavy rains. For instance, snow increases the risk of flying ballast, while other severe weather conditions increases the ballast deterioration. In the case of a poor soil quality the lighter weight of balastless tracks is also an advantage.

With balastless tracks, electromagnetic brakes can be used to provide a better deceleration and to reduce the wear and tear on the wheels and rail. This type of brakes increases the rail

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[76] (Takai, 2007)

[77] (Cazier, La Voie, 2012)

[78] (Zwanenburg, 2012; RTRI, 2011; Cazier, RFF Interview, 2012)

temperature by a few degrees, and the higher stresses induced are better dealt with balastless tracks.

Balastless track is less easily replaceable than ballasted track, thus it requires a higher precision during the construction, yet after that the track is more stable. Nonetheless, CO2 emissions are very important due to large use of concrete, and water drainage and earthworks have to be perfect or the concrete will be worn more rapidly. Ballasted tracks are faster to build and sleepers are easier to change, yet they require a large amount of rocks, which means that the further the quarries, the more expensive it could get to transport the ballast. In general, ballasted tracks are cheaper to build, but require much more maintenance to tamper and replace the ballast. Balastless tracks have a longer lifetime if the quality of the concrete is good enough.

Finally, the ballast also provides a better noise absorption, and the noise level is 5dB (A) lower than with balastless tracks.[79] Yet noise absorption materials or even a layer of ballast with nets to avoid ballast flying can be laid on the concrete to compensate.

3.2.1.3. Track geometry and alignment

In order to provide safe travel and good behaviour of the vehicles, the tracks have to be designed carefully, not only their structure but also the geometry of the track in straight lines and curves. The track geometry is defined by the track gauge and track centre-to-centre distance, the horizontal radius and track cant, and the slope steepness.

3.2.1.3.1. Track gauge and track centre-to-centre distance.

The gauge is the distance between two rails as Figure 19 shows. Most of HSR use the standard gauge (1435mm), except in some countries as mentioned in chapter 0.

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[79] (Ando, Sunaga, Aoki, & Haga, 2001)

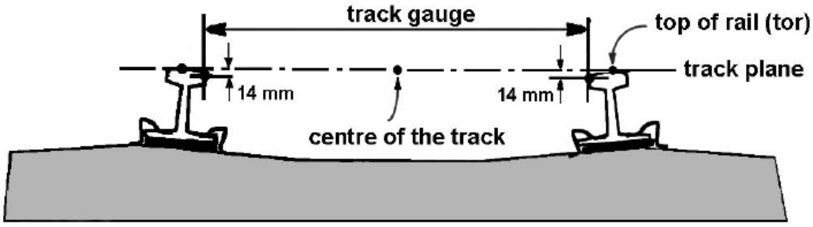

Figure 19 - Definition of track gauge (Lindahl, 2001)

High speed lines are usually built with a double track design. The distance between the centres of both tracks is called centre-to-centre distance. This distance is defined to allow a safe operation especially in curves to avoid a contact between trains on each track.

Furthermore, the pressure waves generated by the trains passing each other[88] must be taken into account to avoid damage, overturn or discomfort for the passengers. In particular, Raghunathan *et al*[80] mention that the peak pressure due to train passing each other is proportional to the square of the speed of trains. Thus it seems necessary to increase the track centre-to-centre distance at higher speed.

A comparison of existing high speed lines shows[81] that although Japanese Shinkansen are larger, the Japanese track centre-to-centre distance is similar or smaller than in most of the other countries. When designing a new high speed line, track centre-to-centre reduction could be considered after ensuring that it does not reduce the safety.

Table 9 – Track centre-to-centre distances in several countries, adapted from (Japanese Overseas Rolling Stock Association, 2004)

Country	Japan	France	Spain	Germany	Italy	Korea	Taiwan
Train width (m)	3.4	2.9	2.9	3.0	2.9	2.9	3.4
Track centre-to-centre distance (m)	4.3 (300km/h)	4.2 (300km/h) 4.5 (320km/h)	4.3 (250km/h)	4.7 (300km/h)	5.0 (250km/h)	5.0 (300km/h)	5.0 (300km/h)

3.2.1.3.2. Horizontal curve radius and track cant

Although the straightest way is the shortest, the topography or other constraints induce the presence of curves. They imply several constraints for the construction and operation. In curves,

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[80] (Raghunathan, Kim, & Setoguchi, 2002)

[81] (Japanese Overseas Rolling Stock Association, 2004)

the track is rotated to compensate the lateral acceleration of the train. The difference of height between the rails is called track cant. In practice, the cant is a trade-off between the comfort of the passenger by the reduction of the lateral forces, and the risk of derailment or falling over if the speed is too high or too low.[82]

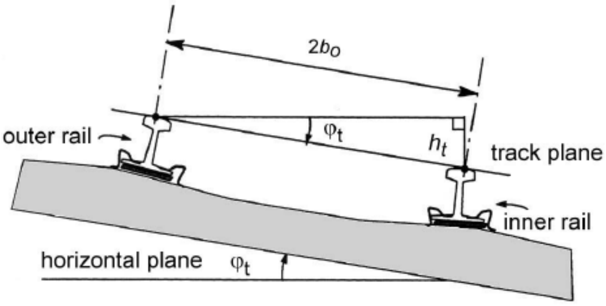

Figure 20 - Definition of cant (Lindahl, 2001)

Figure 20 shows the relationship between the cant h_t, the cant angle ϕ_t and the track distance $2b_0$. Assuming a small angle, ϕ_t can be written as:

$$\varphi_t \approx \sin \varphi_t = \frac{h_t}{2b_0} \tag{3}$$

The cant is in direct relationship with the curvature radius and the speed of the train. For a given speed and a given radius, the equilibrium cant is defined when the lateral acceleration of the vehicle is null.

With v the speed (in m/s) and R the curve radius (in m), the lateral acceleration a is:

$$a = \frac{v^2}{R} * \cos \varphi_t - g * \sin \varphi_t \tag{4}$$

At the equilibrium (a=0), and with V the speed in km/h, equations (3) and (4) give:

$$h_{eq} \approx \frac{2b_0}{g} * \frac{V^2}{3.6^2 * R} \tag{5}$$

As mentioned above, the actual cant is a trade-off between riding comfort and risks of accidents. The difference between the equilibrium cant h_{eq} and the actual cant h_t is called the cant deficiency h_d:

$$h_d = h_{eq} - h_t \tag{6}$$

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[82] (Lindahl, 2001)

$$h_d \approx \frac{2b_0}{g} * \frac{V^2}{3.6^2 * R} - h_t \tag{7}$$

In practice, cant deficiency is determined by the track designers. Existing standards are shown in Appendix 0.

If the speed and cant deficiency is given, the minimal horizontal curve radius of the track can be determined (see Appendix 0), or the limited speed can be fixed to match the infrastructure design:

$$V_{lim} \approx \frac{1}{3.6} * \sqrt{\frac{R * g}{2b_o} * (h_d + h_t)} \tag{8}$$

To reduce the discomfort, the change rate of cant between straight track and curved track or between two curved sections has to be limited. With L_t the length of the transition zone and Δh_d the difference of cant between the two sections, the change rate of cant is given by:

$$\frac{dh_d}{dt} = \frac{\Delta h_d * v_{max}}{Lt} \tag{9}$$

When a line is operated with mixed traffic, with slower and faster trains, the speed in curve will be limited by the slowest trains and that will affect the operation of the line. Introducing tilting train may overcome this limitation to some extent by reducing the discomfort felt by the passengers, yet the speed difference cannot be very high to avoid the increase of risk of derailment or overturn.

3.2.1.3.1. Slope steepness

Like horizontal curves, slopes cannot always be avoided, and the construction of bridges and tunnels is expensive. Steeper slope require more powerful motors and brakes, which increases the energy consumption, and a longer distance to brake, which can impact the safety and operation of the line. Both in France and in Japan, the higher slope gradient used for high speed lines is 30‰.[83] There is also a minimum radius of vertical curvature to avoid discomfort and derailment risks.

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[83] (Japanese Overseas Rolling Stock Association, 2004)

3.2.2. Civil structures

High speed rail tracks are supported by three types of civil structures: earthworks, viaducts and bridges, and tunnels. In this paragraph, the structures are briefly described and Japanese or French examples are illustrated.

3.2.2.1. Earthworks

When high speed track is built on the ground, it is usually either in embankments or cuts to provide a very flat alignment in flat or hilly areas, to ensure a good soil quality below the track over time, or to protect the tracks from floods for instance. Embankments and cuts are designed to grant a good soil quality and to avoid landslides on both sides. For the French LGV lines, the slopes on each side follow a width/height ratio of 2/1.

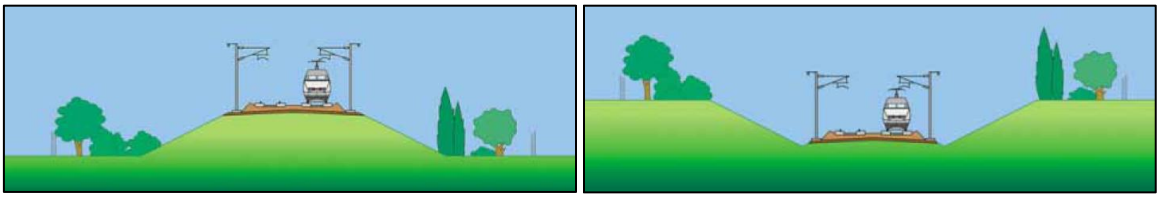

Figure 21 - Embankment (left) and cut (right), from (RFF, 2007)

French high speed line LGV Sud-Europe-Atlantique (LGV SEA) should be built with 45% of the tracks on embankment and 55% on cut, respectively 82km and 100km, with no tunnels and less than 1% of viaducts.[84] In average, embankments are 7.3m high and cuts 8.8m deep. This corresponds to an average width of respectively 51m and 63m including track width and fences, and 58m in average for the whole line.

3.2.2.2. Viaducts and bridges

Viaducts or bridges are used to cross obstacles, to ensure a better separation with ground level, or to overcome natural risks like earthquakes in Japan. Viaducts have a structure with short span while bridges have a longer span to cross wider obstacles like a river.

There are few viaducts in France as mentioned above, but many in Japan, where most of the recent lines are built on viaducts or tunnels. Japanese viaducts have standard anti-seismic

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[84] (RFF, 2007)

designs of concrete viaducts that can resist strong earthquakes such as the Great Tohoku Earthquake in March 2011 with very few damage.[85]

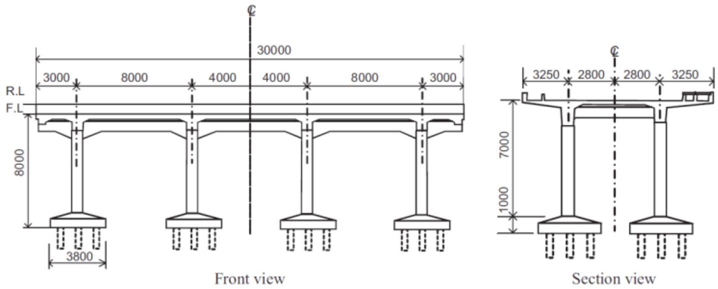

Figure 22 – Typical Shinkansen viaduct unit

There are many different types of bridges and each one is adapted to the location where it is built. Japanese bridges are carefully designed to sustain very strong earthquakes and wind, while in France the earthquake risk is much lower.

3.2.2.3. Tunnels

Tunnels can avoid a lot of curves and slopes in mountainous areas such as Japan, or can be dug undersea when a bridge is not feasible, like the Channel Tunnel between France and England or the Seikan tunnel between Hokkaido and Honshu islands in Japan.

High speed rail tunnels can be dug using blast and drill method or tunnelling machines depending on the ground conditions. Those conditions also influence the tunnel design like the thickness of concrete walls or the length of rock bolts.[86]

There are two main tunnel designs: single-tube or double-tube, as illustrated in Figure 23. Double-tube tunnels have been using in Europe after the fire that occurred in 1999 inside the Mont Blanc road Tunnel located under the Alps between France and Italy.[87] Nowadays, only balastless tracks are used in tunnels to reduce the maintenance needs.

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[85] (East Japan Railway Company, 2011)

[86] [JRTT, 2012] (RFF, 2007)

[87] (Cazier, RFF Interview, 2012)

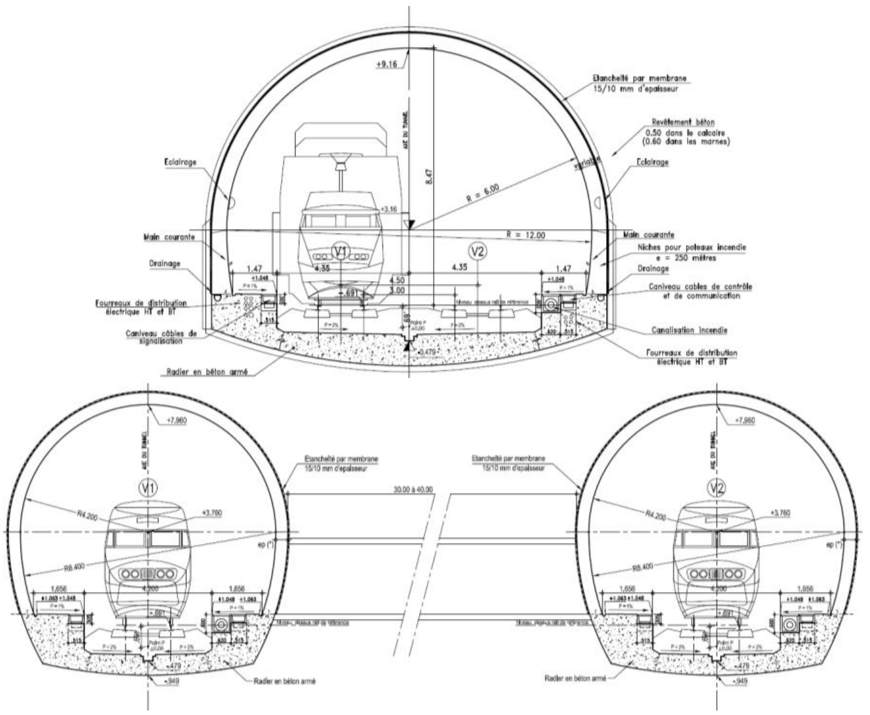

Figure 23 – Single tube (up) and double tube (down) TGV tunnels, from (SETEC International, 2004)

3.2.2.3.1. Micro-pressure waves in tunnels

When a high speed train enters a tunnel, it increases the drag but also generates a pressure wave that may cause discomfort to the passengers in the train, or even ear problems, and create a sound wave at the tunnel exits. Many studies describe and analyse these phenomena[88] and how to overcome it by improving the train aerodynamics as mentioned above or by modifying the shape of the tunnel entrance[89] or the tunnel itself.[90]

The pressure increase that is generated by the train entering can be estimated[91] as a function of the section of the tunnel, the section of the train and its speed:

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[88] (Ricco, Baron, & Molteni, 2007) (Raghunathan, Kim, & Setoguchi, 2002) (Shetz, 2001) (Sakuma & Suzuki, 2011)

[89] (Howe M. S., 2007) (Howe, Iida, & Fukuda, 2003) (Xiang & Xue, 2010)

[90] (N'Kaoua, Pope, & Henson, 2006)

[91] (Raghunathan, Kim, & Setoguchi, 2002) (Ricco, Baron, & Molteni, 2007)

$$\Delta p = \frac{1}{2}\gamma p_o M_t^2 \frac{1-\varphi^2}{\varphi^2 + (1-\varphi^2)M_t - M_t^2}$$

$$\text{With } \varphi = \frac{A_{tunnel} - A_{train}}{A_{tunnel}} \quad (10)$$

Where γ is the ratio of specific heats of air, p_0 the initial pressure inside the tunnel, A_{tunnel} and A_{train} the respective sections of the tunnel and the train, $M_t = \frac{S}{c_{sound}}$ the Mach number of the train with c_{sound} the celerity of the sound.

For a tunnel with double tracks, another phenomenon may increase the pressure further more. In France, network manager RFF and TGV operator SNCF includes this possibility to optimize the size of future tunnels sections according to the existing rolling stock.[92] French high speed network has been built mostly in flat lands and there are less than 5% of tunnels on the whole network, thus it is possible to optimize the tunnel size to match the rolling stock. In comparison, Japan is a very mountainous country and only the Tokaido Shinkansen line has around 10% of tunnels while other lines have from 30% to 70% of tunnels.[93] The Japanese tunnels are also smaller than the French ones, with respective sections of 63.4m^2 and around 100m^2 for double track tunnels, although both TGV Duplex and recent Shinkansen have a section of 10.9m^2. This explains why much more effort is put on improving the aerodynamics of Shinkansen than there is in France and in Europe in general. It is indeed shown that longer and better nose shapes reduce the pressure wave[94].

3.2.3. Power supply

High speed trains are powered by electric motors and thus need to be supplied by the infrastructure while running. Electric power supply is composed of the overhead lines on the tracks, and substations on wayside.

Catenaries are electric cables which power the trains through the pantograph. They are constantly in contact with the latter and must endure years of high speed operation. Figure 24 shows an example of a German overhead line used for high speed operation. Overhead lines are hanging from poles but the wire in contact with the pantograph must be as parallel from the track as possible. Thus the contact wire is hanging from a catenary wire that is tensed to

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[92] (Réseau Ferré de France, 2006)

[93] (Japanese Overseas Rolling Stock Association, 2004)

[94] (Shetz, 2001)

overcome the forces and vibrations generated by the relative movement of the pantograph and the power wire.[95]

In addition, the overhead wires are not perfectly straight but zigzag horizontally from a pole to the next. This is to ensure a longer lifetime for the pantographs. If the cables were straight the pantographs would be used only in one narrow surface, instead they are used slowly on a larger surface.

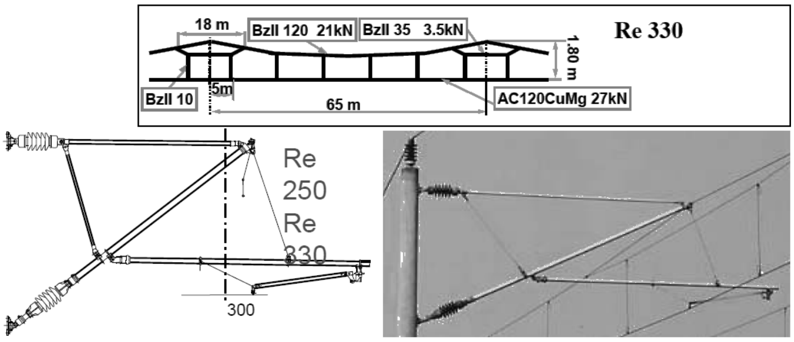

Figure 24 – Example of German overhead line for high speed railways (Tessun, 2008)

The substations have two roles: convert the current from the high voltage power lines to traction current and feed the overhead lines. The traction current itself can be direct or alternative, although direct current is less efficient. In Europe, traction current varies among countries so that interoperable trains have on board converters to operate with two or more alternative or direct traction currents.

3.2.4. Security, signalization and communication

When a train is operated at high speed, the signalization has to be displayed on board; otherwise the driver cannot distinguish fixed lights or may not have enough time to react fast enough. On-board signalization is one of the most important parts of the system because it grants the safety of high speed rail operation. In addition to the signalization, advanced communication systems have been or are in the process of being implemented. These systems allow the trains to be detected with enough precision to improve the capacity of the tracks without increasing the risks of accidents. All these systems can be classified from the train level to the management level.

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[95] (Yamashita & Ikeda, 2012) (Aboshi & Tsunemoto, 2011)

3.2.4.1. Automatic Train control

Automatic train control, or ATC, regroups the systems that enable a safe interaction between trains and between a train and the infrastructure, and that help the driver to travel at a safe speed. The main challenge is to overtake the conventional railway signalization and communication, which are not visible at high speed. Train control is also very important to manage and increase the capacity of a line. The more precisely the trains can be located and the more information is gathered about their speed, acceleration and braking performance, the closer the trains can be operated. Thus those systems have been much improved over the years. They are now called automatic, as more and more mechanisms tend to be automatized to avoid a human failure. Obviously those systems have to be very reliable and redundant. Automatic train control systems can be divided into three main categories, or levels, that are now described. Further evolution of ATC is also mentioned.

3.2.4.1.1. Level 1: traditional train control

In the traditional train control system, the lines are divided into small sections, called “blocks”, to approximately locate the train. The blocks are actually a simple electric circuit, with the two parallel rails connected at each extremity of the block, so that a train passing on a block creates a short circuit as shown in Figure 25.

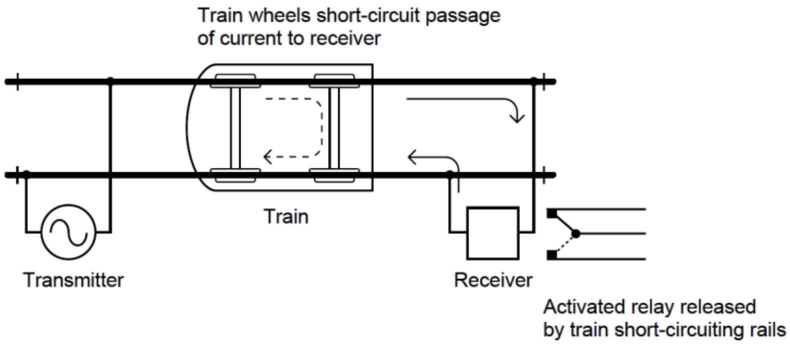

Figure 25 - Principle of track circuit (Takeshige, 1999)

In level 1, a speed limit is assigned to each block. This limit is sent to the train through a beacon when enters it, and the train is going faster than the assigned speed, train will decelerate to match the block speed. Access to a block where a train is and to the one before it, is forbidden for any following train and it is signalled on the side or on board. If a train goes beyond this point, it is automatically stopped or slowed to avoid a collision, as Figure 26 shows.

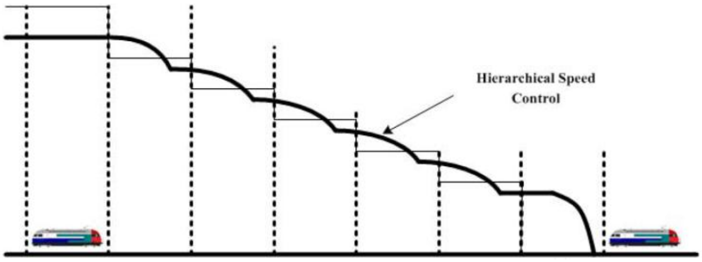

Figure 26 - Hierarchical speed control (Wang, Wang, Cai, ShangGuan, Wang, & Zhang, 2011)

In Japan, such a system is designated simply as ATC, and in Europe as ETCS1 (European Train Control System), although European countries have their own equivalent systems and other JR companies may use different names, such as EJTC1 (East Japan Train Control) by JR East.[96] There are a few differences: the European system still uses beacons (EuroBalise) to communicate with the trains, while the Japanese use a leaky coaxial cable along the tracks.[97]

A particularity of the European systems, both ETCS and national systems, is the addition of a “dead-man switch” that requires the driver to press a button at a very short interval of time. If the driver fails to press this button, an alert will ring. If the driver fails to answer the alert signal, the train will be automatically stopped. There is no such system on the Shinkansen, but it does not mean that passengers are not as safe. In February 2003, a Shinkansen stopped by itself a hundred meter ahead of Okayama station platform. The driver was found unconscious and the train may have travelled 26km with him unconscious, but the train performed just as well. The small distance ahead of the station was caused simply because actual stopping points in stations are located after the end of the platform, and the drivers slow the train using manual control under normal operation.[98]

3.2.4.1.2. Level 2: continuous speed control

The second level introduces a major upgrade regarding speed control. Instead of providing the speed limit for each block, the speed is controlled continuously to provide smoother operation and increased riding comfort. Figure 27 illustrates this principle. In Europe, level 2 is called ECTS 2; while in Japan it is usually known as Digital-ATC (D-ATC).

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[96] (Matsumoto, 2005)

[97] (Takeshige, 1999)

[98] (Hood, 2006)

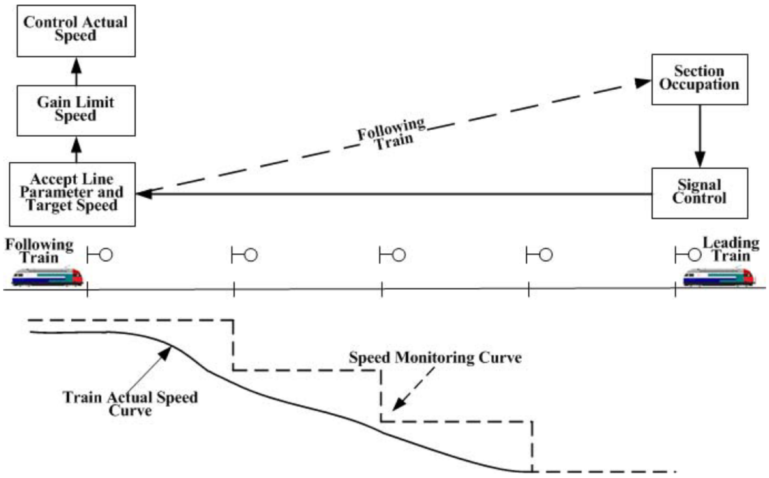

Figure 27 - Continuous speed control with fixed blocks (Wang, Wang, Cai, ShangGuan, Wang, & Zhang, 2011)

3.2.4.1.3. Level 3: moving blocks

The fixed block system is limited by the size of the blocks: the longer the blocks, the longer the minimum distance between trains. To overcome this problem, moving blocks are introduced with the third level of ATC. Although called moving blocks, this new system does not use physical blocks. The trains are instead located precisely using a geolocation device. Speed profile is then defined by the infrastructure design speed ahead of the train, and by the location of other trains. As Figure 28 shows, a safe distance is kept behind the trains, and the train performances and line parameters are used to generate a speed curve, which is updated in real time. Then the driver can drive at any speed below the speed limit displayed in the cabin, which is the maximum safe speed.

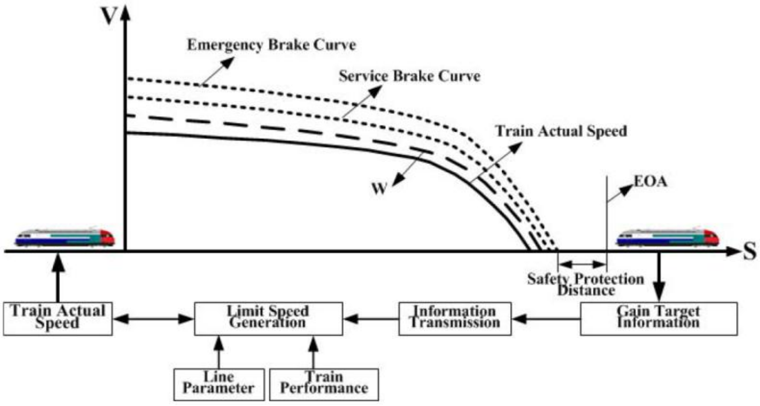

Figure 28 - Continuous speed control with moving blocks (Wang, Wang, Cai, ShangGuan, Wang, & Zhang, 2011)

This upgrade is significant but needs the installation of new devices for geolocation and wireless communication between the train and the infrastructure. Train integrity has to be checked at all time, although it may be safe to assume that a high-speed train would obviously not work properly if a car is lost.

There is currently no use of this third level for high speed operation, but it is described as ECTS 3 in the European interoperability standards, and JR East has developed a similar system called ATACS. This system is currently being implemented by JR East on the conventional Senseki line in the area hit by March 2011 East Japan Earthquake and Tsunami.[99] Europeans have developed a specific wireless communication standard based on GSM standards, called GSM-R (GSM-Railway), while ATACS uses digital radio communication.[100]

3.2.4.1.4. Beyond moving blocks: relative braking distance

Although ATC level 3 is not yet implemented on high speed networks, researchers and practitioners are already working on the next generation ATC.[101] With level 3, the limitations are the rolling stock and the infrastructure themselves, but also the way the speed curve is calculated. Next generation ATC will not only rely on trains with better brakes and straighter lines, but could also allow a closer distance between trains by using a relative braking distance. Instead of having an absolute safety distance behind each train where the following train would come to a halt, the system would compute a stopping point *ahead* of the first train, considering that this train has its own deceleration curve itself, as well as the train before it, and so on. Deceleration curve could be based either on normal braking or even emergency braking. This new ATC would obviously increase the capacity of the line, yet it poses many safety concerns: if a train is suddenly stopped as it happened in the Eschede accident, the following train would not have enough distance to stop, increasing the casualties.

Whichever the train control system, it must achieve a perfect reliability by being redundant and using very reliable components. The recent Wenzhou collision is reported to be partly caused by a mechanical failure in the signalization system, which a driver failed to notice.[102] Increasing the speed and decreasing the headway will require several years of developing and testing the new

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[99] (East Japan Railway Company, 2011)

[100] (Matsumoto, 2005)

[101] (Emery, 2011; Aulagnier & Sarrazin, 2011)

[102] (Areddy & Jie, 2011)

systems under as many different situations as possible. Table 10 summarizes the three ATC levels that are currently used or to be implemented for high speed rail operation.

Table 10 - Comparison of train control levels, adapted from (Matsumoto, 2005)

	Level 1	**Level 2 (currently in use for HSR)**	**Level 3**
Signalling system	Way side signal	Cab signal	
Block system	Fixed blocks		Moving block
Train detection	Track circuit		Train itself
Transmission train-ground	Beacon and antenna		Wireless
Position recognition	Nothing	On-board	
Control method	Punctual	Continuous	

3.2.4.2. Centralized traffic control and integrated train management

Above the Train Control is the Centralized traffic control (CTC). The main role of the CTC is to control the switches and make sure that the trains are on the right tracks. It regroups all the equipment that enable the operator to have a representation of the traffic on a single control room, and therefore to identify where and when a train has a problem, and to eventually decide how to manage the traffic in such a situation. In France, each TGV line has its own CTC, like in Japan.[103]

An integrated train management system allows the operator to manage its fleet and to interact with the network manager as well as with the passengers. The system helps with the decision of train patterns that are negotiated with the network manager, and coordinates the CTC and the management of the substations. Information about train timetable and delays are also gathered and sent to the stations to be displayed.[104]

3.2.4.3. Earthquake detection systems

The Great East Japan Earthquake that occurred on March 11, 2011 caused only little damage to the Tohoku Shinkansen track, and no casualties, despite the very powerful shake and the numerous aftershocks according to East Japan Railway Company[105]. Because of the earthquake threat over Japan, the Shinkansen system has been designed from the very beginning to

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[103] (Taniguchi, 1992)

[104] (Takeshige, 1999)

[105] (East Japan Railway Company, 2011)

integrate several measures to protect the passengers and drivers, and has been upgraded after other powerful earthquakes, so that it could sustain one of the most powerful earthquakes in history on mankind.

The most critical system is the integration of the Japanese Early Earthquake Warning System that detects the possibility of an earthquake. When an earthquake happens, two series of waves are emitted. The primary waves (P-waves) are weaker the secondary waves, which cause most of the damages. Once the P-waves are detected by seismograph, the epicentre and magnitude of the coming earthquake are estimated and a warning is sent to every Early Earthquake Warning receiver (cellular phones for instance). In the case of Shinkansen, the signal is sent to the transformer to cut the power and activate emergency brake in the potentially affected areas. Thus the train is completely stopped in a short time to avoid any derailment risk at high speed. On March 11, the P-waves were first detected on the coast only 12 to 15 seconds before the S-waves but it was enough to stop safely Shinkansen operations.

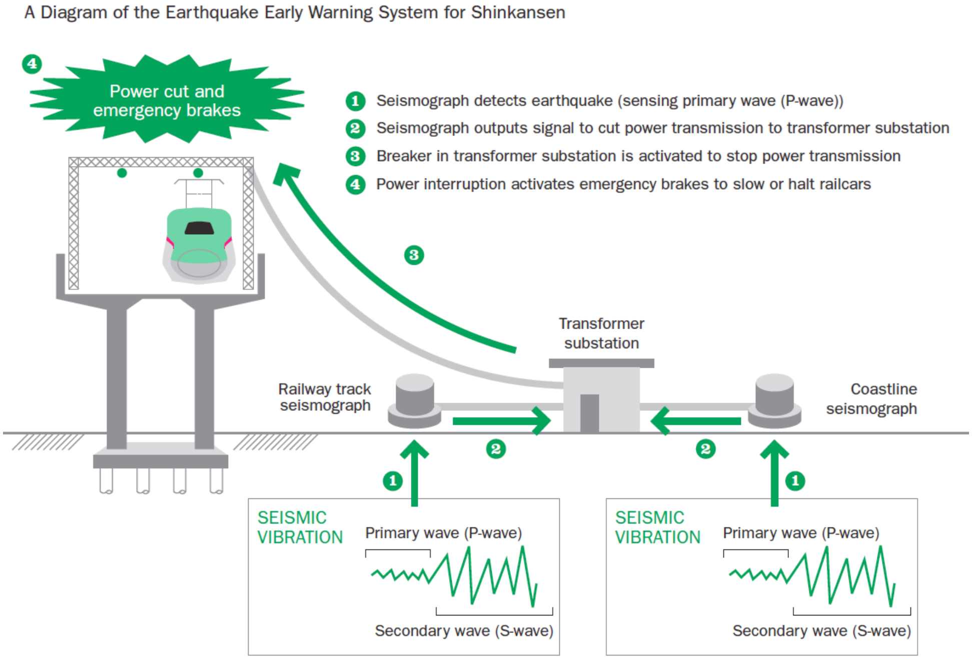

Figure 29 - Early Earthquake Warning System for Shinkansen (East Japan Railway Company, 2011)

In addition, the infrastructure is obviously designed to resist powerful earthquakes, and has been improved and fortified over the years. No parts of the Tohoku track, including bridges and tunnels, were collapsed after March 11 Earthquake although it is the most powerful recorded. Yet some damaged occurred at approximately 1200 sites along the 500km track:

- Electric poles collapsed in some sections because a lighter design was introduced: the poles were in two parts (one for each track) instead of one part, thus they were very weak to lateral moves
- Overhead wires were snapped
- Some viaduct columns suffered from damage but could be repaired and improved quickly
- No part of the infrastructure was hit by the tsunami.

It took only 49 days to restore the Tohoku Shinkansen line. In comparison, it took 66 days to restore the Joetsu line after the Niigata Chuetsu Earthquake in 2004, and 81 days to restore the Sanyo line after the Kobe Earthquake in 1995, both of which had the same maximum seismic intensity than the Great Tohoku Earthquake (7 on the Japanese Meteorological Agency scale). But on both cases the infrastructure suffered more damage (viaduct column toppling, tunnels collapsed). After the earthquake, the focus on earthquake protection has been obviously raised, and aseismic reinforcement will be improved even more in areas near active fault lines.

These efficient measures to protect a high speed rail system against the risk of a powerful earthquake are very particular to Japan, which is currently the only country in the world which operates a high speed rail while facing such a high risk, until California high-speed network is built.

3.3. High speed line maintenance

Safety and security of high speed rail operation also relies on the quality of the infrastructure over the time. But maintaining the line requires works to be performed on the tracks. Such works may affect the availability of the line, and thus it must be managed carefully to ensure the continuity of high speed rail operation with the lowest risks.

In order to maximize the availability of a line, the network manager has to define a maintenance strategy that will organize the maintenance process. There are two main maintenance strategies: corrective maintenance and preventive maintenance. The first occurs when a failure is expected or has happened while the second occurs when a failure is anticipated.[106]

Corrective maintenance has a high impact on availability and cost since it may require long and complicated interventions to repair the failure.

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[106] (Ly, Simeu-Abazi, & Leger, 2006)

There are several kinds of preventive maintenance, with two main types: periodic maintenance and condition-based maintenance. Periodic maintenance is based on the observation of the lifetime of each element of the system. When the lifetime and its statistical distribution are known, the manager can establish a maintenance schedule. This fixed schedule has a reduced impact on the availability without sacrificing the safety. Condition-based maintenance requires a monitoring of the infrastructure to detect the defects. Instead of scheduling the intervention on a regular basis, they are requested on demand when the quality of the infrastructure is below a threshold. This threshold is fixed by the network manager and must keep a high level of safety without impacting the availability too much. Condition-based maintenance is now very popular among railway operators since it offers a greater availability than periodic maintenance.[107]

Even with evolved condition-based maintenance, curative maintenance is still needed. Indeed a non-forecasted event can always happen, caused either by the defect of one or more elements of the system, or by external factors as it happened with the Great Tohoku Earthquake in Japan.

Practitioners and researchers have established various models to assess the degradation of parts of the infrastructure and to optimize the inspection and intervention schedules. For instance, Antoni and Meier-Hirmer, who work at SNCF, have jointly or separately published several papers to propose maintenance optimisation models. Meier-Hirmer proposed and compared[108] different types of stochastic model for intervention planning and maintenance cost optimization using SNCF database. Antoni and she[109] studied the optimisation of maintenance strategies for tracks, signalling equipment and overhead line components by adapting a stochastic model to SNCF data. Antoni[110] focused on improving the track maintenance on both conventional and high speed line by considering the relationship between grinding, ballast tamping and ballast replacement.

These models require a large database. To ensure efficient track maintenance and accumulate maintenance data, the tracks are inspected on a regular basis to look for defects and to collect data about their state. This database is very important since it allows the network manager to

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[107] (UIC, 2010)

[108] (Meier-Hirmer, Riboulet, Sourget, & Roussignol, 2006)

[109] (Antoni & Meier-Hirmer, 2008)

[110] (Antoni, Modelling of the Ballast Maintenance Expenses, 2011)

identify the recurring problems and to optimize and improve their maintenance strategy.[107,111] Inspection of the tracks and overhead power supply is done with a high speed inspection train such as Japanese Dr Yellow on the Tokaido Shinkansen or IRIS320 on the French LGV.[112] These inspection trains allow a precise measurement of the behaviour at high speed.

3.4. Conclusion of the chapter

In this review of high speed rail systems, it has been found that there is diversity of solutions for the same purpose of providing a safe high speed railway transportation system with very similar performance. This diversity of systems includes the infrastructure, the rolling stock, the signalisation and other equipment. These differences can be explained by the local contexts described in chapter 0, such as gauge, weather conditions and earthquake risks, political choices to cite a few. Most importantly, the different solutions have been designed as fully integrated systems, and should be considered as such. However, the vision being developed in Europe aims towards a separation of activities. The next chapter aims to verify which approach the feasibility and cost assessments of high speed rails follow.

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[111] (Antoni, SNCF: Asset maganement and Safety, 2012)

[112] (UIC, 2011)

4. COST STUDIES OF HIGH SPEED RAIL

There have been several studies about the cost of high speed rail, in various countries, situations, and using various approaches. But interestingly, one can find very few studies that cover the lifecycle of high speed rail systems as a whole. Additionally, they usually do not establish a comparison of different high speed rail technologies, considering an average high speed rail system. First, feasibility studies are reviewed, then the different types of life cycle cost studies, and finally a more inclusive life cycle approach is proposed.

4.1. Feasibility studies and cost-benefit analysis

Feasibility studies focus on the cost of building and operating a transportation system project. The case of the Californian high speed rail project has been considered for several years and from several approaches, and illustrates the various studies that can be made regarding the cost of high speed rail on a specific line. Kagiyama[113] has conducted a study which considers the implementation of the Shinkansen technology in California, also based on a specific hypothetical line. The author compares an estimation made by the California High-Speed Rail Authority (CaHSRA) to the Tokaido Shinkansen and the Japanese magnetic train project. The comparison is mainly focused on the characteristics of the two markets and is more an economic assessment than an engineering comparison. More recently, Chester[114] has been focusing on the environmental assessment of the Californian project. In their article, they compare rail, road and air transportation to show that the rail is more suitable for the environment. Levinson *et al*[115] made a very detailed analysis of the total direct and indirect costs of introducing a high-speed railway in California. They estimate the total cost as a sum of several components related to the infrastructure, rolling stock, operation costs and external impacts. For each cost, a specific cost model is used. According to their conclusions, high speed rail was not sustainable, but the latest studies from the California High speed Rail Authority suggest that it should be profitable,

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[113] (Kagiyama, 2000)

[114] (Chester M. V., 2008) (Chester & Horvath, 2010)

[115] (Levinson, Mathieu, Gillen, & Kanafani, The Full Cost of High-speed Rail: an Engineering Approach, 1997)

with a positive cost-benefit analysis[116]. They use a four step model to estimate the ridership, very common in transport demand modelling.

Those studies have various purposes: to show the competitiveness of a specific high speed rail system or to analyse the impacts of an average high speed rail system. Yet they all are some kind of preliminary studies, and are important to show several opinions to the stakeholders about the feasibility of high speed rail. However, they do not help the stakeholders to choose the most adapted high speed rail system since the studies use various scope and models.

Regarding the choice of system, the conclusion of the California High Speed Rail Authority is interesting: "it is apparent that that the marketplace for high-speed train sets, capable of operating at 220 mph, has been focused on a single-level distributed power electric multiple unit configuration. A train set procurement that specifies this type of configuration will result in maximum competition."[117] This convergence of design was highlighted in chapter 0, yet it is surprising that they do not consider other train designs, at least as a sensitivity analysis. Discussions about high speed rail take many years, and the manufacturers could have enough time to propose more suitable designs, provided that the authority has analysed the best options.

4.2. Life Cycle Cost studies

According to a report commissioned by the Dutch Ministry of Infrastructure and the Environment[118], life cycle cost (LCC) can be defined as "*the cost induced by a product (good or service) in its life cycle as borne directly and indirectly by public and private actors involved, and possibly including cost of external effects as resulting for current and future generations through environmental mechanisms*." This encompassing and clear definition highlights the fact that LCC aims to assess not only the initial cost, but also all the costs that occur during the lifetime of the product and at its disposal, as well as the social costs generated by its use. According to the same report, those costs are generally:

- *Research, development and design*
- *Primary production*

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[116] (California High-Speed Rail Authority, 2011)

[117] (Parsons Brinckerhoff, 2009)

[118] (Huppes, Rooijen, Kleijn, Heijungs, de Koning, & van Oers, 2004)

- *Manufacturing*
- *Use and maintenance*
- *Disposal management*

Life cycle costing is very common in the building construction for instance, several handbooks have been written, such as the ones by the State of Illinois[119] or Alaska[120]. However, there are no international standard or common methodology for LCC as mentions Zoeteman in his thesis[121]. Thus the definitions, methodologies and goal are various.

One can find three types of high speed rail LCC studies: studies focusing on the costs borne by the operators, studies focusing on railway infrastructure management and RAMS analysis, and lifecycle assessments.

4.2.1. Operator's costs

There are actually few studies that focus only on the operator costs. The UIC has published a report[122] that identifies the relations between operating costs and speed. Based on European experience, Spanish in particular, they develop a very detailed cost estimation of operator costs, including:

- Direct operating costs, related to the movement of trains
- Commercial costs, related to the ticket sales, marketing and passenger services, but also capital costs
- Infrastructure charges, paid to the infrastructure manager and related to the use of the network

It highlights the very high impact of speed on high speed railway costs and a sensitivity analysis provides more precisions about the variation with other parameters. Since it is based on existing experience, it gives an average output that can be applied in Europe, yet an application in other regions would require a careful analysis of the structural and local differences.

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[119] (State of Illinois, 1991)

[120] (State of Alaska, 1999)

[121] (Zoeteman, Railway Design and Maintenance from a Life-Cycle Cost Perspective, 2004)

[122] (Garcia, Relationship between Rail Service Operating Direct Costs and Speed, 2010)

A compilation of studies published by the BBVA Foundation[123] provides a deep review of the cost of high speed rail in Europe, based on the database of existing lines. This review is then used to establish a cost estimation of high speed rail over forty years: five years of construction and thirty-five years of operation. They include construction, maintenance, and operation; and focus on illustrating the cost variation for three scenarios – called best, medium and worst cases – with respect to the speed, the length of the line, train capacity and demand. They show a very high cost variation depending on the scenario and the sensitivity analysis. This study highlights some of the underlying mechanisms of high speed rail system and shows the heavy weight of fixed costs, yet the cost estimation itself is, again, only applicable in Europe or in a similar situation. Infrastructure and rolling stock are both considered as fixed designs: only the length and capacity can be set, but neither the type of track or structure, nor the type of trains. Nonetheless, the methodology used is interesting since it considers the relationship between the demand and the service provided.

Sánchez-Borràs *et al.*[124] have proposed a study about rail access charges that the operators pay to access the network. They examine the theoretical pricing and actual pricing strategies, and conclude that actual price may be underestimated and could be raised. Although those charges are paid by the operator, they are actually based on the construction repayment and maintenance of the infrastructure, and thus are borne by the infrastructure manager.

4.2.2. Railway infrastructure management and RAMS analysis

As described in Chapter 0, the European railway policy has introduced a vertical separation between infrastructure managers and railway operators. As a result, the performance of the infrastructure is very critical and the pressure on infrastructure managers has increased to improve the reliability and availability of the tracks as well as the operational conditions, with a limited budget. Thus infrastructure managers and researchers are focusing on reliability, availability, maintainability and safety (RAMS) assessments and on life cycle cost optimisation.

The European railway sector has recently concluded an important research work regarding infrastructure LCC. Innotrack[125] was a project launched in 2006 and funded by the European Commission that aimed to *"Increase the competitiveness of the railway sector by decreasing track*

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[123] (de Rus, et al., 2009)

[124] (Sánchez-Borràs, Nash, Abrantes, & López-Pita, 2010)

[125] (INNOTRACK, 2010)

related life cycle costs." It focuses on the improvement of performance and cost effectiveness of infrastructure construction and management. For that purpose, major European stakeholders and researchers have jointly created the project, such as Deutsche Bahn, SNCF or Alstom. Innotrack is a logical response to the standardisation of European railway policy and to the vertical separation requested by the Commission. The project develops a very detailed LCC model based on many data and return of experience from the European stakeholders, in order to identify the cost drivers and best options to improve and upgrade European railway infrastructure in a cost-efficient yet safe manner. They consider every component of the infrastructure and give many outputs for infrastructure managers. Unfortunately, they do not consider high speed rail operations in details, nor include operating costs.

Patra[126], who has participated in the Innotrack project, insists that the implementation of LCC and RAMS in the railway sector is still at a very early stage. She also highlights the use and purpose of RAMS:

- *To estimate costs of a maintenance/renewal work*
- *To assist in the selection of the best maintenance option/strategy in terms of economic return under specified time and financial constraints*
- *To assist in the scheduling of maintenance works in the most effective way*

Zoeteman[127] mentions that with the recent changes in the European railway sector, infrastructure managers face many new challenges and much pressure to reduce their costs and increase their performance. However, they have difficulties adapting to the new context and to assess the long term impact of their technological decisions. A better track management and RAMS in particular, can help the infrastructure managers meet the requirements, yet these processes at still at an early stage. Thus Zoeteman develops a decision support system to assess the lifecycle costs of wide range of track designs and maintenance solutions, helping the relationships between the infrastructure management and maintenance stakeholders. The model considers a wide range of costs borne by an infrastructure manager: construction, maintenance, renewal, delay, and organizational costs. It was tested on a few lines in the Netherlands and had positive feedback, yet Zoeteman mentions that it requires much empirical data and much commitment from the stakeholders, which are both difficult to gather. In particular he states that life cycle cost "*is able to influence decision-making but that gaining*

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[126] (Patra, 2007)

[127] (Zoeteman, 2004)

commitment by stakeholders is difficult". The Innotrack project and intensive research about the topic[128], show that this commitment is growing. The improvement of maintenance strategies is a very hot topic in railways in general, not only high speed railway.

4.2.3. Life Cycle Assessment

The LCA is a methodology that provides a framework to evaluate the environmental impacts of a project over its lifecycle. This can be applied to various fields of study. One of the main characteristic of the LCA is that it can be formulated as a framework, and it has even become an ISO standard[129], but other frameworks have been developed. Finnveden *et al.*[130] summarize the state of the art in LCA and insist on its advantages and drawbacks. LCA needs a large database to give precise and reliable output, which can consume many resources to fill. All of the impacts covered by LCA are not covered equally or with the same precisions and despite the standardization many different methodologies exist and their choice may influence the results. In spite of that, LCA seems very mature.

In relation with the railway topic and in addition to the studies from Chester cited above, Chang and Kendall[131] assess the greenhouse gas emissions from the California high speed rail project. Kato *et al*[132] evaluate the environmental impacts of inter-regional high-speed mass transit projects with a complete analysis of the impacts of every part of airline, high-speed rail and MAGLEV system.

Another trending LCA is the carbon footprint, very popular to assess the risks on climate change in particular. The UIC has recently published a report about the carbon footprint of high speed rail[133], with a very detailed framework that includes a deep inventory as well as a quick comparison with other modes. In France, the first complete carbon footprint assessment has been established for the latest line LGV Rhin-Rhône and its future extension[134], using the

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[128] (Antoni, SNCF: Asset maganement and Safety, 2012)

[129] ISO 14040-2006 for the last revision

[130] (Finnveden, Hauschild, Ekvall, Guinée, & Heijungs, 2009)

[131] (Chang & Kendall, 2011)

[132] (Kato, Shibahara, Osada, & Hayashi, 2005)

[133] (Baron, Martinetti, & Pépion, 2011)

[134] (ADEME, RFF & SNCF, 2009)

methodology developed by Ademe, the French Environment and Energy Management Agency called “Bilan Carbone” (carbon assessment).

All those frameworks only apply to the specific topic of environmental impacts, and thus are very restricted in their use, but they show the importance of considering the whole lifecycle of a system, especially a system as complex as high speed railways, and railways in general.

4.3. Life cycle cost of high speed rail

Interestingly, there is a very different focus between LCC and other cost studies, and LCA. High speed rail cost studies usually focus on the viewpoint of either the operator or the infrastructure manager, while LCA considers the system as a whole, from the society viewpoint. RAMS and maintenance optimisation studies focus on improving the maintenance and design of the tracks, LCA assess the environmental performance, and a few cost studies provide information about average operating costs. Yet those three points of view are complementary and should be integrated together. Especially when designing a new high speed rail network, stakeholders should have the opportunity to study various technical options. Inspired by the objectives given by Patra[135] and mentioned above, a life cycle cost model of high speed rail should help the stakeholders:

- To estimate the costs of a new high speed rail system
- To assist in the selection of the best design options in terms of economic return under specific local constraints
- To assist in the decision making process by providing the cost structure to allow a discussion among stakeholders.

Nowadays, the vertical separation introduced by recent reforms guided by political and economic viewpoints tends to consider each part of the railway system separately. Yet from an engineering point of view, high speed rail is a very elaborate and complicated system, in which every subsystem is integrated as has been shown in the previous chapter.

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[135] (Patra, 2007)

5. PRESENTATION OF THE MODEL

Most of the LCC models described in chapter 4 mainly focus on infrastructure and maintenance costs. This focus is the result of the recent trend to vertically separate infrastructure managers and railway operators, as mentioned in chapter 0. Yet it high speed rail is a complex system, as explained in chapter 3, and from an engineering perspective it seems better to include every part of the system in the LCC calculation. As Figure 30 shows, a lower cost for the infrastructure manager does not necessarily mean a lower cost for the operator, and a more global optimum may be achieved by considering all the costs from the start. In a country were high speed rail is introduced for the first time it is of the utmost importance to consider the system as a whole and not only a part of it to avoid a biased vision. Even though the initial costs are more expensive, achieving a lower LCC under the same operating constraints will benefit the user, and the society.

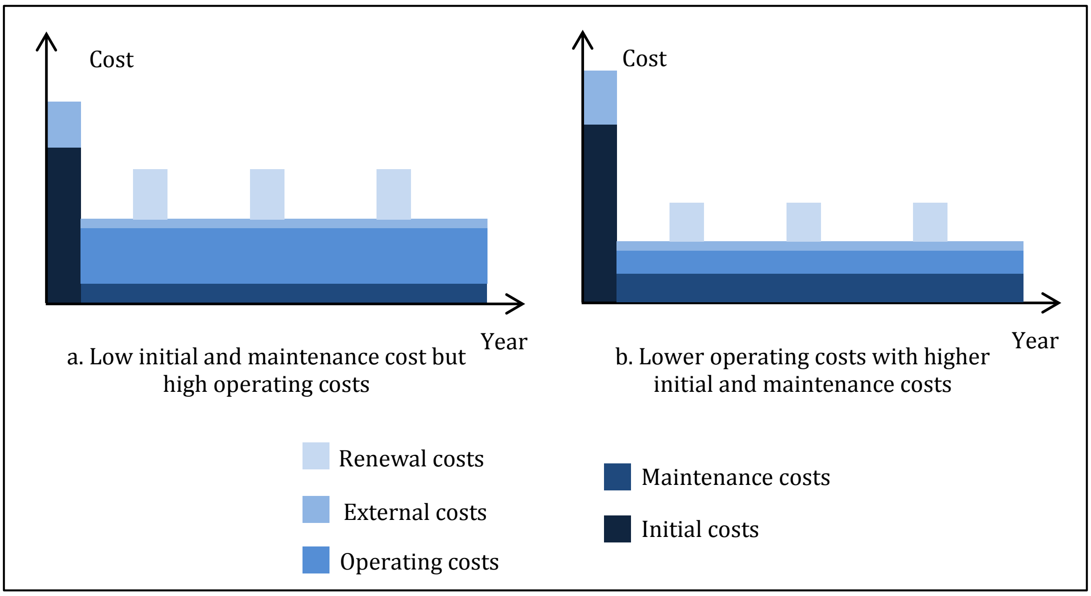

Figure 30 – Illustration of life cycle trade-off

This chapter aims to describe the LCC model developed for this study. First, it presents shortly the theoretical framework resulting from the previous analysis of high speed railway system. Then, the boundaries and parameters of the actual model are explained, and finally the cost components and hypothesis for each of them are detailed.

5.1. Presentation and boundaries

This lifecycle cost model aims to highlight the phenomena occurring when a high speed line is operated. This chapter will describe the hypothesis and data used.

The model was developed with Microsoft Excel 2010 using Microsoft VBA programming language. Thus the input data and results can be manipulated directly and simply with Excel.

5.1.1. Theoretical framework

After reviewing the high speed rail system in the previous chapter, a theoretical framework can be established to illustrate the factors affecting the cost. In the present study, those factors are train design, track type, infrastructure parameters, local constraints, and operational parameters as shown in Figure 31. For each cost category, a detailed framework is established. Each detailed cost framework is in Appendix A3.

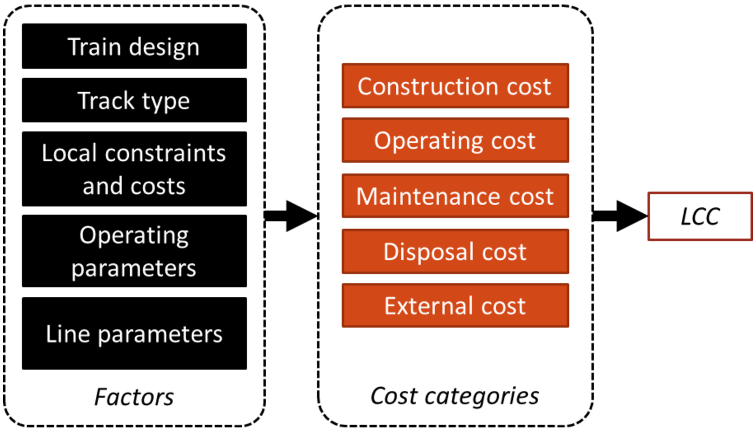

Figure 31 – LCC Framework overview

Based on the detailed frameworks and the data collected through interviews and in the literature, some simplifications or changes have been made for two reasons:

- Limited data availability, for train aerodynamics and energy consumption for instance
- Too detailed model that would necessitate a very precise knowledge of the local parameters, such as precise geology, precise dimensions of the civil structures, or precise construction cost evaluation in a local context. A slightly simplified model is more suitable to allow a comparison of train designs and alignments options with a wider focus and an easier adaptability to different conditions. As mentioned in chapter 4, very precise cost evaluations are difficult to transfer. Yet the model has been designed to be easily upgraded with more refined or precise estimations if the user wishes to satisfy its needs.

When simplifying, it has been carefully verified that the simplifications were still enough for the use of the model. Next paragraph highlights the main parameters and boundaries, and the following describe the cost models. This chapter is concluded by the overview of the calculation model, as a result from the cost models.

5.1.2. Model boundaries and parameters

Four cost categories are considered: construction, operation, maintenance and external costs. Disposal cost is not a separate category; rolling stock disposal cost is included in the operating costs and there is no residual value for the infrastructure.

The lifetime considered is fifty years. The economic study compiled by the BBVA Foundation suggests that a too long lifetime increases the level of uncertainty[136], yet fifty years is usually considered in the infrastructure projects. Infrastructure construction is assumed to take place before and construction costs are aggregated as initial costs. Financial risks are not included, and the actualisation rate can be specified. The default value, used in this study, is $i = 4\%$.

The lifecycle cost is calculated as the net present value (NPV):

$$LCC = \sum_{y=0}^{50} \frac{C_y}{(1+i)^y} \tag{11}$$

Where y is the year, C_y is the total annual cost with C_0 the total initial costs.

5.1.2.1. Main parameters of the line

In this version of the model, a simple line is considered, running between two terminal stations, with as many stations as the user wants. Mixed traffic is not allowed in order to study only the impact of high speed rail, and service through the conventional network is not considered as it is not high speed. Both cases may be introduced with an upgraded model.

The main parameters of the line determine the main performance of high speed rail:

- Demand is given and assumed symmetric, constant through the year. Input demand is the total demand, for both ways, in million passengers per year (Mpax). A single annual growth rate can be applied. The number of years to reach the total demand can also be specified; a linear growth is applied.

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[136] (de Rus, et al., 2009)

- Speed is given as the maximum design speed. Actual average speed between stations is 20% lower as mentioned in the previous chapter but this value can be modified.
- Infrastructure length and number of intermediary stations.

Those parameters are given by the user, assuming that they are fixed by the competition with other modes. Yet the model can be included in a cost-benefit analysis; in that case the main parameters must be optimized with respect to the cost-benefit analysis.

5.1.2.2. Local conditions

In addition to the main parameters, local conditions should be specified. Those are local environmental conditions such as the risk of strong earthquakes and heavy snowfall, technical conditions such as the choice of AC or DC power supply, and the energy production mix, and economic conditions such as the wages, and energy and land cost. They are very important for the choice of the best system.

5.1.2.3. Operating parameters and constraints

Several operating parameters are considered and can be modified to some extent. They are important elements because they determine the basic constraints of the system: the maximum number of services that can be operated, and the maximum number of roundtrips per trains. The operating parameters are:

- Operating hours OH: high-speed infrastructure cannot sustain non-stop operation, mainly because of maintenance requirements. Operating hours can be adjusted to match the user requirements with a thirty minutes interval.
- Train occupancy rate τ: the default occupancy rate is 75% but the user can adjust the parameter for sensitivity analysis.
- Headway $t_{headway}$: minimum time between two trains. In this study, 3 minutes headways are considered. This value, similar to TGV and Shinkansen, has been chosen to acknowledge both improvements in traffic management and limitations due to higher speeds mentioned in paragraph 3.1.1.
- Minimum time in station $t_{station}$: how long does it require for passengers to embark and disembark and what time buffer the operator wants. This value depends on the train design: a higher capacity means that more time is needed, and non-articulated designs only have one door per car, which increases the alighting and boarding time. Calculation of $t_{station}$ is shown in paragraph 5.2.2.3.
- The amount of first class ϕ, given in percentage.

Under those operating constraints, the maximum number of services per day σ_{max} can be calculated:

$$\sigma_{max} = \frac{OH * 60}{t_{headway} + t_{station}} \tag{12}$$

That value determines the capacity of the line: the actual number of operated services cannot be greater than this constraint. σ_{max} depends on the operating parameters but also on the design of the train.

The maximum number of roundtrips per trains can also be calculated:

$$\theta = \frac{OH}{2 * \left(\frac{L}{Saverage} + N_{stops} * \frac{t_{station}}{60} + \frac{t_{turnover}}{60}\right)} \tag{13}$$

The variable θ is rounded up to the closest half decimal unit to allow the trains to make both roundtrips and single trips. θ depends on the infrastructure, the operating parameters and the train design.

$S_{average}$ is the average speed between stations. The data found in the 2007 world speed survey[137] shows that for recent lines, the average speed is around 80% of the maximum speed, as Table 11 illustrates. The value of 80% is used in the study, but can be modified by the user as an operating parameter.

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[137] (Taylor, 2007)

Table 11 – Relationship between maximum speed and average speed between stations

Country	Maximum speed	Distance	Average speed	Average speed / max speed
France	320	167.6	279.3	87%
	320	129.7	259.4	81%
	320	657	255.6	80%
	320	206.9	253.3	79%
	320	730.7	250.5	78%
	320	749.4	249.8	78%
Japan	300	144.9	255.7	85%
	300	192	250.4	83%
	300	128.3	248.3	83%
	300	171.1	238.7	80%
	300	294.1	238.5	80%
	300	137	234.9	78%
Taiwan	300	179.5	244.7	82%
	300	93.6	244.1	81%
	300	152.6	212.9	71%
	300	85.9	214.6	72%
	300	62.3	207.6	69%
Germany	300	144	233.5	78%
Spain	300	307.2	227.6	76%
	300	219.3	226.9	76%
Average				**79%**

5.1.2.4. Infrastructure parameters

In order to calculate both infrastructure cost and land cost, the user must specify not only the overall length of the infrastructure, but also break down this length for each structure type – earthworks, viaducts, tunnels and bridges – into three population density categories: rural, urban and city centre. For each category is assigned a land cost that the user can modify as well, thus the three categories can be defined differently depending on the country to have the best cost estimation.

The number of stations and average number of platforms by stations must be given for each density category as well.

Based on these parameters, the model can estimate the lifecycle cost of high speed rail. The following paragraphs detail how the model was designed.

5.2. Cost components and hypothesis

In order to calculate the lifecycle cost of high speed rail, each cost component has to be analysed and estimated. There are two main cost categories: operator costs, which are the costs that the operator has to bear to provide the service; and external costs, which represent the external impacts of high speed rail operation. The currency used in the model is the American dollar; costs are expressed in 2010 in that currency, also written $\$_{10}$. Values in different currencies are expressed without inflation except when it is mentioned.

5.2.1. Local costs

In order to consider the local context, local costs have to be inputted. Those costs are the wages, the electricity price and emissions from energy mix, and land cost.

The wages and electricity prices and energy mix can be found in the database from United Nations, OECD and IEA.

For the land cost, data is not easily available. For California, the rural land cost was provided by the 2007 Census of Agriculture[138], then the data for urban area and city centre was estimated from the study from Davis and Palumbo about the price of residential land in large U.S. cities.[139]

5.2.2. Rolling stock design

The impact of train design on train capacity is significant and depends on the factors described above. This section aims to highlight the relationships between design and capacity and to show the assumptions and hypothesis that are made to incorporate those relationships into the model. The following paragraphs describe the hypothesis regarding rolling stock design. A summary of the different rolling stock designs of the model can be found in Appendix 0.

5.2.2.1. Body type

First, the choice of body type (wide or narrow, single or double deck) is considered. By analysing existing Shinkansen and TGV, those impacts can be evaluated as shown in the table below. Compared with a narrow body, single deck train set, the choice of a wide body adds an additional seat per row as mentioned before. In the case of a second deck, the capacity is

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[138] (U.S. Department of Agriculture, 2007)

[139] (Davis & Palumbo, 2007)

increased by 40%. However, the choice of both wide body and double deck increases the capacity by only 70%, probably because of additional space required for stairs, toilets, and additional equipment. The estimated relative capacity will be applied to model the capacity of each design based on the narrow, single deck train only. This reduces the calculation time for the model.

Table 12 - Train section and relative capacity

Train shape	Width (m)	Section (m^2)	Relative capacity ρ
Narrow, single deck	2.9	9.6	1
Narrow, double deck	2.9	10.9	1.4
Wide, single deck	3.4	10.9	1.25
Wide, double deck	3.4	12.4	1.7

5.2.2.2. Motorization and structure

Regarding the choice of motorization and articulated or non-articulated structure, the capacity of the train is calculated by considering the capacity of each car. As mentioned in paragraph 3.1.5, the length of a car, and thus number of seats per car, varies with the choice of the train design. Table 13 shows the assumed values. They are divided into middle car and first/last car, to take into account the reduction of capacity due to the driver cab and nose length or the locomotive. For articulated structure, middle car length is the same as existing TGV and AGV, assuming that an articulated EMU has slightly shorter cars to compensate the increased weight of the bogies. For non-articulated structures, it is assumed that the 25m length of Shinkansen and German ICE3 is kept for both EMU and non-EMU middle cars. For the first cars, the same logic was applied. There is a particularity of the articulated locomotive design. Since the first and last passenger cars do not share a bogie with the locomotives, they are slightly longer and have more seats. In order to introduce it in the model, the additional length and seats are transferred to the locomotive, so that the overall capacity, length and number of bogies are the same and the same calculation than other designs can be used.

Train capacity also depends on the train layout, and more precisely on the division into one or several classes. The capacity of 1st class is assumed to be 60% of the second class, as it is the case on French single deck TGV and Japanese E2 Series. The variability is quite important especially for Shinkansen (from 32% on JR West N700 to 77% on JR Central N700) but the average value is around 60%.

Table 13 - Train design and structure

Train structure	Middle car length L_M (m)	First car length L_F (m)	Average capacity in 2nd class q_{2M}	Average capacity in first car in 2nd class q_{2F}
Articulated, locomotive	18.7	22	65	0
Articulated, EMU	18	19	56	39
Non-articulated, locomotive	25	27	89	0
Non-articulated, EMU	25	27	89	70

Hence the train length L_{train} and capacity q of a train set with N_{cars} cars, R restaurant cars, and a proportion of 1st Class ϕ is given by:

$$L_{train} = 2 * L_F + (N_{cars} - 2 - \mathrm{R}) * L_M \tag{14}$$

$$q = ((N_{cars} - R) * q_{2M} + 2 * q_{2F}) * (1 - 0.4 * \phi) * \rho \tag{15}$$

With ρ the relative capacity of train design as mentioned in Table 12. In the model, train length is optimised and is limited to a maximum of 410m, as it is the case on every high speed line. If passenger trains are too long, that would create some problems for the passengers to reach their seats for instance.

5.2.2.3. Alighting and boarding time

A simple model of alighting and boarding is included in the model. It considers an operational margin of 30s and a time for boarding and alighting of 3s per passenger as suggests Heinz[140]. The user can modify these values and specify the average proportion of passengers embarking and disembarking at intermediary stations. In the model, articulated trains have one door per car, like TGV, and non-articulated trains have two doors per car like Shinkansen.

In terminal stations, the default time for turnover is 30 minutes. It may seem to be a long time for Japanese, but it is slightly shorter than the turnover time of TGV. This value is not optimized because it depends mostly on the operator's needs and requirements.

Thus the time in station $t_{station}$ is given by:

$$t_{station} = 30 + 3 * proportion\ alighting * q \tag{16}$$

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[140] (Heinz, 2003)

5.2.3. Operating costs

Among the operator costs should be distinguished the rolling stock ownership costs, the running costs, and the fixed operating costs.

5.2.3.1. Rolling stock ownership

Rolling stock ownership consists in acquisition, rolling stock maintenance and refurbishment, and rolling stock disposal.

5.2.3.1.1. Amount of rolling stock needed

The annual number of trains *RS(n)* needed for operation is a function of the annual demand *D(n)*, the train capacity q, the occupancy rate τ and θ given by equation (13):

$$\frac{D(n)/(2 * 365)}{\tau q} = RS(n).\theta \tag{17}$$

This equation means that a number of trains RS is required to transport the demand *D(n)* given the operating parameters. The left member of the equation is $\sigma(n)$, the number of services required:

$$\sigma = \frac{D(n)/(2 * 365)}{\tau q} \tag{18}$$

The demand can be satisfied only if $\sigma < \sigma_{max}$ with σ_{max} the maximum number of services defined by equation (12).

Once the number of trains needed is known, a contingency factor is applied to account for the trains being maintained and it case a failure would arise. This parameter can be modified, and the value of 25% is used in this study. Then, three variables are defined:

- The number of trains to acquire $RS_a(n)$:

$$RS_A(n) = \big(RS(n+1) - RS(n)\big) * 1.25 - RS_D(n+1) \tag{19}$$

- The number of trains to dispose of when the train reaches its lifetime λ_{RS}, $RS_D(n)$:

$$RS_D(n) = RS_A(n - \lambda_{RS}) \tag{20}$$

- The number of trains to refurbish at the train half-life $RS_R(n)$:

$$RS_R(n) = RS_A\left(n - \frac{\lambda_{RS}}{2}\right) \tag{21}$$

5.2.3.1.2. Rolling stock acquisition cost

In order to compare every design, a cost ratio is applied when selecting a wide body and a second deck. Fröidh[141] considers a 5% increase of the price to account for a wide body option or for a tilting option for the Green Train. The same value is considered in the present model, and a 10% increase is applied to the double deck, which gives a 15.5% increase when both wide body and second deck options are selected. Thus the train unit acquisition cost is:

$$c_{RSacquisition} = c_{motorization} * \left(1 + \delta_{wide} * 0.05 + \delta_{double\ deck} * 0.1 + \delta_{tilting} * 0.05\right) \tag{22}$$

And the rolling stock acquisition cost is given by:

$$C_{RSacquisition}(n) = c_{RSacquisition}(motorization, options) * L_{train} * RS_A(n) \tag{23}$$

Rolling stock acquisition cost was based on TGV and Shinkansen exportation costs. Table 15 shows the cost value considered in the model. In 2010, Alstom has sold 14 of its TGV Duplex to Morocco for a total price of 400M€[142], including specific adaptations requested by the operator. This gives a cost of 37.5M$\$_{10}$ for a locomotive, narrow double-decker, 200m train set. Taiwan High Speed Rail Corporation has recently expressed the wish to buy thirty new 700T train sets for a contract estimated at 3BT$[143], or 34.4M$\$_{10}$ for EMU, wide single decker, 250m trains.

5.2.3.1.3. Rolling maintenance, refurbishment and disposal

Thus the cost of rolling stock maintenance, refurbishment and disposal is given by:

$$C_{RSmaintenance} = c_{RSmaintenance} * N_{bogies} * (1.1 - 0.1 * \delta_{articulated}) \tag{24}$$

$$C_{RSrefurb} = c_{RSrefurb} * q * RS_R(n) \tag{25}$$

$$C_{disposal}(n) = c_{disposal} * L_{train} * RS_D(n) \tag{26}$$

Rolling stock maintenance and refurbishment unit costs have been deduced from the contracts between Alstom, CAF and RENFE. In 2004, a maintenance contract for 75 trains over 14 years was established for total amount of 840M€[144] and in 2002, Alstom won a maintenance contract for 24 trains and 21 locomotives over 14 years, for 500M€.

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[141] (Fröidh, Green Train, Basis for a Scandinavian High-Speed Train Concept, 2012)

[142] (Alstom, 2010)

[143] (Reuters, 2011)

[144] (Alstom, 2004)

When actualized and divided by the total number of bogies, it gives an average train maintenance cost of 145k$\$_{10}$/bogie. In its presentation of the AGV[145], Alstom mentions that the maintenance cost of a bogie represents 30% to 40% of the total maintenance cost. Since articulated trains have fewer bogies, it is assumed in the study that the ratio is 30% for articulated trains, and 40% for non-articulated trains. Thus the cost per bogie applied to non-articulated trains is 10% lower.

The refurbishment cost arises once in a lifetime of the train. The Thalys trains have been refurbished in 2009, for a cost of 1.8M€ per unit, for 377 seats.

Finally, very limited data could be found about the disposal cost. It is assumed to be twice the refurbishment cost.

5.2.3.2. Running costs

Running costs occur when the high speed rail service is provided. It consists in manning and energy costs.

$$C_{manning}(n) = c_{wages} * 365 * \sigma(n) * N_{manning} \tag{27}$$

$$C_{Energy}(n) = c_{energy} * 365 * \sigma(n) * E_{conso}(q, S_{max}, A_{train}) \tag{28}$$

In the study, it is assumed that 5 employees are needed per service to operate the train, control the tickets and take care of the on board services. This parameter can be easily modified.

Energy costs are induced by the train running at high speed on the tracks. It depends on various factors such as:

- The running resistance, mentioned in chapter 3; running resistance is greatly influenced by the aerodynamic drag of the train.
- The acceleration and brake performances of the train, as well as the use of regenerative brakes, and the energy efficiency of the motors, which depends on the speed.
- The alignment of the line and eco-driving, that is when the train is coasting to reduce the consumption

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[145] (Alstom, 2009)

Unfortunately, a detailed energy consumption model could not be set up because very limited information could be gathered about each previous point after several discussions with RFF. First, TGV aerodynamic drag is a confidential value, and it cannot be guessed or estimated easily. However, some values are available for Shinkansen and could have been adapted if this was the only limiting factor. Precise measurements about train consumption with respect to speed, acceleration and traction performance are being measured by RFF and the data has not been published yet. Actually, relationships between alignment, speed and consumption are the subject of much interest from RFF, but it means that data is not available yet. To overcome this lack of information, a simpler model has been designed and data about average energy consumption has been gathered through various sources to output an average consumption for locomotive and for EMU.

Three assumptions were made to design the energy consumption model:

- Firstly, the motors are designed to reach their maximum efficiency at the line design speed. The energy conversion efficiency of an electric train is lower at a specific design speed, and it should match the operator's requirements. Discussions with RFF[146] show for instance that TGV reaches its maximum efficiency at 320km/h, its design speed.
- Secondly, given the continuous improvements on energy consumption as illustrated in Figure 32 and the fact that new train sets are designed for speeds around 350km/h, it is assumed that the energy consumption collected will be the same for a speed of 350km/h. This seems reasonable considering the increasing concerns to reduce energy consumption.
- Thirdly, the energy consumption is assumed to be proportional to the hydraulic diameter of the train and the square of the speed to introduce aerodynamic effects, according to equations (1) and (2). This means that the mechanical resistance is assumed to be negligible compared with the aerodynamic drag. Reference hydraulic diameter is $\sqrt{10.9}$ for both EMU and locomotive since the data has been gathered for Shinkansen and TGV Duplex, which have the same train section of 10.9m^2 as mentioned earlier. Reference speed is 350km/h according to the second hypothesis.

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[146] (Cazier, RFF Interview, 2012)

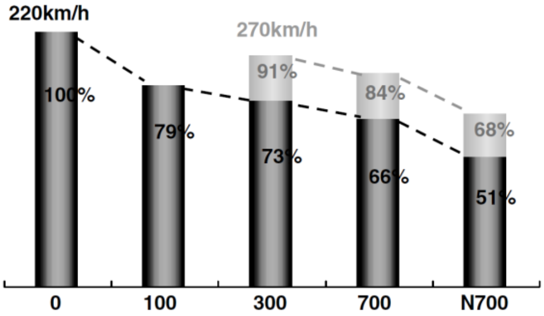

Figure 32 – Continuous improvements in Shinkansen energy consumption (Hagiwara, 2008)

Thus, the energy consumption E_{conso} is given by:

$$E_{conso}(q, S_{max}, A_{train}) = e_{conso}(\delta_{EMU}) * q * \left(1 + losses(\delta_{AC})\right) * \frac{A_{train}}{10.9} * \left(\frac{S_{max}}{350}\right)^3 \qquad (29)$$

With $e_{conso}(\delta_{EMU})$ the consumption in kWh per passenger for EMU or locomotive in the pantograph, and $losses(\delta_{AC})$ the losses between the substation and the pantograph for either AC or DC current.

The values for e_{conso} have been collected through various sources and converted in kWh/pkm. The following table shows the results for several trains.

Table 14 – Energy consumption

Line name	Train	Speed	Energy consumption	Source
Tokaido	700	270	0.028 kWh/pkm	(Takagi R. , 2005)
Tokaido	N700	270	0.023 kWh/pkm	See Figure 32 (Hagiwara, 2008)
Tohoku	E2	275	0.026 kWh/pkm	(Kobayashi, 2010)
Tohoku	E5	**320**	**0.026 kWh/pkm**	[East Japan Railway Company, 2010]: the energy consumption of the E5 at 320km/h is the same than the E2 at 275km/h
LGV Rhin-Rhône	TGV	**320**	**0.050 kWh/pkm**	RFF

The values highlighted in bold are the ones that have been chosen in the model. Regarding the losses between the substation and the pantograph, a report from the UIC about energy consumption and emissions[147] give a percentage of the total consumption, and this value has been readjusted after discussing with RFF. For AC and DC current, the chosen values are respectively 5% and 20%.

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[147] (Garcia, High Speed, Energy Consumption and Emissions, 2010)

5.2.3.3. Fixed operating costs

Fixed operating costs are costs that are independent from the number of services or train sets. Two categories can be distinguished: commercial costs and station and management costs. Commercial costs are the costs induced by the ticket sales, and advertisement; they are proportional to the demand. Station and management costs occur when the line and stations are operated; they are proportional to the number of station and, the operating time.

$$C_{OPcommercial} = c_{commercial} * D \tag{30}$$

$$C_{OPstation}(n) = c_{station}(n) * N_{platform} * OH \tag{31}$$

In this study, commercial costs are not considered because it depends on the company strategy, and little information is available on that topic. Yet a value can be specified by the user. Station costs have been considered equal to the costs borne by SNCF Gares & Connections, a subsidiary of SNCF in charge of operating the stations[148]. The cost has been divided by the number of stations in France, and then by two, considering that in average, French stations have two platforms. This is an underestimation of the real number of platforms, but it is assumed that the cost to operate a high speed station or platform is more important to provide guidance or services to the passengers. As a result, it gives a fixed cost of 0.23M$_{10}$ per platform for 18 hours of operation.

5.2.3.1. Summary of operating unit costs

Table 15 summarizes the values chosen for the operating unit costs

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[148] (SNCF, 2012)

Table 15 – Operating unit costs

Category	Option	Value used
Acquisistion	Locomotive-hauled train	163 k$\$_{10}$/m
	EMU train	131 k$\$_{10}$/m
	Wide body	+5%
	Double-deck	+10%
	Tilting mechanism	+5%
Maintenance	-	145 k$\$_{10}$/bogie
Refurbishment	-	0.80 k$\$_{10}$/seat
Disposal	-	1.6 k$\$_{10}$/seat
Energy consumption	Locomotive	0.050 kWh/seat.km
	EMU	0.026 kWh/ seat.km
Losses	AC	5%
	DC	20%

5.2.4. Infrastructure costs

Infrastructure costs are broken down into five categories: track cost, including communication and signalization equipment and overhead lines

5.2.4.1. Tracks, signalization and overhead lines

Track width depends on the train width and is calculated to have the same gap between trains on opposite tracks as the Shinkansen, the smallest around the world although the trains are wider. For wide trains, the track centre-to-centre distance is 4.3m and the gap 0.9m for speeds below 320km/h, and respectively 4.5m and 1.1m above. For narrow trains, the distance is reduced to keep the same gap between trains. Two different tracks are considered in this version of the model: ballasted and slab tracks. Slab track is always used in tunnels, and if the user specifies that the line is in an area with heavy snowfalls. In tunnels, the tracks are assumed to have a constant price. Signalization equipment and overhead lines is included in the track cost. Cost data for ballasted tracks has been collected from interviews[149] and several LGV projects[150]. For slab track, data was collected from existing literature and interviews as well[151]. Both tracks are assumed to use 60kg/m continuously wielded rails.

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[149] (Antoni, SNCF: Asset maganement and Safety, 2012) (Cazier, RFF Interview, 2012) (Zwanenburg, 2012)

[150] (RFF, 2007) (RFF, 2011)

[151] (JRTT, 2012) [JRTT, 2012] (Ando, Sunaga, Aoki, & Haga, 2001)

Track cost is given by:

$$C_{ballasted\ track} = c_{ballasted\ track} * (9.4 + center\ to\ center(train\ width)) \tag{32}$$

$$C_{slab,normal} = c_{slab,normal} * (9.4 + center\ to\ center(train\ width)) \tag{33}$$

$$C_{slab,snowy} = c_{slab,snowy} * (9.4 + center\ to\ center(train\ width)) \tag{34}$$

$$C_{slab,tunnel} = 1.95M\$_{10}/km \tag{35}$$

Table 16 – Track unit costs

Track type	Cost in M$₁₀/km
Ballasted track	0.34
Slab, normal	0.51
Slab, snowy	0.52
Slab, tunnel	1.95

5.2.4.2. Earthworks, viaducts and bridges

The cost model for viaduct and earthworks is similar and depends on the train width. There are two bridges options depending on the seismic risk, and their cost is fixed.

$$\begin{aligned} &C_{earthworks} \\ &= c_{earthworks} * (49.9 + center\ to\ center(train\ width) - train\ width) * L_{earthworks} \end{aligned} \tag{36}$$

$$C_{viaduct} = c_{viaduct} * \left(11.84 - 2 * (3.4 - train\ width)\right) * L_{earthworks} \tag{37}$$

$$C_{bridge,normal} = c_{bridge,normal} * L_{earthworks} * (1 - \delta_{seismic}) \tag{38}$$

$$C_{bridge,anti-seismic} = c_{bridge,anti-seismic} * L_{bridge} * \delta_{seismic} \tag{39}$$

Earthworks model has been established according to French LGV design, described in paragraph 3.2.2.1. Embankments have an average height of 7.3m, and cuts have an average depth of 8.8m, with a proportion of 55% and 45% each. It represents an average width of 58m for wide trains above 350km/h, and an area of 5.8ha/km. Then cost data have been collected from interviews[149] and several LGV projects[150].

The viaduct design considered is the Japanese viaduct, adapted to the train width. Regarding land cost, the area needed for viaduct and bridges is limited by the viaduct width, although in reality this area depends on the standards in one country and the location of the viaduct. Cost data was collected through interviews[152].

Table 17 – Structure unit costs

Track type	Cost in M$_{10}$/km
Earthworks	0.29
Viaduct	2.6
Bridge, normal	53
Bridge, anti-seismic	73

5.2.4.3. Tunnels

As mentioned in paragraph 3.2.2.3, aerodynamics phenomena occur in tunnels and may cause discomfort or problems for the passengers. Once a train design is selected, the tunnel section is adapted to limit the pressure increase given the train section, and then the cost is estimated.

5.2.4.3.1. Tunnel section

To find the optimal tunnel section, both phenomena of micro-pressure wave and train passing each other should be considered.

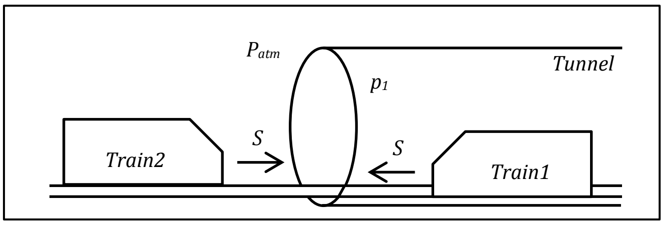

Figure 33 – Trains passing each other in tunnel

As shown in Figure 33, when a train Train1 is in the tunnel, it generates a micro-pressure wave with a pressure increase $\Delta p_{train1} = p_1 - p_{atm}$. The wave propagates in the tunnel, and when a second train Train2 enters the tunnel, the second micro-pressure wave may add up with the first one, increasing pressure from $\Delta p_{train2} = p_2 - p_1$. In the worst case, the trains are passing each other at maximum speed in the same time, with a third pressure increase proportional to the square of the speed[153] and train section. The total pressure increase Δp_{total} can be written as:

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[152] (RTRI, 2011) (Zwanenburg, 2012) (Cazier, RFF Interview, 2012)

[153] (Raghunathan, Kim, & Setoguchi, 2002)

$$\Delta p_{total} = \Delta p_{train1} + \Delta p_{train2} + \alpha . A_{train} . S_{max}^2 \tag{40}$$

Δp_{train1} and Δp_{train2} are given by equation (10):

$$\Delta p_{train1} = \frac{1}{2} \gamma p_{atm} M_t^2 \frac{1-\varphi^2}{\varphi^2 + (1-\varphi^2) M_t - M_t^2} \tag{41}$$

$$\Delta p_{train2} = \frac{1}{2} \gamma p_1 M_t^2 \frac{1-\varphi^2}{\varphi^2 + (1-\varphi^2) M_t - M_t^2} \tag{42}$$

With $\varphi = 1 - \frac{A_{train}}{A_{tunnel}}$ and A the section of train or tunnel

By replacing p_1 with $p_{atm} + \Delta p_{train1}$ in equation (42), it becomes:

$$\Delta p_{train2} = \frac{1}{2} \gamma p_{atm} M_t^2 \frac{1-\varphi^2}{\varphi^2 + (1-\varphi^2) M_t - M_t^2} + \frac{1}{2} \gamma \Delta p_{train1} M_t^2 \frac{1-\varphi^2}{\varphi^2 + (1-\varphi^2) M_t - M_t^2} \tag{43}$$

The first term is Δp_{train1}, thus equation (40) can be written as:

$$\Delta p_{total} = \alpha . A_{train} . S_{max}^2 + \Delta p_{train1} . \left(2 + \frac{1}{2} \gamma M_t^2 \frac{1-\varphi^2}{\varphi^2 + (1-\varphi^2) M_t - M_t^2} \right) \tag{44}$$

The value of α has been determined by using the French tunnel sections, which are respectively 104m^2 at 320km/h and 135m^2 at 350km/h according to RFF simulations[154]. First, calculation of $\Delta p_{train1}$and Δp_{train2} is made using equations (41) and (43). Then according to (40), α is deduced from the difference between the two results:

$$\begin{gathered} \Delta p_{train1}(320) + \Delta p_{train2}(320) - \Delta p_{train1}(350) - \Delta p_{train2}(350) \\ = \alpha . A_{train} . (350^2 - 320^2) \end{gathered} \tag{45}$$

Thus it is found that $\alpha = 1.05 * 10^{-6}$. With this value, the pressure generated by Shinkansen is given below.

Table 18 – Values of pressure increase for TGV and Shinkansen

	Speed	Train section	Tunnel section	Pressure
TGV	320km/h	10.9m^2	104m^2	3.635kPa
Shinkansen	300km/h	10.9m^2	63.4m^2	4.870kPa

---

[154] (Réseau Ferré de France, 2006)

The pressure increase calculated for the Shinkansen is much more important than TGV, but in practice the better aerodynamics of Shinkansen may give a lower pressure increase.

Those two values are used in the model to estimate the optimal tunnel section. The user can choose whether to use Japanese or French standards.

Finally, the optimal tunnel section is determined by using equations (41) and (44). When Δp_{total} is given, equation (44) can be rewritten as a quadratic equation for φ^2 with one positive solution. Then the tunnel section A_{tunnel} is given by $A_{tunnel} = \frac{A_{train}}{1-\sqrt{\varphi^2}}$.

As an example, the results for the three different train sections considered in the model and for both Japanese and French standards are given in Table 19.

5.2.4.3.2. Tunnel cost

Once the optimal section is determined, the cost is calculated.

For that purpose, an analysis of tunnel construction cost in England has been carried on using the database available on the website of the British Tunnelling Society[155]. Unfortunately, very few data of construction cost, tunnel length and tunnel section was available for other countries.

The construction cost, tunnel length and section of 20 different tunnel projects has been collected, other tunnels had incomplete data. The analysis shows that there is a linear correlation between the construction cost and the square root of the tunnel section as Figure 34 shows. Thus the tunnel cost per kilometre is given by:

$$C_{tunnel} = 4.2699 * \sqrt{A_{tunnel}} - 2.7509 \tag{46}$$

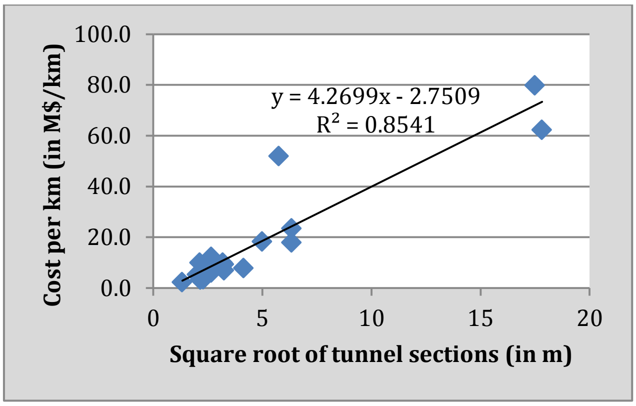

Figure 34 - Correlation between tunnel cost and section

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[155] (The British Tunnelling Society, 2012)

This formula has been used as it is for the calculations in the model as it gives a very close result compared with the Japanese average cost. Yet the user can specify a cost ratio to adapt the cost to a specific country, or implement different cost estimations. Table 19 shows the results of both tunnel section and cost for the three train sections considered in the model.

Table 19 – Tunnel sections and costs at 350km/h

Train section	Tunnel section at 350km/h, Japanese standards	Tunnel cost per km ($M\$_{10}$/km)	Tunnel section at 350km/h, French standards	Tunnel cost per km ($M\$_{10}$/km)
9.6	$77m^2$	34.7	$111.3m^2$	42.3
10.9	$91m^2$	38	$135m^2$	46.9
12.4	$109m^2$	41.9	$167m^2$	52.4

5.2.4.1. Stations, workshops and maintenance bases

Station construction cost is assumed proportional to the total number of platforms $N_{platform}$ and to the length of the trains, with a 10m margin at each train extremity:

$$C_{station} = c_{platform} * N_{platform} * (L_{train} + 20) \qquad (47)$$

Optionally, the user can specify to use a longer platform length.

Workshops and depots are used to maintain and park the rolling stock. Workshops can be used as depots as well. Their number depends on the amount of rolling stock. A look at the Taiwan high speed rail infrastructure shows that there are 3 depots and workshops for 30 trains, with a total cost of $310M\$_{10}$[156], and by measuring with satellites images, it is found that there are around 1.4ha per train. The cost of workshop construction is given by:

$$C_{workshop} = c_{workshop} * L_{train} \qquad (48)$$

To store maintenance equipment with an easy access to the infrastructure, maintenance bases are installed at a regular interval along the infrastructure. The UIC[157] specifies the coverage in several countries as shown in Table 20.

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[156] (Bowe & Lee, 2004)

[157] (UIC, 2010)

Table 20 – Maintenance base coverage in several countries (UIC, 2010)

Italy	Spain	Taiwan	France	Belgium
50	150	70	70	70

In the presentation of the LGV SEA project[158], RFF mentions that a maintenance base is 3 to 4ha large and should cover 80 to 100km. This coverage is slightly larger than the majority of countries shown in the table above, yet the UIC does not specify the area required. Thus the values from RFF are chosen.

$$C_{base} = c_{base} * L \tag{49}$$

Table 21 – Unit costs of fixed structures

Option	Unit cost
Station	0.053 M$_{10}$/platform.m
Workshop and depot	0.012 M$_{10}$/m of train
Maintenance base	0.10 M$_{10}$/km

5.2.5. Maintenance costs

As mentioned in chapter 3, there are many studies aiming to improve and optimise maintenance schedule and maintenance cost. However, those stochastic models either depend on local database and context, or target a very specific part with a level of detail that is not aimed in this study. In addition, many of the models based on past experience do not consider speeds above 300km/h or 320km/h, while higher speeds are targeted in this study. Therefore, it proved difficult to implement a stochastic maintenance model given the short time to develop the model. A simpler deterministic model has been adapted, yet the user can implement and integrate a better model.

With this model, both maintenance staff and track maintenance tasks are considered.

5.2.5.1. Maintenance staff

In order to inspect the tracks and structure, and to perform the necessary interventions, a dedicated workforce is necessary. The UIC[159] examines the dedicated maintenance workforce

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[158] (RFF, 2007)

[159] (UIC, 2010)

for several high speed lines around the world, and the following table shows the number of employees per kilometre are required for ballasted tracks or slab tracks. The first is based on European lines, the second on the Taiwanese High Speed Rail.

Table 22 – Workforce required for inspection and maintenance operations

Track type	Employees required for inspection and maintenance
Ballasted track	0.47 employee/km
Slab track	1.01 employee/km

5.2.5.2. Track maintenance tasks

Maintenance tasks have been modelled with a simple deterministic model: an element is changed when the lifetime is reached. The lifetime is a fixed number of years for the elements except rails and ballast, as shown in Table 23 with the unit costs. In addition, a track renewal implies both ballast and rail renewal, and a rail renewal is usually coupled with a ballast renewal to reset both lifetimes and avoid faster degradation.[160] For slab tracks, the lifetime is longer than the lifecycle period, but 1% of tracks and subbase are replaced every year.

Table 23 - Lifetime of track components

Part	Lifetime	Replacement cost
CWR Rails	700Mt	460 k$_{10}$/km
Ballast	Deterministic model	460 k$_{10}$/km
Concrete sleepers	40 years	1.4 M$_{10}$/km (track regeneration)
Concrete slabs	60 years	20 k$_{10}$/km (replacement of 1% of slabs and subbase)
Overhead power supply	30 years	970 k$_{10}$/km

For rails, the cumulated annual traffic tonnage is calculated, and when it reaches 700Mt, the rail is replaced. Rail lifetime λ_{rail} is given by:

$$\lambda_{rail} = \frac{700*10^6}{365*\sigma*train\_weight} \quad (50)$$

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[160] (Antoni, SNCF: Asset maganement and Safety, 2012)

For the ballast degradation, Öberg[161] reviews several models and Sugiyama's model seemed appropriate since it gives the growth of vertical irregularities μ for CWR with respect to speed and annual tonnage in particular:

$$\mu = k * \sqrt[3]{T} * S_{average} * M \tag{51}$$

Where T is the cumulative tonnage k is a constant of proportionality and M a structure factor depending on the quality and composition of the track.

This model is applied to estimate the ballast lifetime using the lifetime of existing tracks. For the LGV Rhin-Rhône, the ballast is expected to last 35 years. In addition, the wheelbase induces a resonance phenomenon that increases the ballast scattering. This frequency is:

$$f = \frac{S}{wheelbase} \tag{52}$$

Thus at the same speed, the frequency is inversely proportional to the wheelbase.

With equation and, and the operating conditions of the LGV and an average speed of 80% of the maximum speed, the ballast lifetime $\lambda_{ballast}$ is expressed as:

$$\lambda_{ballast} = 35 * \left(\frac{37.4*10^3}{trainweight*\sigma}\right)^{\frac{1}{3}} * \left(\frac{300}{S_{max}} * \frac{wheelbase}{3}\right) \tag{53}$$

Finally, Antoni[162] mentions that in average there are 20 ballast tamping interventions before the ballast is changed, and that grinding the rails once a year provides substantial cost savings. Both conditions are satisfied with the model.

5.2.6. External costs

The last cost element is the external costs. In this version of the model, only CO_2 emissions are considered but other elements can be added.

The general model for the emissions is linear. With p_{tCO2} the price of a ton equivalent of CO2, f_{CO2} the emission factor and the quantity of materials, area or length of each element *i*, the total emission cost can be written as:

$$C_{emissions} = p_{tCO2} * \sum_{i=elements} f_{CO2}(i) * quantity(i) \tag{54}$$

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[161] (Öberg, 2006)

[162] (Antoni, Modelling of the Ballast Maintenance Expenses, 2011)

The emissions can be divided into two categories: the construction emissions and the operation emissions.

The CO2 emissions from the construction have been estimated with the Carbon assessment of the LGV Rhin-Rhône published by Ademe, RFF and SNCF[163] except for the slab tracks, civil structures and stations. Slab track and civil structures emissions have been estimated from the Japanese documents detailing the last phase of the Tohoku Shinkansen[164], for the stations the emissions have been estimate from the LCA of California high speed rail from Chester[165].

The emissions from the operation are induced by the energy consumption and depend on the local energy mix. Data is available

5.3. Life Cycle Cost model and optimisation model flowcharts

Based on the available data and different cost models, the life cycle cost model was finalized to integrate the cost models described in paragraph 5.2 and minimise the total cost given the boundaries and input parameters described in paragraph 5.1. After the LCC model was established, it was modified to incorporate rolling stock design and track type optimisation. Thus two models have been created: a LCC model to assess the cost of specific options, and the optimisation model to propose the most suitable options given the local context. Figure 35 shows the flowcharts of both models.

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[163] (ADEME, RFF & SNCF, 2009)

[164] [JRTT, 2012]

[165] (Chester M. V., 2008)

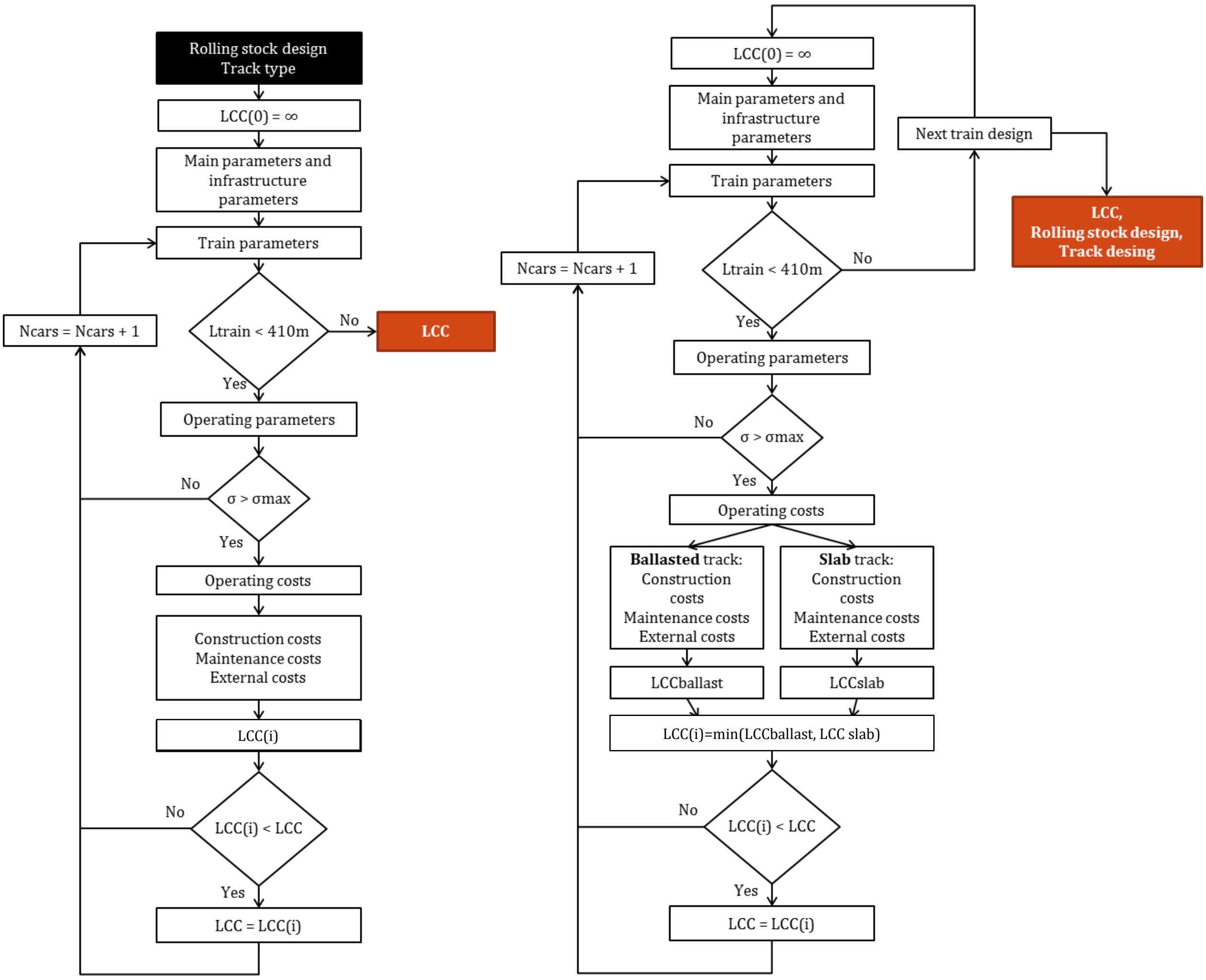


Figure 35 – Life cycle cost model and optimisation model flowcharts

6. APPLICATIONS AND DISCUSSIONS

To present the potential of a high speed rail life cycle model, it has been applied to two different examples. First, it is used as a decision support to assess the choice of best and second-best train design under various constraints. Then, it is adapted to present the impacts of the vertical separation of railway activities on the lifecycle cost.

Both cases show significant outputs, and prove that the model highlights several underlying mechanisms of high speed rail. Through these two applications, the cost drivers are identified, as well as the robustness of the model.

6.1. Decision support for best and second-best train designs

Several simulations have been run with the newly developed model to highlight the influence of several parameters in the choice of the best train designs. This aims to answer the following questions:

- Are there one or several train designs that are adapted to every situation, or does each situation requires an adapted design? If so, what are the main choice drivers?
- Are current train designs among the best options, especially the single-decker, non-articulated EMU train?
- How are the results affected when a different weight is given to the cost components, especially in the case of a vertical separation of railway activities?

First, the methodology used for the simulations is described, then the outcomes are analysed. Finally, an application to the vertical separation of railway activities is presented.

6.1.1. Methodology

In order to answer the questions mentioned above, around ten thousands scenarios have been simulated to try several demand, speed and length values, but also various parameters. The parameters of the reference case are described in the following paragraphs, as well as the presentation of the sensitivity analysis and the changes inputted in the parameters.

6.1.1.1. Main parameters

The table below shows the main parameters used for the reference case. In total, 7 different demand values and 5 speed values have been considered.

Table 24 – Main parameters (Reference case)

Parameter	Value
Demand	5 to 150MPax
Design speed	300 to 380km/h
Average speed	80% of design speed
Interest rate	4%
Years to reach the demand	5 years
Annual demand growth	0%
Inflation of local costs	0%

6.1.1.2. Operating parameters

The table below presents the different operating parameters inputted for the reference case.

Table 25 – Operating parameters (Reference case)

Parameter	Value
Hours of operation	18 hours (6am to midnight)
Percentage of 1st class seats	15%
Restaurant car	None
Occupancy rate	75%
Turn-over time	40min
Headway time	3min
Number of intermediary stops	1 stop every three stations
Boarding and alighting	50% of the passengers alights/boards a train
Minimum time in station	30s margin + 3s per passenger

6.1.1.3. Infrastructure parameters

The table below shows the infrastructure parameters used for the reference case. Three different infrastructure length have been considered.

Table 26 – Infrastructure parameters (Reference case)

Parameter	Value
Length	100, 300 and 500km
Percentage of tunnels and viaducts	5% of each
Stations	One every 50km and two terminal stations. Terminal stations in city centre, intermediary stations equally distributed in urban and rural areas
Platforms	10 for terminal stations, 4 in urban area and 2 in rural areas

6.1.1.4. Sensitivity cases

Four sensitivity analyses were performed to highlight the influence of other parameters and situations on the choice of train design.

- **Sensitivity case 1: Influence of tunnels and viaducts.**

As its name suggests, this case introduces a higher proportion of civil structures along the line. Tunnels and viaduct proportions have been set at 25% and 70% each, giving three different cases. The expected result is a preference for smaller trains when the amount of civil structure increases.

- **Sensitivity case 2: Influence of different operating parameters.**

Several simulations have been made with a higher proportion of 1st Class of 30%, a lower occupancy rate of 50%, reduced operating hours from 18 hours to 14 hours, and a demand growth of 2%. Those cases mainly introduce a stronger constraint on the train capacity or on the demand, and it is expected to show that trains with more capacity are preferred.

- **Sensitivity case 3: Case of a developing country.**

The last sensitivity case introduces some of the particularities of a developed country to analyse the impact on the choice of design. Those particularities are lower local costs and wages with a high inflation. Given that many costs do not depend directly on the local market, this case may show only few differences with the reference case.

6.1.2. Results and analyse

This part describes and analyse the results from the simulations, first the reference case and then the sensitivity cases.

6.1.2.1. Reference case

6.1.2.1.1. Slab track

- **Variation of minimum lifecycle cost**

The figure below shows the variation of the minimum lifecycle cost per kilometre for various line length, demand and speed.

Despite the speed increase, the lifecycle cost is quite stable especially for shorter lines. Interstingly, it appears that for a given demand, the cost does not necessarily increase with the speed. For both 100km and 300km lines, the cost variation shows two minimums at 320km/h and 360km/h, while there is one minimum at 320km/h on the longer line. When the speed increases, trains may be able to make one more trip and thus it reduces the total amount of trains needed. Thus a speed slightly higher or lower than the design speed could reduce the costs. For instance, a 20km/h difference in the design speed induces less than 10% change in the travel time on board, and even less change in the overall travel time waiting time and travel time to and from the stations are added.

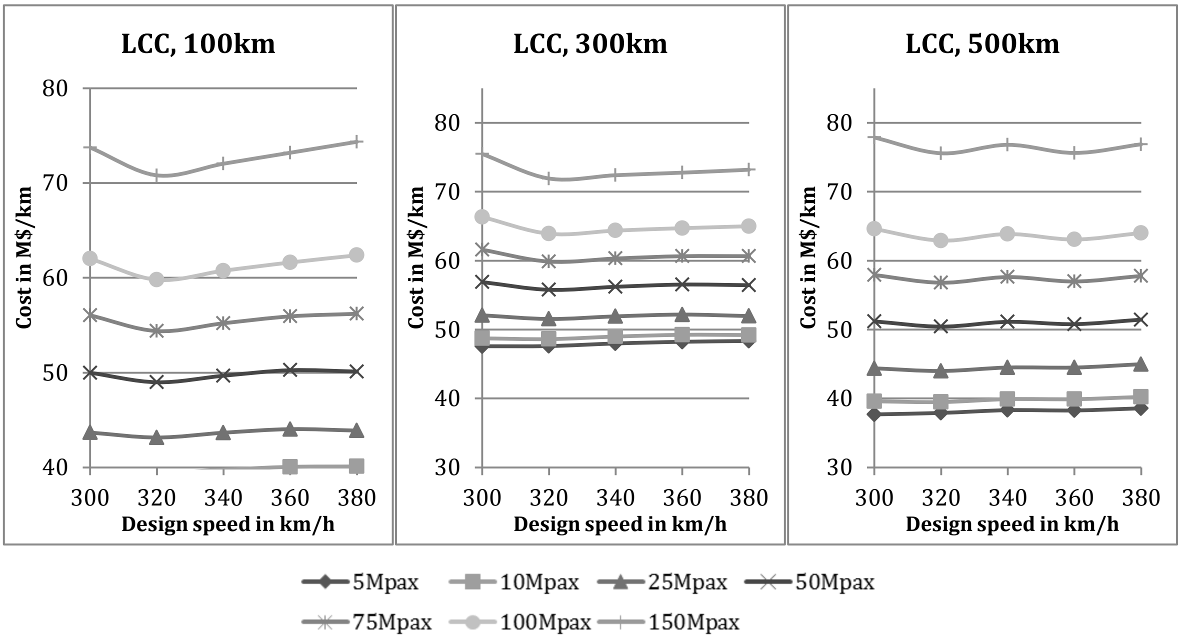


Figure 36 – LCC variation with demand, speed and length of the line

- **Choice of best and second-best design**

The results of the reference case with slab tracks show clear differences between high and low demand.

When the demand is above 50Mpax per year, there is a clear preference for the train design that offers the higher capacity to accommodate the demand: wide, double-decker articulated EMU. This reveals the importance of the demand constraint even when the line becomes longer. However, there is an exception for the 500km line at 380km/h. With those conditions, the narrow version is preferred. This is explained by the fact that with this particular design, the trains can make one more trip compared with the wide design. Thus narrow trains become more efficient. This highlights the effect of the time in station: the gain of time brought by the narrow train counterbalances the slightly lower capacity, while the more important weight of the construction cost for longer lines make smaller trains more interesting.

For lower demand, the impact of the length of the line is very visible. When the line is short, the non-articulated section is preferred to reduce the time in station. The size of the train decreases with the demand, since it reduces the operating and construction costs. For all lines, the effect of the speed is visible and can lead to change the preferred design twice or more. First, an increase reduces the constraint on the time in station and a larger train can be chosen. Second, the speed increase may allow smaller trains to make one more trip and to be more competitive than larger trains. When the speed increases again, larger trains can make one more trip as well, and the situation is similar to the first speed increase. For the longer line in particular, the change of train corresponds indeed to the minimum cost seen in Figure 36. The choice between the articulated or non-articulated structure, and between single or double deck then depends on the further advantages brought either to the time in station, or to the construction costs.

Finally, double-decker trains are preferred to wide single-decker trains and this is quite understandable. The capacity increase of the second deck is more important than the wider body, with a limited cost difference and less impact on the construction cost.

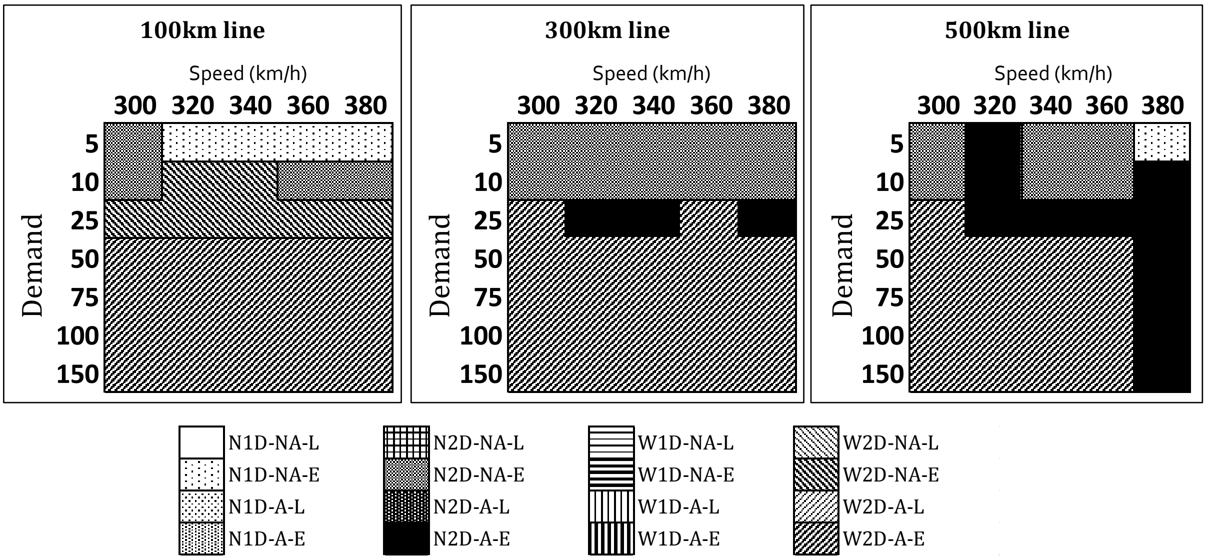


Figure 37 – Best designs for the reference case with slab tracks

Regarding the choice of the second-best design, there is a larger variability. Larger trains are still preferred for high demand, yet depending on the length of the line the choice is either the articulated locomotive design or the non-articulated EMU. There is a clear trend to prefer an articulated design when the line is longer. Their lower impact on the track degradation make them more competitive on longer lines, but on smaller lines the lower energy consumption of EMU results in a lower lifecycle cost. Again, smaller trains are selected when the speed increase allows it, especially when the line is long because of the construction cost. The first and second choices are very similar for lower demand: there is a clear preference for non-articulated trains, with the narrow, double-decker, non-articulated EMU also selected.

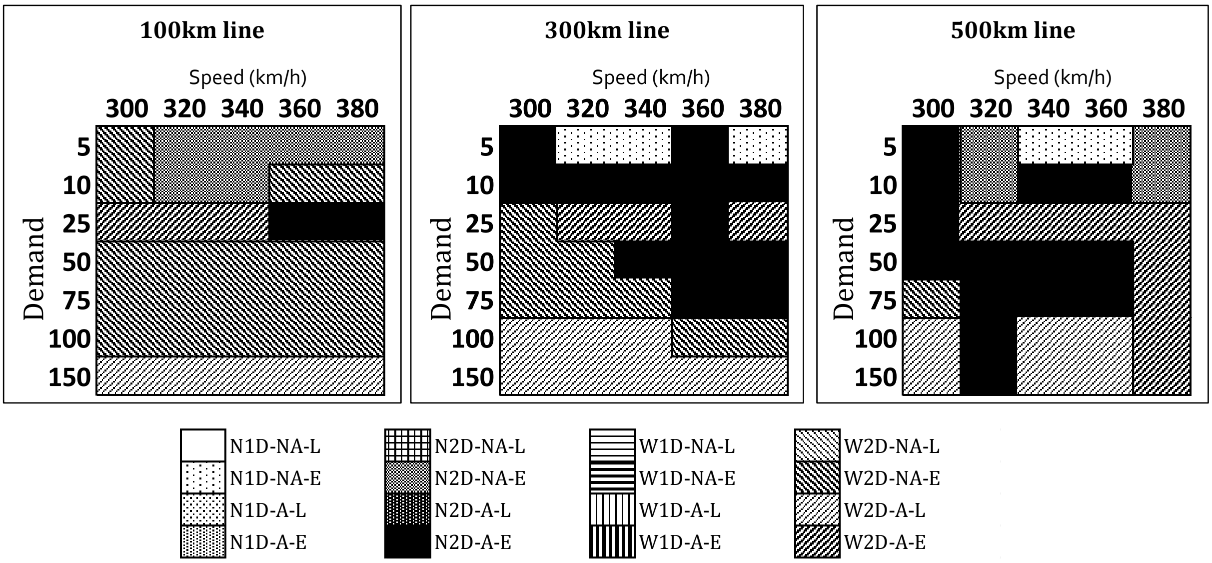


Figure 38 –Second best designs for the reference case with slab tracks

- **Cost difference between first and second-best design**

The figure below shows that the life cycle cost difference between best and second-best design are small to moderate, with a clear increase for higher demands. The length of the line has no significant impact. It shows that if the best design does not exist, or if more manufacturers propose the second-best design, the second-best design can be chosen with a very limited impact on the life cycle cost.

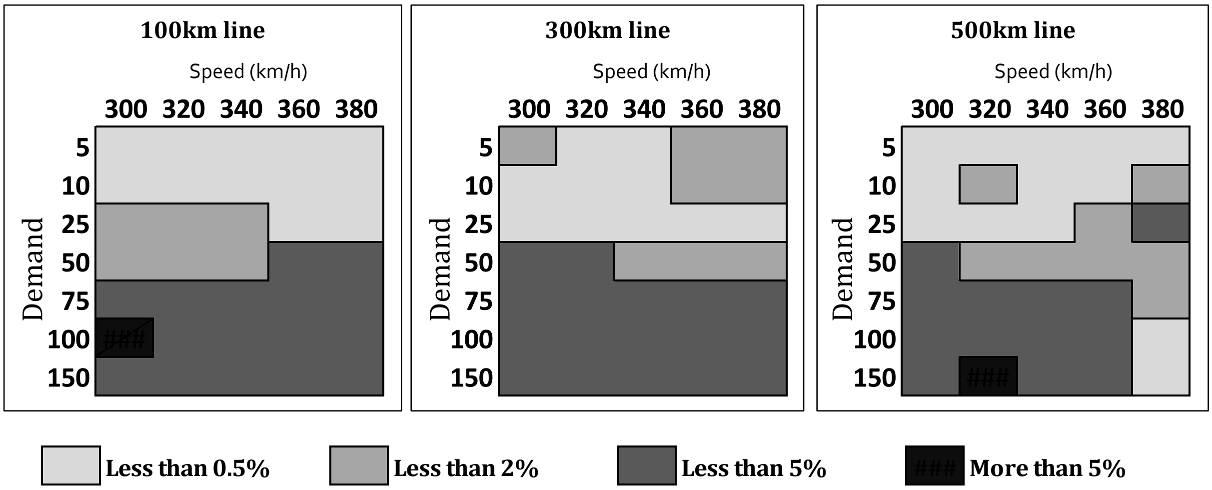


Figure 39 –Relative LCC difference between best and second-best designs, reference case

6.1.2.1.2. Ballasted track

The influence of the track type is very limited; the reference case with ballasted tracks shows very similar results than with slab tracks. Only in a few occasions the results show an inversion of best and second-best designs. A more refined ballasted track degradation model may impact the choice more significantly for longer lines at lower demands. Further simulations only consider slab track in order to reduce the calculation time.

It also means that with a ridership forecast of around 25Mpax, California would benefit from the choice of double-decker non-articulated EMU. Unfortunately this design is not proposed by the manufacturers.

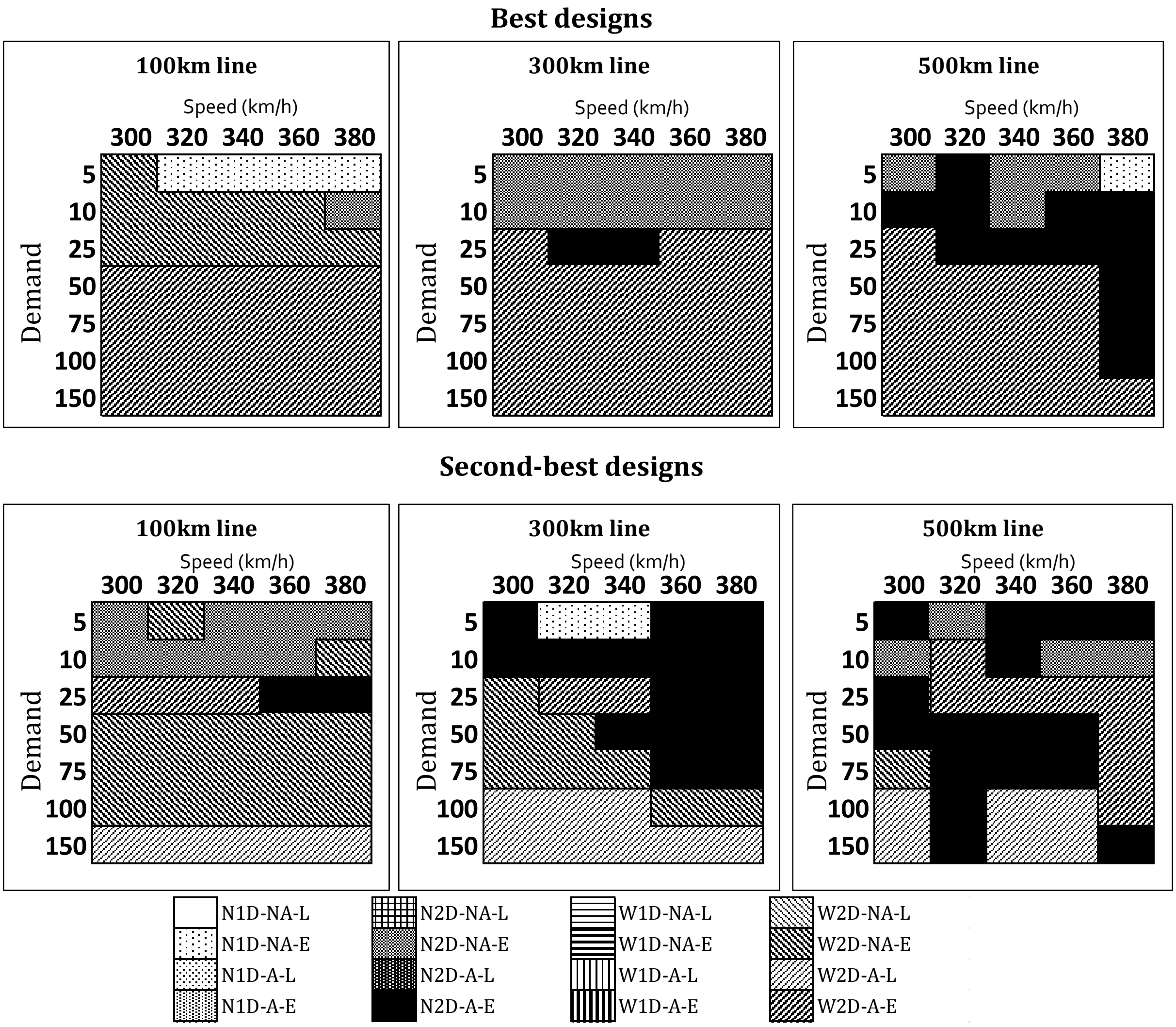


Figure 40 – Best and second best designs for the reference case with ballasted tracks

6.1.2.2. Sensitivity analysis

6.1.2.2.1. Influence of tunnels and viaducts

The influence of the proportion of tunnels and viaducts is very significant, as the following figure shows for 500km lines and proportions of tunnels of viaducts of 25% or 70%. The results for shorter line lengths are visible in Appendix A5.

- **Cost variation**

The cost variation induced by an increased proportion of civil structures is significant, especially with tunnels as Figure 41 shows. Yet the cost increase is lower at 380km/h, and when the proportion of civil structures is important, a speed increase from 360km/h to 380km/h results in a lower increase of the cost or even a cost decrease. When raising the speed, fewer trains can be used, resulting in a decrease of the operating costs that can compensate the increase in construction cost. This effect is less visible when the demand increase since the speed increase is not high enough to reduce the number of trains and the reduction of operating costs is not significant.

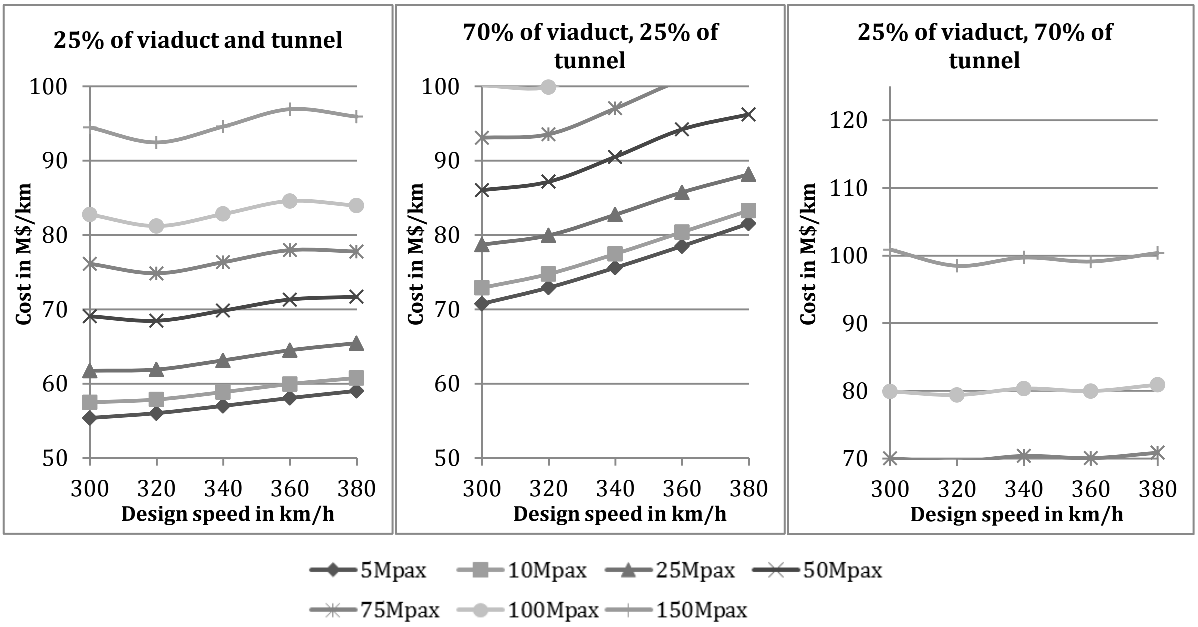


Figure 41 – LCC variation with an increasing proportion of civil structures

- **Train design**

As one can expect, trains become smaller when the proportion of viaduct and tunnel increases as Figure 43 shows.. In comparison with the reference case, wide trains are avoided except when the demand becomes very high and the seed is relatively low. There is a clear preference for the double-decker articulated EMU design, yet there is much variation for the second best option, with a common preference for EMU motorisation. This variation is explained by the trade-offs between train capacity, time in station, number of trips and number of services.

- **Relative cost difference between best and second-best design**

Like in the reference case, the relative cost difference is very low between first and second-based design, and slightly increasing with the demand.

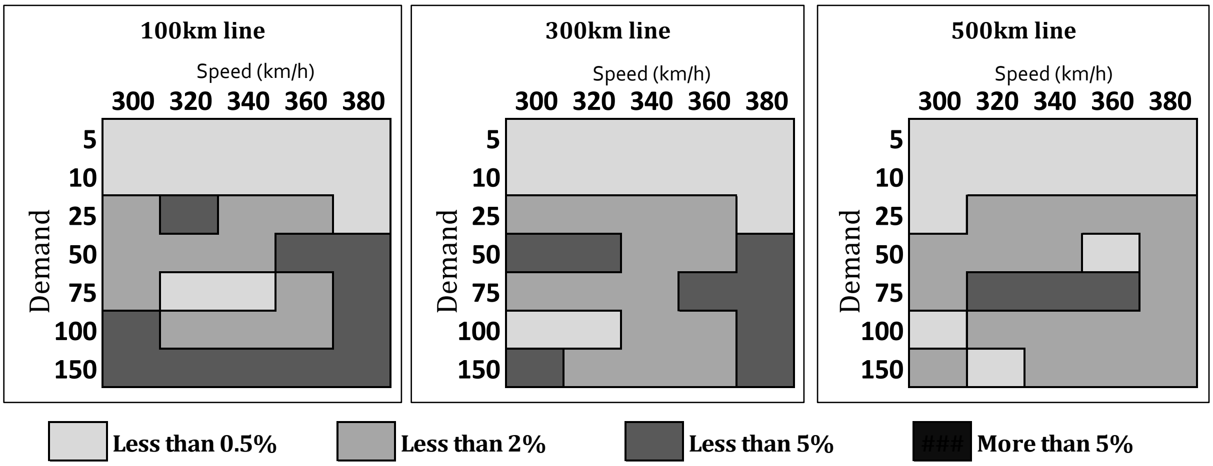


Figure 42 –Relative LCC difference between best and second-best designs, sensitivity case 1

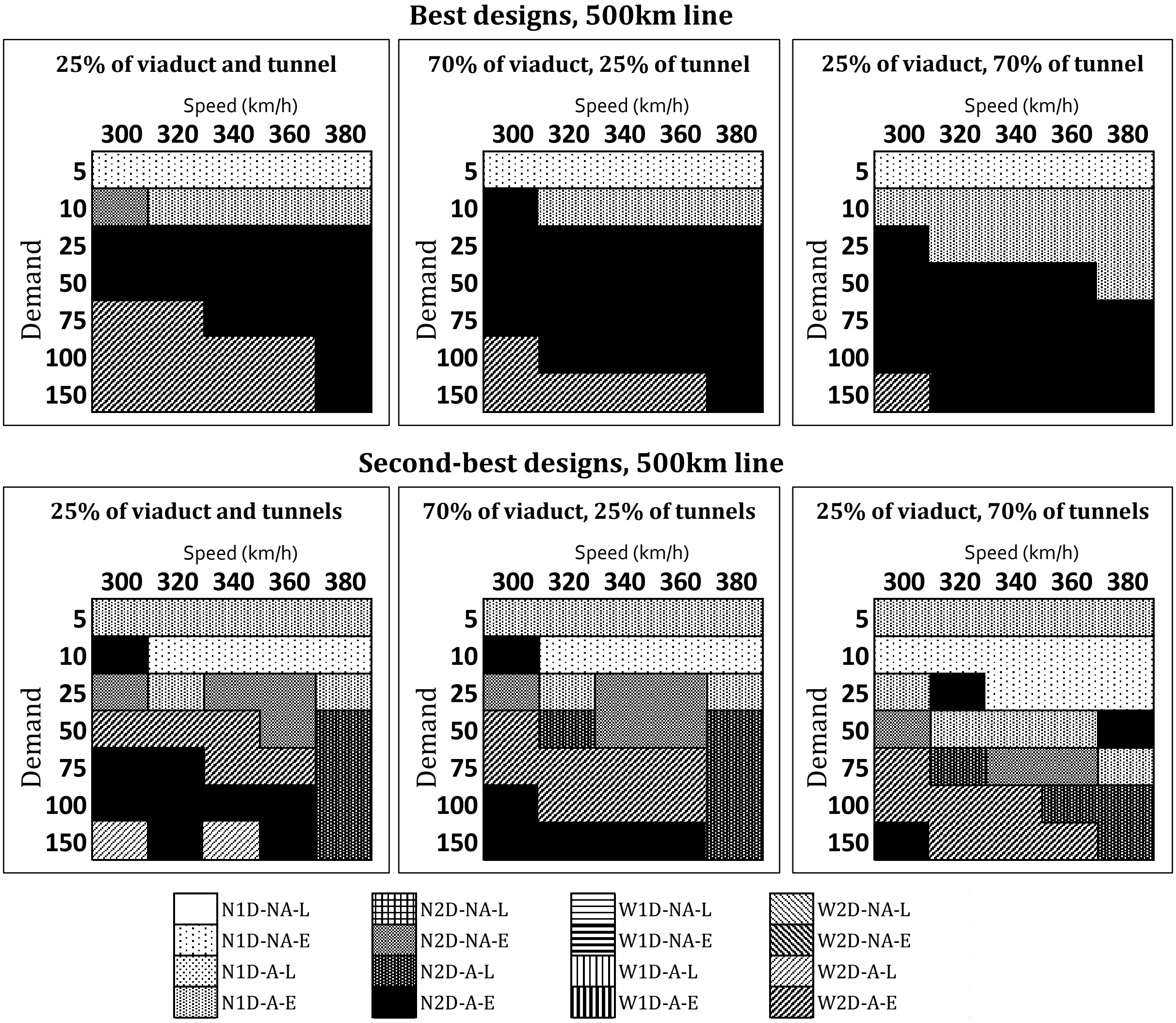


Figure 43 – Second best designs for sensitivity case 1 and 500km lines

6.1.2.2.2. Influence of operating parameters

When increasing the proportion of first class or decreasing the occupancy rate, it increases the constraints on the train capacity. Here, the proportion of first class is doubled and the result is displayed for a 300km line. It shows that it is not exactly similar to a simple demand increase. The double-decker non-articulated EMU and locomotive are chosen although the non-articulated locomotive design was not selected in the reference case.

The impacts of the length of hours of operations, of the occupancy rate or of the number of stops are not very significant compared with the reference case, since they mostly increase the demand constraint. A simulation with a 2% demand growth has been run as well, with an expected result of choosing larger trains for low demand. Because of their limited impact, the results are not described here but are shown in Appendix A5.

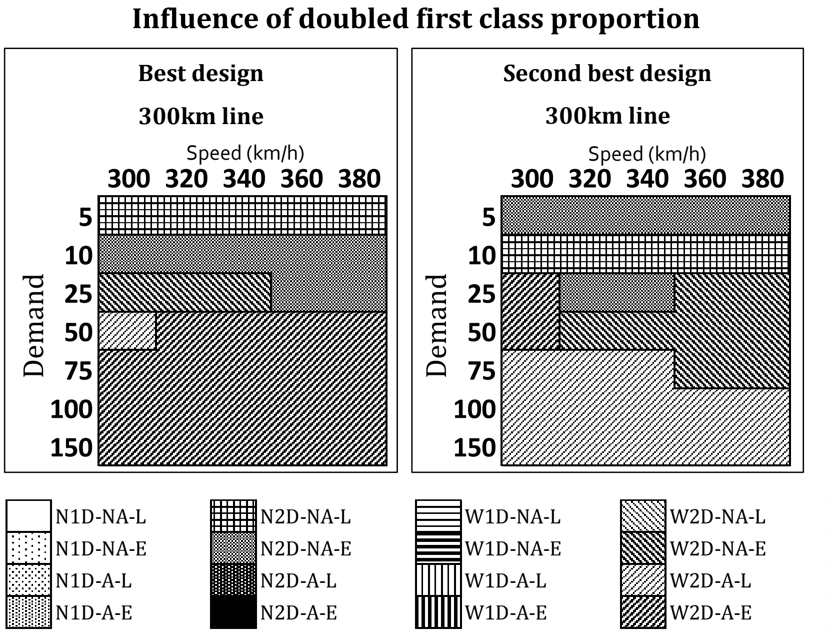


Figure 44 – Best designs (left) and second-best designs (right) for sensitivity case 2 and a 300km line

6.1.2.2.3. Case of a developing country: lower local costs with high inflation

The last sensitivity case consider an situation similar to a developing country, where local costs and wages are lower than in developed countries, with a very high inflation. In this case, wages and energy costs have been divided by 50, and land cost by 200 and the inflation rate is 6%.

The results are actually very similar to the reference case when the demand is high. Yet when the demand decreases, double-decker trains are preferred. A signle-decker articulated EMU is selected as a second best option only when the demand is very low. With such a high inflation rate, it eventually becomes more interesting to run fewer trains with more capacity to reduce the running costs. Yet, many costs do not depend on the local market costs such as the rolling stock if it is manufactured abroad, or a significant part of the construction cost. This sensitivity case shows that the specificity of a developing country is significant mostly for low demands. Yet developing countries expect a large population growth, especially in urban areas, which should induce a large demand for high speed rail.

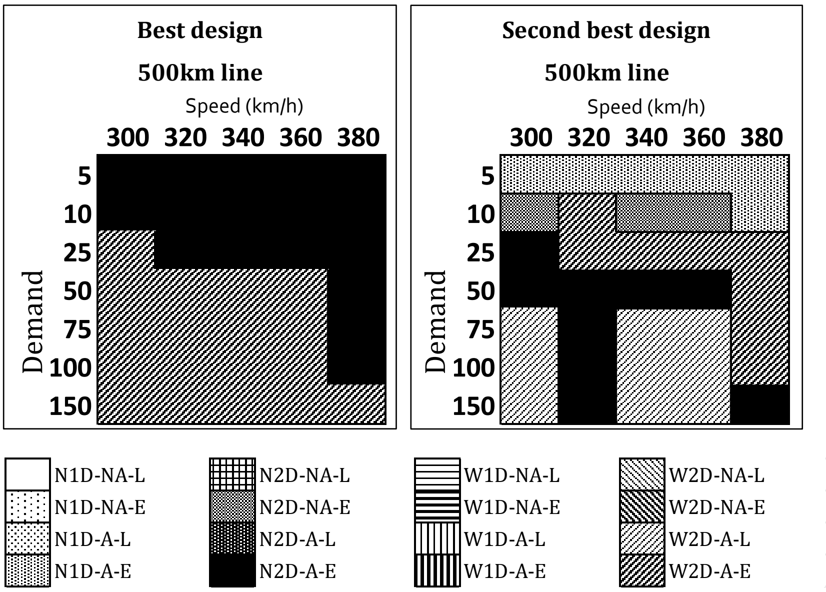


Figure 45 – Best designs (left) and second-best designs (right) for sensitivity case 3

6.1.3. Discussion

The model has been applied to a wide range of situations to show the impact of various parameters, factors and situations on the most suitable train design. The outputs are very positive and show many interesting facts.

Firstly, it shows the importance of the local conditions such as the demand, the speed and the length of the line, but also the proportion of civil structures and operating parameters. For high demands, trains with high capacity are always required, but when the demand decreases various train designs can be selected depending on the input parameters.

Secondly, the family of double-decker articulated EMU train sets seems is often preferred, and almost always for high demands. There is more variability for lower demands depending on the context. Yet the design currently proposed or developed by most of the manufacturers has not been chosen as a best or second-best option. This is not surprising given the competitive advantage of a second deck.

6.2. Impact of the vertical separation of railway activities

This application aims to compare the results if a different weight is assigned to each cost component, in particular in the case of a vertical separation. For that purpose, a weight is assigned to each cost categories before minimising the cost. Three simulations have been run to represent three viewpoints: the operator, the infrastructure manager and the government. For each case, the design is optimised with respect to the respective cost components: operating costs, construction and maintenance costs, and external costs. The results vary significantly among stakeholders, highlighting the conflicts induced by the vertical separation.

6.2.1. Optimisation according to each stakeholder's viewpoint

For each optimisation, a weight of 1 was given to the cost categories representing a stakeholder, and 0 to other cost categories. The results are displayed and analysed independently in the following paragraphs.

6.2.1.1. Operator viewpoint: operating costs minimisation

With respect to the operating costs, the results are quite obvious: the larger train is used to minimise the number of services. When the line is long, the speed increase can give a competitive advantage to narrow trains that can run one more trip. This can be observed in the figure below when the narrow second-decker articulated EMU is chosen.

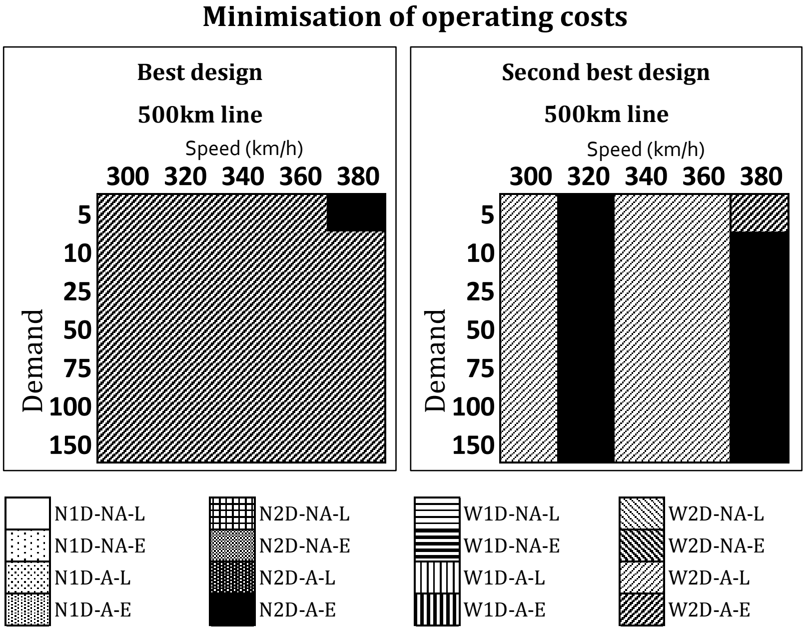


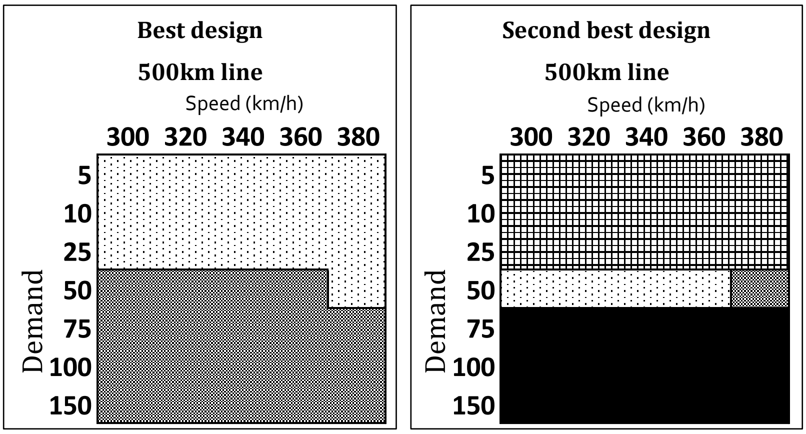
Figure 46 – Best designs (left) and second-best designs (right) from the operator viewpoint

6.2.1.2. Infrastructure manager viewpoint: construction and maintenance cost minimisation

From the infrastructure manager viewpoint, the minimisation of construction and maintenance costs gives completely different results. Two cases have been considered: a case with only 5% of tunnels and viaducts, or “French” case, and a case with 45% of each tunnels and viaducts, or “Japanese” case. Of course, smaller and lighter trains are preferred to build a smaller infrastructure, especially in the “Japanese” case.

Single decker, non-articulated trains are preferred for low demands because they have a lighter weight per axle compared with single-decker articulated trains. When the demand constraint becomes too high, a double-decker articulated train is preferred since the difference in weight per axle is lower and articulated trains have fewer bogies.

Minimisation of construction and maintenance costs, "French" case



Minimisation of construction and maintenance costs, "Japanese" case

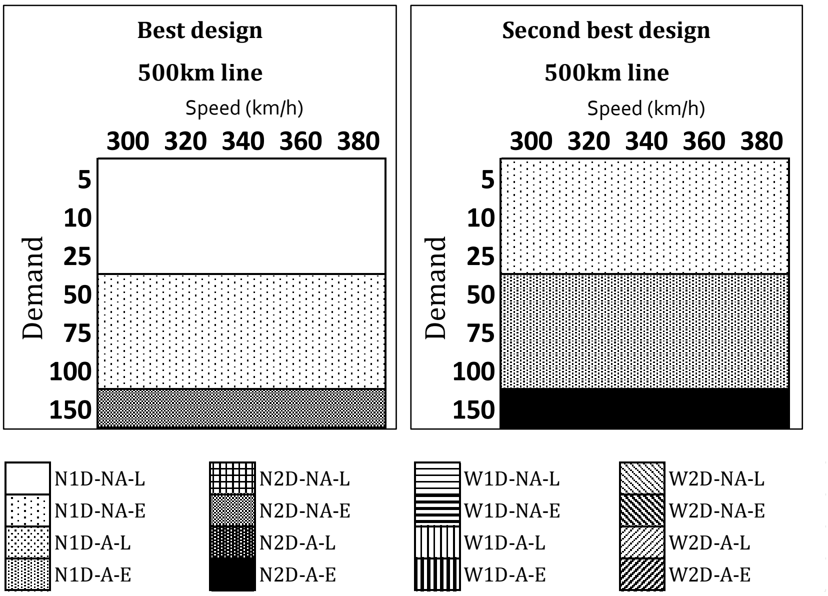


Figure 47 – Best designs (left) and second-best designs (right) from the infrastructure manager viewpoint

6.2.1.3. Government: environmental impacts minimisation

When minimising the external costs, the best option is similar to the operator point of view: running less large trains consumes less energy, and emits less CO_2. The second best choice is different because the locomotives consume much more energy than EMU. Thus a narrow double-decker articulated EMU is mostly preferred instead of a locomotive design except when the demand is larger. When the demand is low, the emissions from the construction have more impact and a smaller train is preferred to reduce this part.

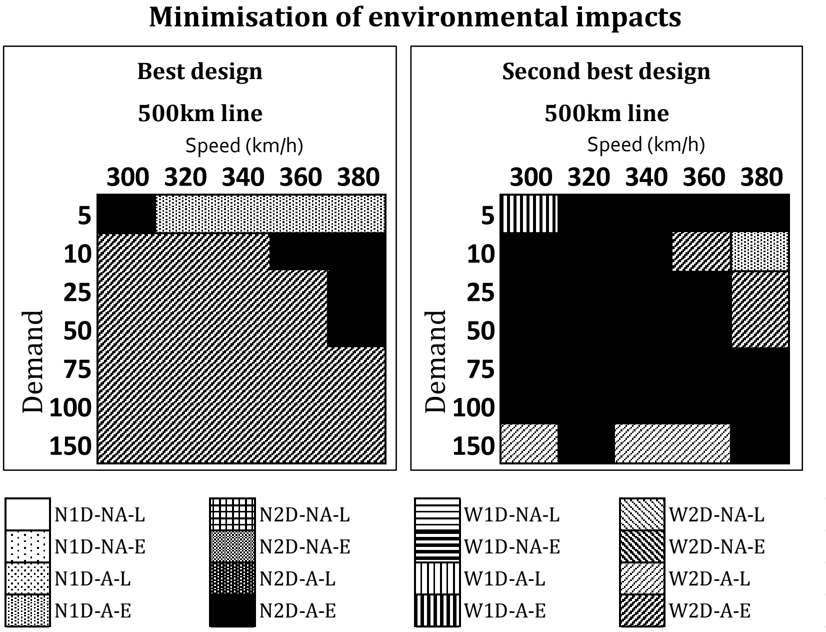


Figure 48 – Best designs (left) and second-best designs (right) from the government viewpoint

6.2.2. Comparison of the three viewpoints

Although the choice of first and second best design shows the divergence of the viewpoint of the stakeholders, it does not show if these decisions have a significant impact on the life cycle cost. Thus the lifecycle costs induced by each stakeholder's choice have been compared to the optimal lifecycle cost and the results are shown in Figure 49.

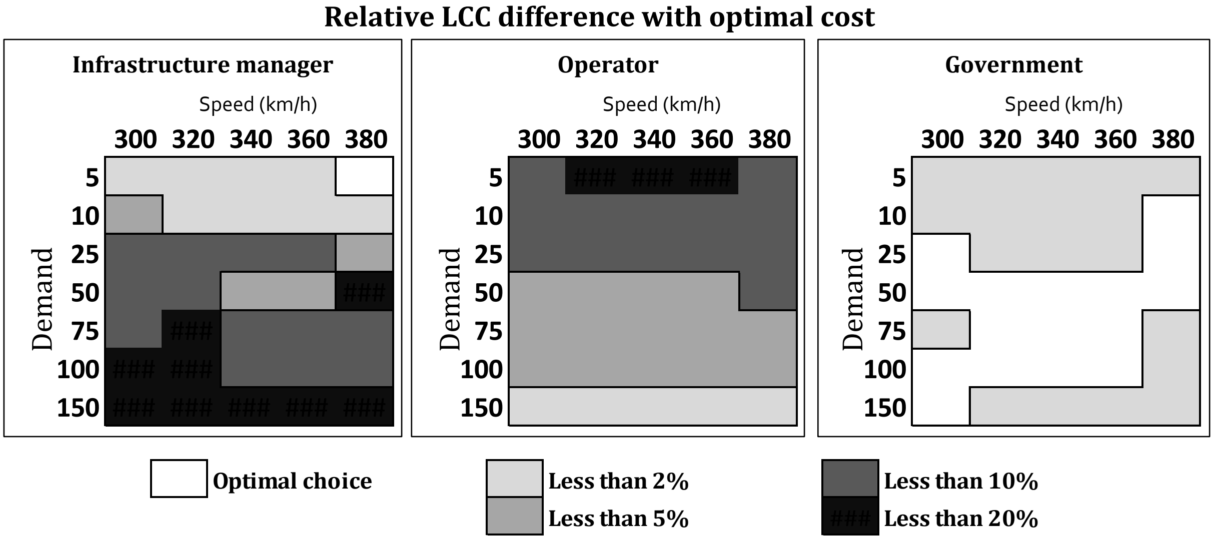


Figure 49 – Relative LCC difference with optimal cost from each stakeholder's viewpoint, 500km lines

It is striking to see that both infrastructure manager and operator may lead to significant cost increase of more than 10%. The infrastructure manager has a tendency to prefer train designs that are more adapted to a lower demand, while the proposition of the operator is not suitable for low demand. For high demand, the cost is slightly different although the train design is the same. This is explained by a different train length: operators chose a longer train to reduce the operating costs, but the other costs increase gives a larger life cycle cost. Finally, the minimisation of environmental loads leads to the optimal choice or to very small cost differences. It means that optimising the lifecycle cost of high speed rail have a very positive impact on the reduction of environmental loads.

6.2.3. Discussion about the vertical separation

This application shows that diverging interests lead to non-optimal choices from the life cycle approach viewpoint, and can lead to significantly higher costs for the users. In countries where high speed rail is planned, stakeholders must discuss together to make sure that the future system will be the most suitable, not only from the cost issue but also from the environmental viewpoint. Fortunately, both points lead to the choice of systems with close lifecycle costs and lower environmental impacts. But for such results, the regulators must evidently consider as many options as possible and carefully examine each of them before setting the guidelines of the future system. Policy makers and railway authorities are the key actors for a more sustainable high speed rail system.

7. CONCLUSIONS AND SCOPE FOR FUTURE WORK

7.1. Summary

A high speed rail life cycle cost minimisation model was developed by considering high speed rail as a fully integrated system. The review of high speed rail history showed that the focus shifted from the integrated approach to a vertically separated industry to introduce more competition and interoperability. A first consequence is a standardisation of rolling stock designs and the development of cost optimisation and decision support tools to increase the competitiveness of infrastructure management, which both aim at improving high speed rail services.

However, the loss of focus from the integrated system is not optimal from an engineering approach as shows the study of the high speed rail systems. Engineering choices were historically guided by the local contexts of each country or region, and new markets should have the opportunity to develop a system according to their own context. From the engineering approach, high speed rail systems are different answers to a given problem, just like a suspended bridge and an arched bridge are subject to the same physical problem. The choice of either bridge depends on the local conditions, just like the choice of high speed rail systems should.

For these reasons, a life cycle cost model is proposed to optimise the choice of high speed rail systems under a given context. The model aims to fulfil the following objectives:

- To estimate the costs of a new high speed rail system
- To assist in the selection of the best design options in terms of economic return under specific local constraints
- To assist in the decision making process and allow a discussion among stakeholders.

7.2. Conclusions

Although it is a relatively simple model developed in a short time, it has very positive outputs regarding the influence of different contexts, and highlights the trade-offs between train design, infrastructure design, and operating constraints. In addition, it requires relatively few input parameters and has been developed with Excel VBA, which make the model easy to use and upgrade. When comparing the optimisation outputs and the current situation of high speed rail, interesting figures appear.

There is a clear difference between the convergence of rolling stock designs proposed by the operators and the different design obtained by the optimisation model. Of course it does not imply that operators are making wrong decisions, but that new double decker designs could be explored when exporting to new markets. The advantage of EMU design is to propose better performance with reduced train consumption, but also an easier adaptability to different train lengths. Some manufacturers are now proposing both narrow and wide gauge, introducing a family of design, flexible in length and width. The next step might be to increase the size of the family with a double-decker design, and to add a third dimension to high speed train design flexibility.

Finally, the most valuable output of the application is the illustration of a very divergent interest not only between high speed rail stakeholders, but also with the optimal choices. This situation can lead to significant cost increases that would eventually be borne by the users or by the society. Thus the regulatory authority must not only coordinate the stakeholders but ensure that their propositions and choices do not significantly increase the costs and benefits. And for that, the regulatory authority should carefully design the requirements by reviewing all the possible options and their impact from multiple angles thanks to several decision support tools, among which life cycle cost is but one approach.

7.3. Scope for future work

The model has been designed to be easily upgraded and updated, and offers a wide scope for future work. Inputting more accurate and up-to-date cost elements would ensure more precise cost estimations without modifying significantly the model. But improving the cost estimation itself could prove more efficient. For instance, limited available data led in simple maintenance and energy cost estimations, and more refined estimation models would reduce the uncertainties. Integrating the model with existing decision support tools is one of the possible further future works, by providing an interface with alignment design software, to eventually provide an optimisation of the alignment itself. However, as a life cycle cost model it is by nature limited by the data availability. Fortunately, the numerous high speed rail projects that are being implemented will provide both data for the model, and new lessons for always more efficient and sustainable high speed rail systems.

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APPENDIX

A1 Schedule of interviews

Organization	Interviewees	Day	Topic
RTRI		November 25 2011	Japanese Shinkansen
JARTS	Yoshihiro AKIYAMA	December 9 2011	Exportation of Shinkansen technology
JRTT		January 11 2012	High speed infrastructure: slab tracks
JR East		February 24 2012	The cost of Shinkansen
RFF	Olivier CAZIER	March 9 2012	High speed infrastructure for the future
Consultant	Willem-Jan ZWANENBURG	March 12 2012	High speed tracks and maintenance
Professor at the University of Cardiff	Christopher HOOD	March 13 2012	Shinkansen, From Bullet Train to Symbol of Modern Japan
SNCF	Marc ANTONI	March 16 2012	Railway maintenance

A2 Technical standards of track design around the world

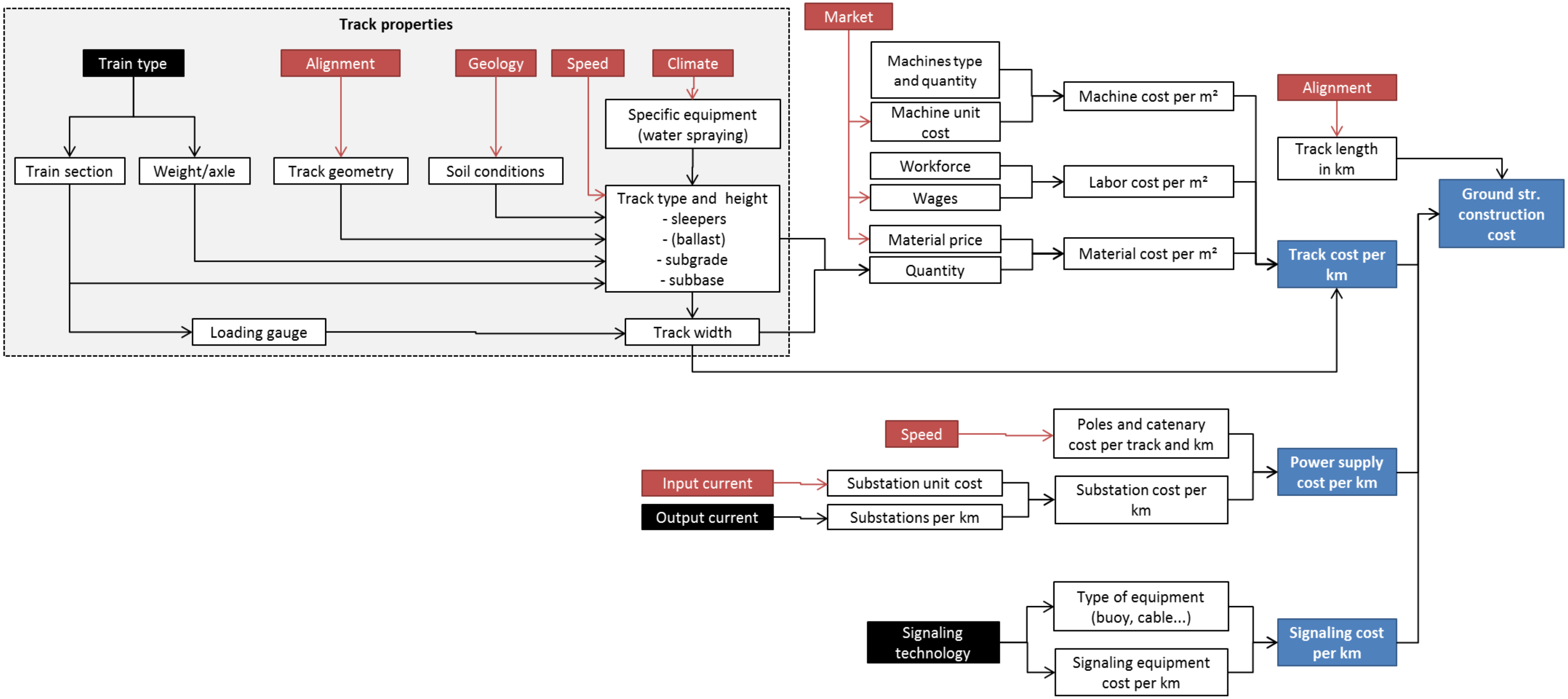
	Japan	France	Spain	Germany	Italy	Korea	Taiwan
Gauge	Standard	Standard	Standard and wide gauge	Standard	Standard	Standard	Standard
Maximum operation speed	300 km/h (320 in 2013)	320 km/h (designed for 350km/h)	300 km/h	300 km/h	300 km/h	300 km/h	300 km/h
Track type	Ballasted (Slab)	Ballasted	Ballasted	Balastless (Rheda)	Mixed	Ballasted	Ballastless
Track centre-to-centre distance	4.3m	4.5m	4.3m	4.7m	5.0m	5.0m	4.5m
Minimum curve radius	4,000m	7,000m		7,000m		7,000m	6,500m
Max. cant	200mm	180mm	140mm	150mm	105mm		180mm
Permissive cant deficiency	90mm	55mm	100mm	60mm	92mm		60mm
Steepest gradient	3.5%	3.5%	1.2%	1.25%	1.8%	1.5%	3.5%
Radius of vertical curvature	15km	25km	24km	25km	25km		19km
Tunnel cross-section	63.4m^2	100m^2 and 2×46m^2	75m^2	82m^2	76m^2	100m^2	90m^2

Sources: (UIC, 2011), (Japanese Overseas Rolling Stock Association, 2004), (RFF, 2007), (Cazier, La Voie, 2012)

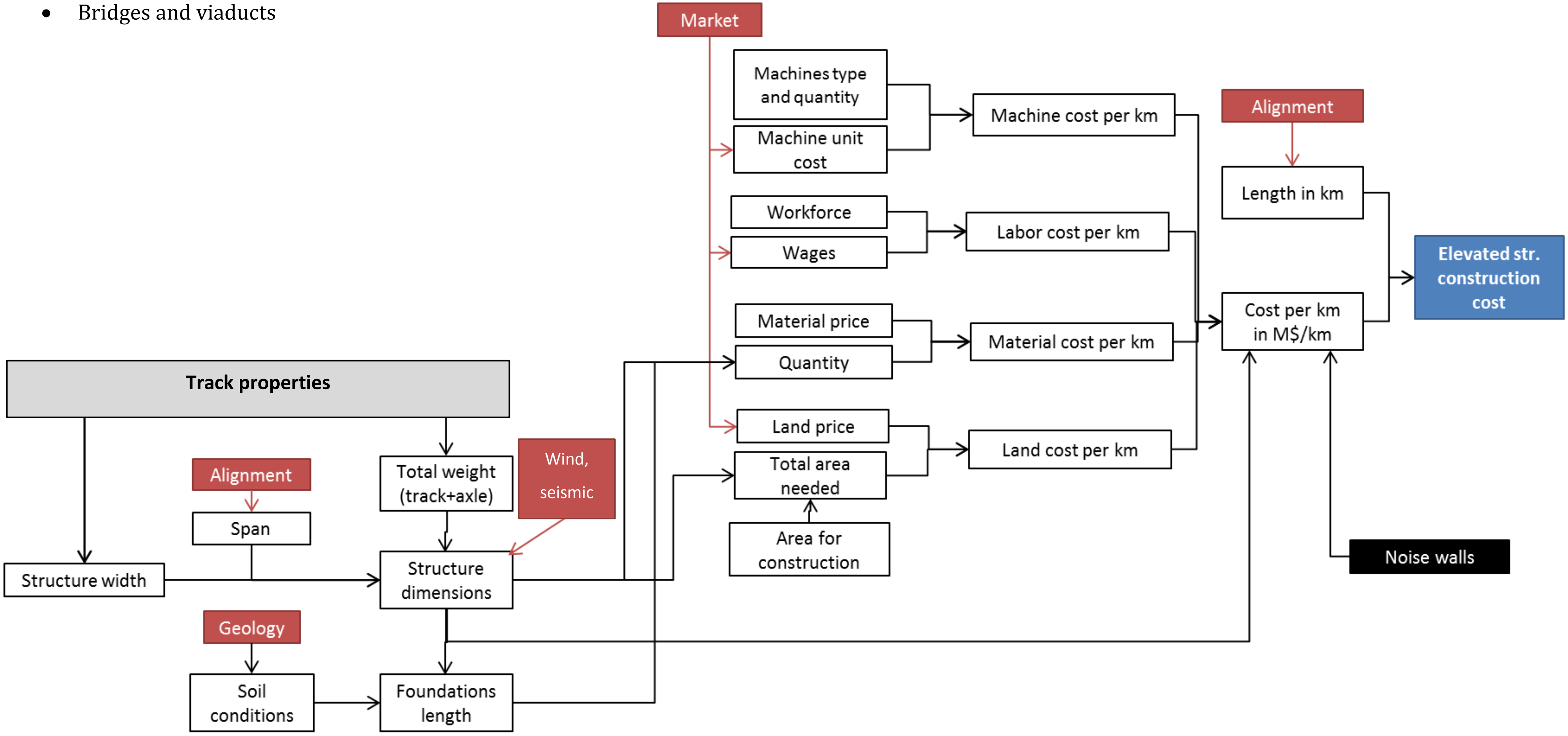
A3 Theoretical LCC frameworks

A3.1 Construction costs

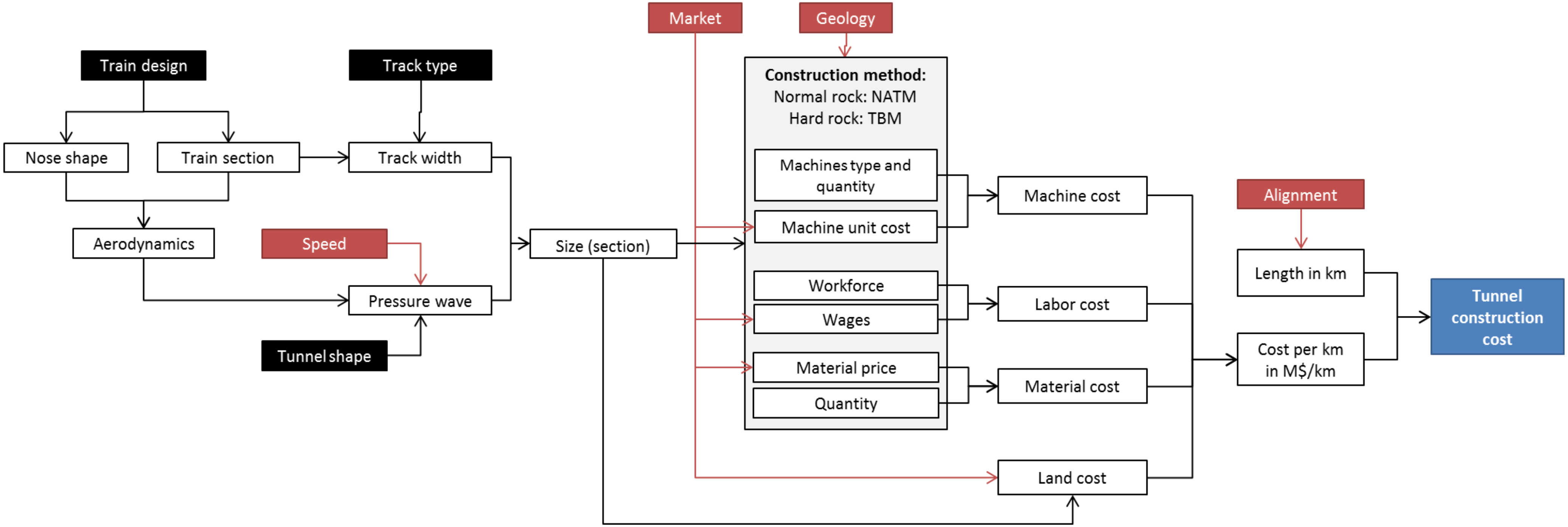
- Track and earthworks



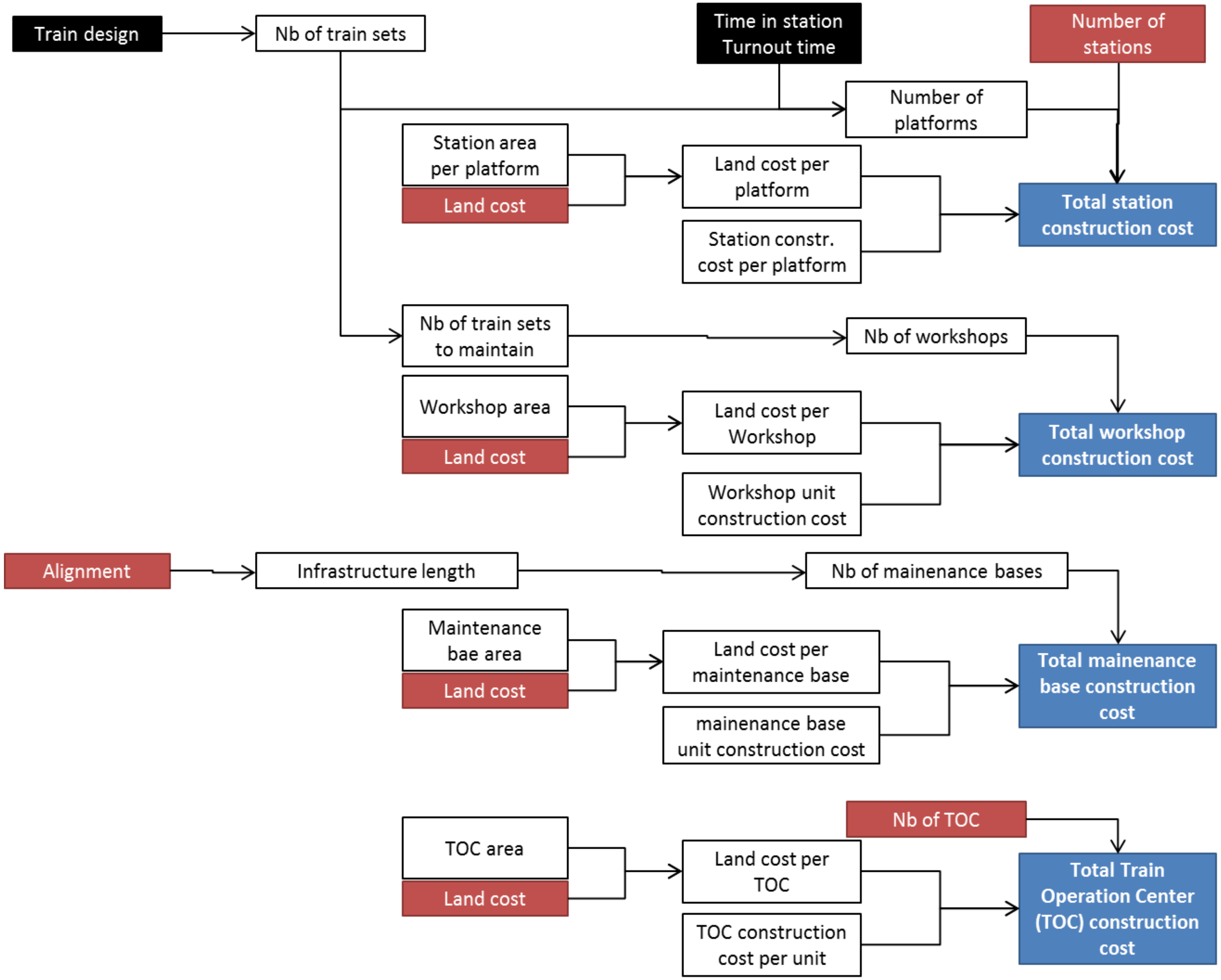
- Bridges and viaducts



- Tunnels

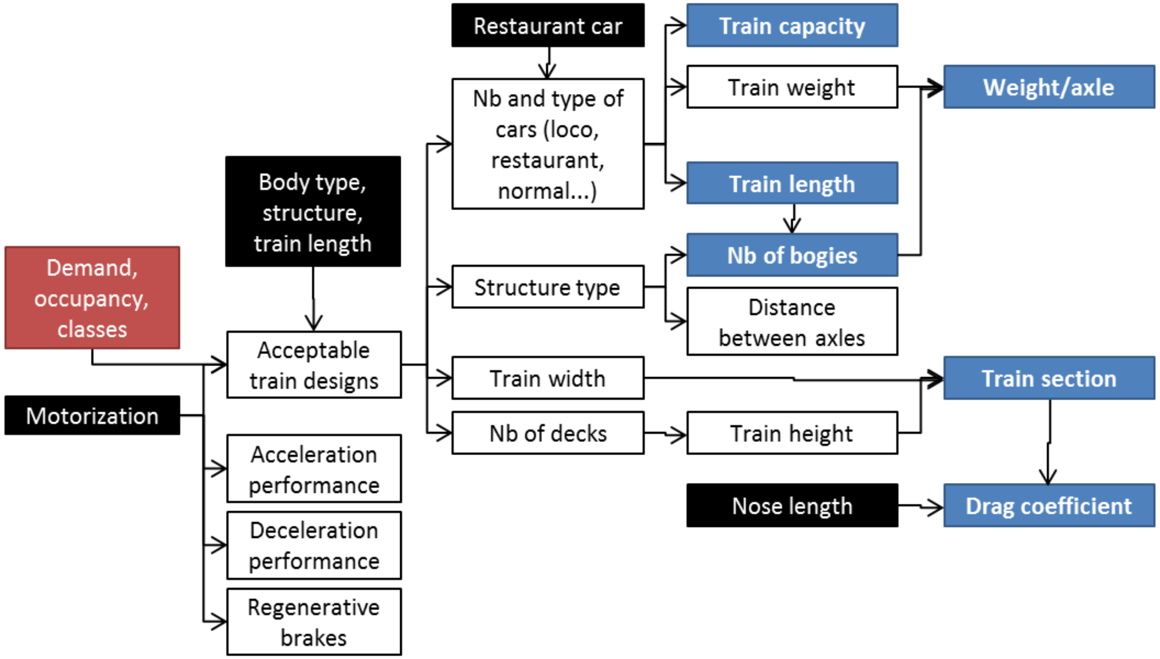

Market
Geology
Train design
Track type
Construction method:
Normal rock: NATM
Hard rock: TBM
Nose shape
Train section
Track width
Machines type and quantity
Machine cost
Alignment
Machine unit cost
Aerodynamics
Speed
Size (section)
Length in km
Workforce
Tunnel construction cost
Pressure wave
Labor cost
Wages
Cost per km in M$/km
Tunnel shape
Material price
Material cost
Quantity
Land cost

- Non-linear structures: Stations, Workshops, Maintenance bases and Train Operation Centre

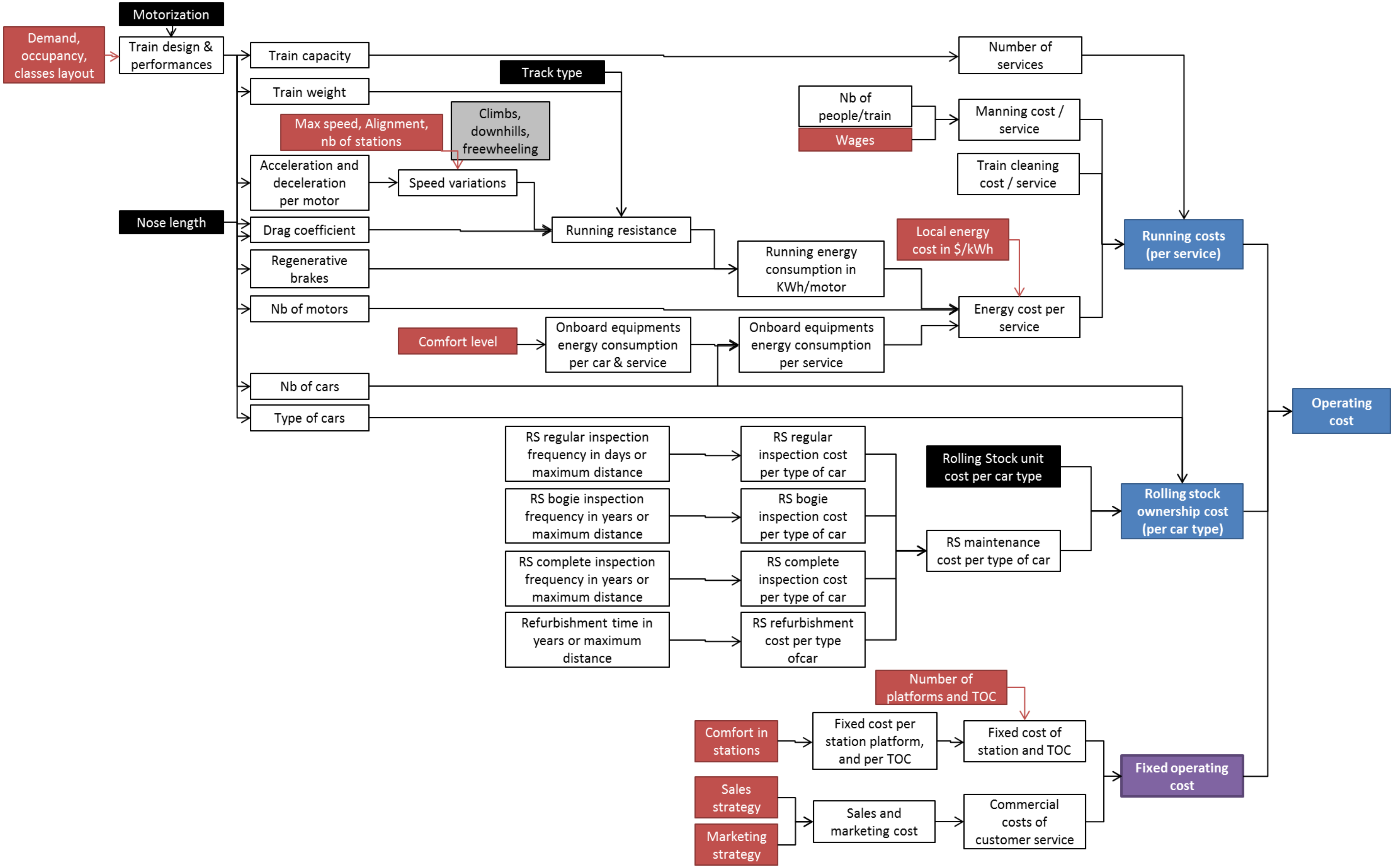


A3.2 Operating costs

- Train design



- Operating costs



A4 Rolling stock designs considered in the model

No	Type	q_{2f}	q_{2m}	ρ	L_f	L_f	Section	Width	Wheelbase	Existing or hypothetical name	Legend
0	N1D-NA-L	0	72	1	27	25	9.6	2.9	2.5	ICE1&2	□
1	N1D-NA-E	56	72	1	27	25	9.6	2.9	2.5	ICE3 / Mini-shinkansen	░
2	N1D-A-L	10	60	1	23	18.7	9.6	2.9	3	TGV /KTX	░
3	N1D-A-E	39	56	1	19	18	9.6	2.9	3	AGV	▒
4	N2D-NA-L	0	72	1.4	27	25	10.9	2.9	2.5	*Double decker ICE1&2*	▦
5	N2D-NA-E	56	72	1.4	27	25	10.9	2.9	2.5	*Double decker ICE3/Mini-Shinkansen*	▒
6	N2D-A-L	10	60	1.4	23	18.7	10.9	2.9	3	TGV Duplex	▓
7	N2D-A-E	39	56	1.4	19	18	10.9	2.9	3	*AGV 2*	■
8	W1D-NA-L	0	72	1.25	27	25	10.9	3.4	2.5	*Wide ICE1&2*	▤
9	W1D-NA-E	56	72	1.25	27	25	10.9	3.4	2.5	Shinkansen, Velaro, Zefiro	▤
10	W1D-A-L	10	60	1.25	23	18.7	10.9	3.4	3	*Wide TGV / KTX*	▥
11	W1D-A-E	39	56	1.25	19	18	10.9	3.4	3	*Wide AGV*	▥
12	W2D-NA-L	0	72	1.7	27	25	12.4	3.4	2.5	*Double-decker, wide ICE1&2*	▧
13	W2D-NA-E	56	72	1.7	27	25	12.4	3.4	2.5	Shinkansen E4	▩
14	W2D-A-L	10	60	1.7	23	18.7	12.4	3.4	3	*Wide TGV Duplex*	▨
15	W2D-A-E	39	56	1.7	19	18	12.4	3.4	3	*Wide AGV2*	▨

Body: N: Narrow; W: Wide; 1D: single-deck; 2D: double-deck

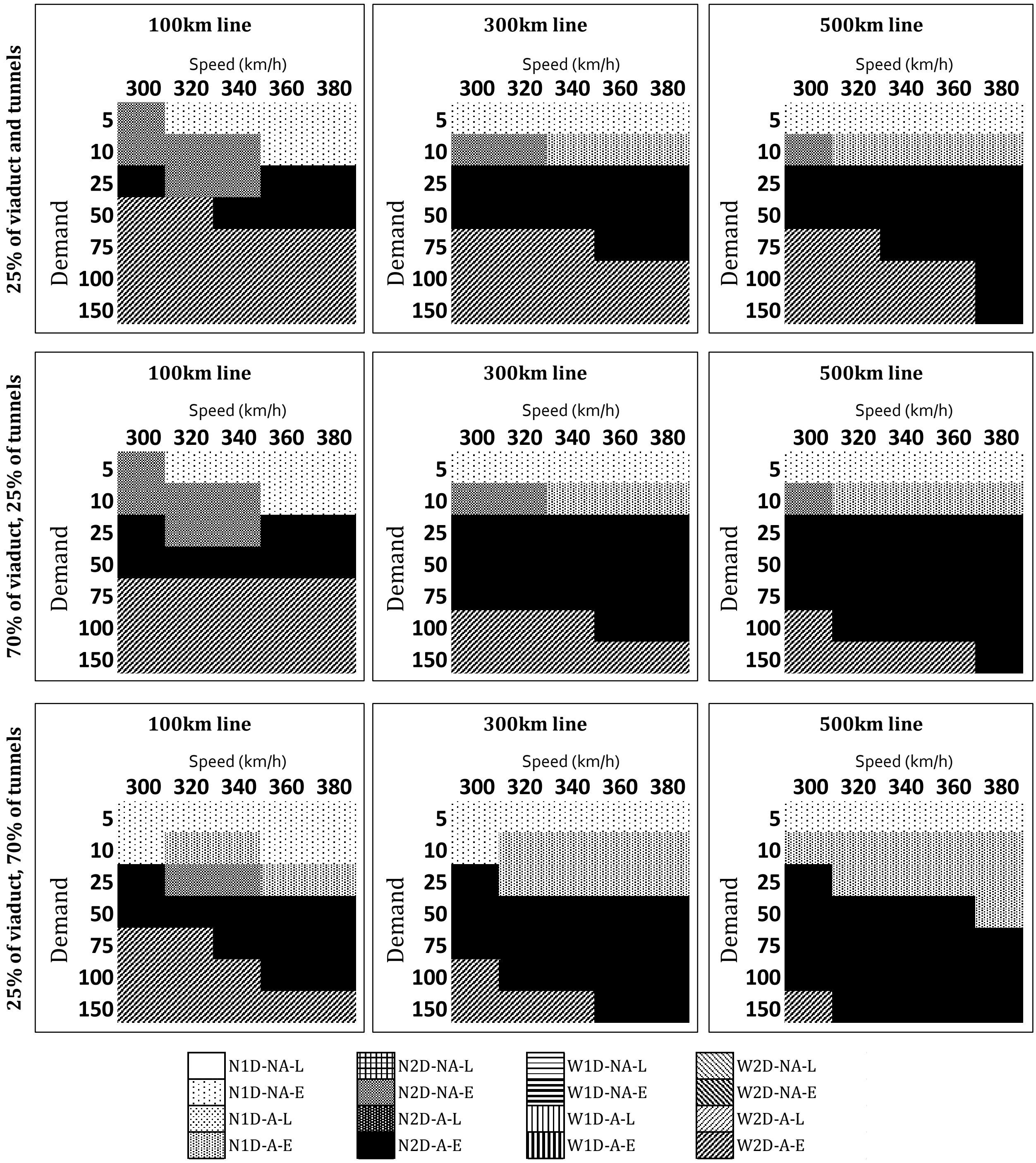
Structure: A: Articulated; NA: Non-articulated

Motorization: E: EMU; L: Locomotive

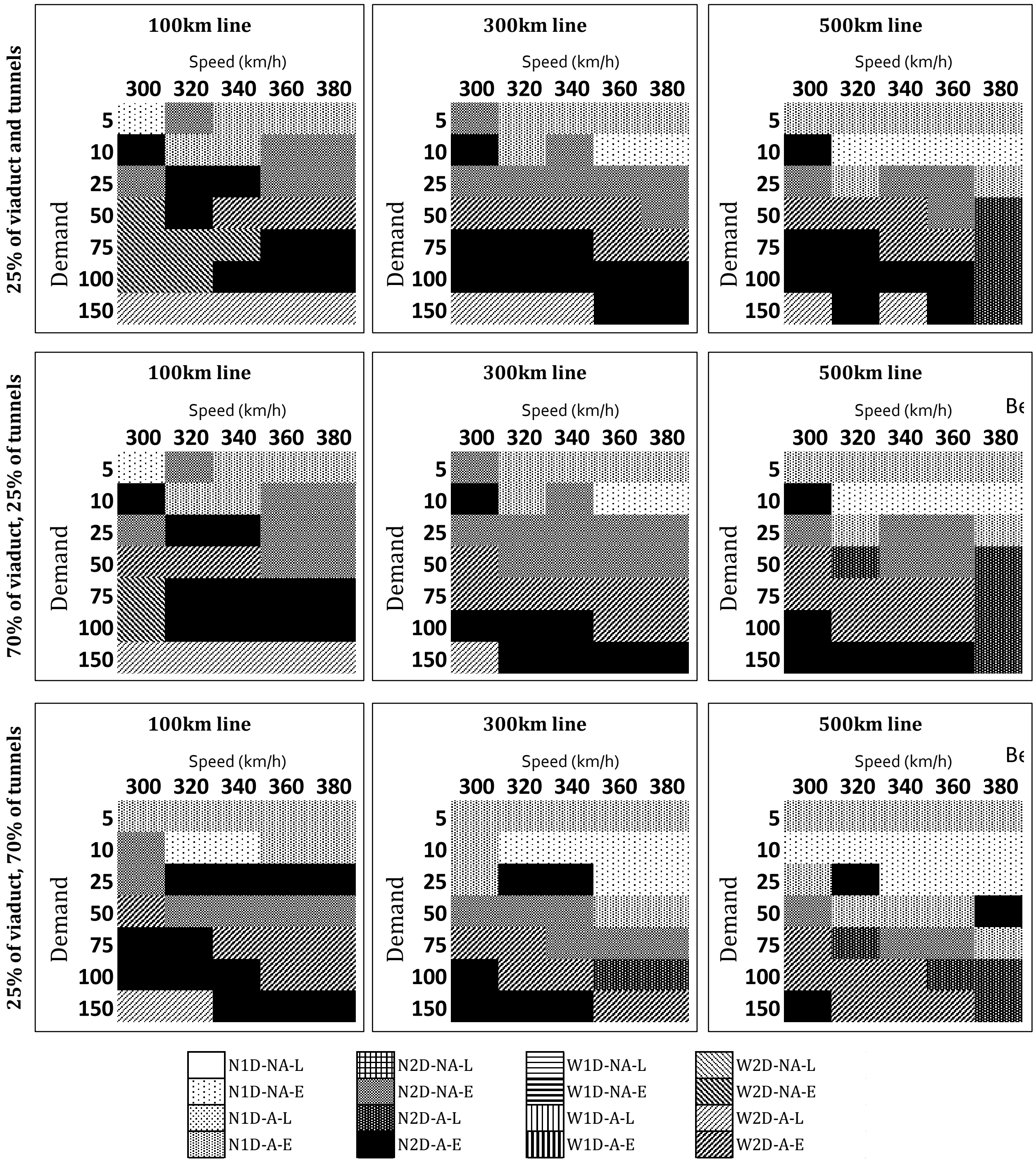
A5 Simulation results

A5.1 Sensitivity case 1: tunnels and viaducts

- Best designs

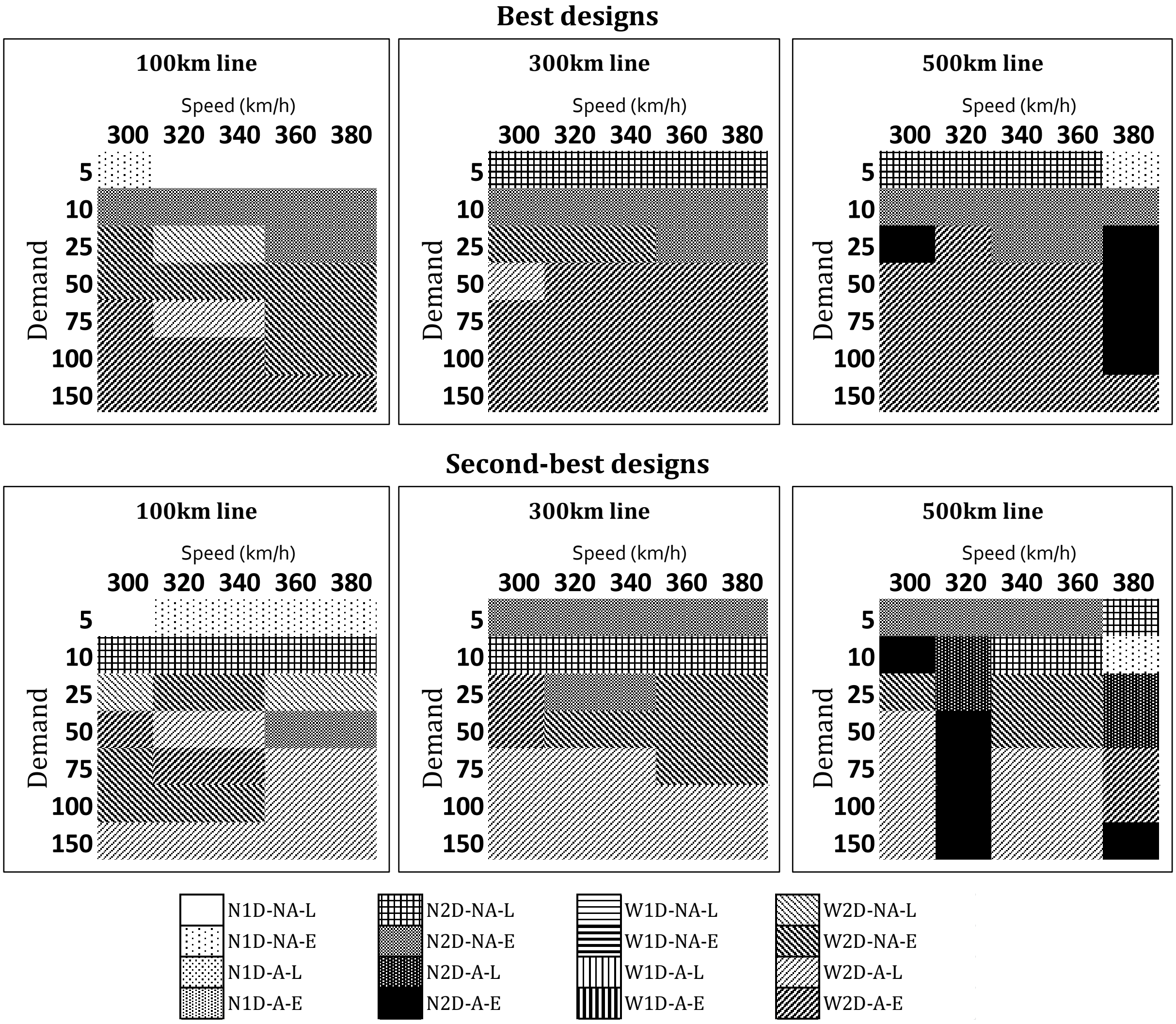


- Second-best designs



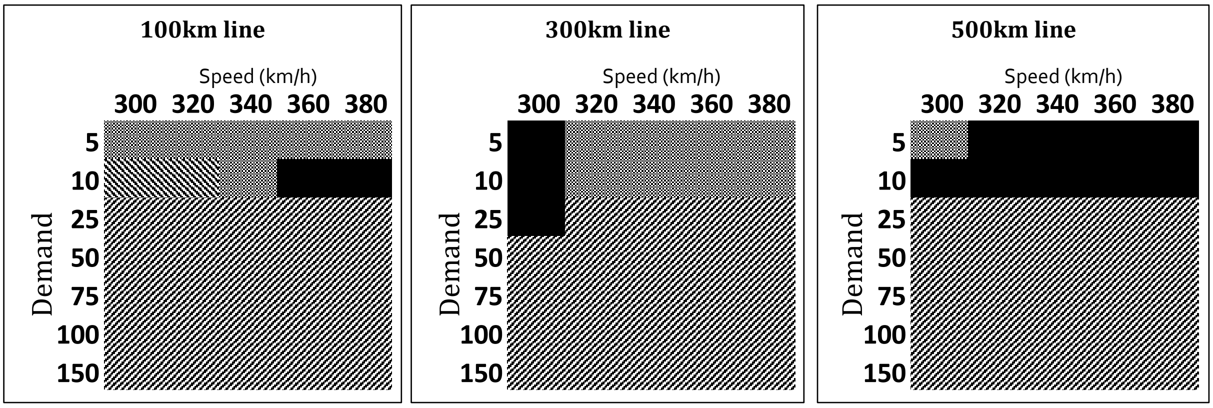
A5.2 Sensitivity case 2: operating parameters

- Doubled proportion of 1st Class

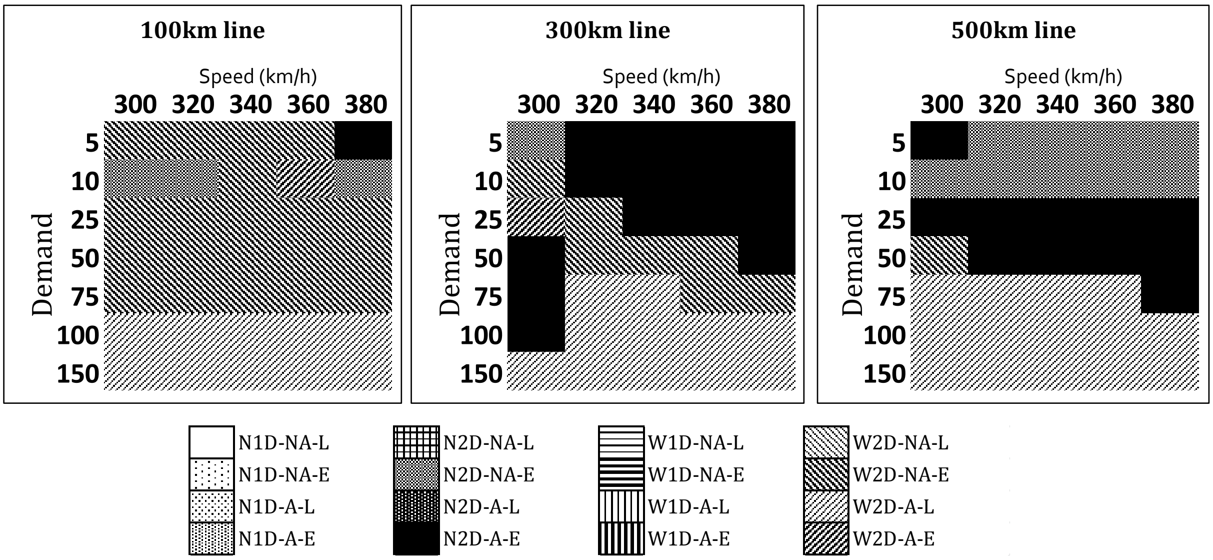


- Occupancy rate reduced to 50%

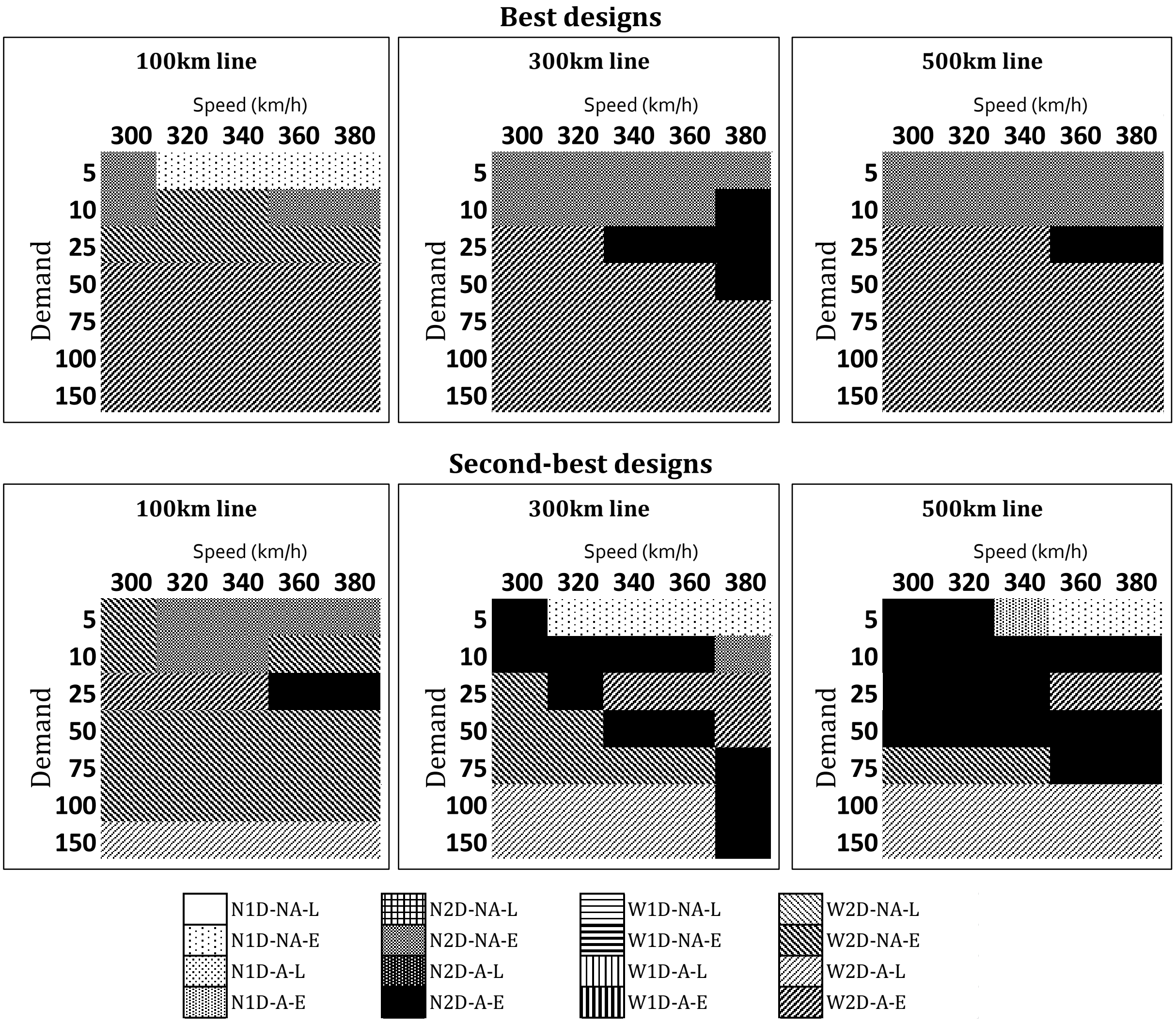
Best designs



Second-best designs

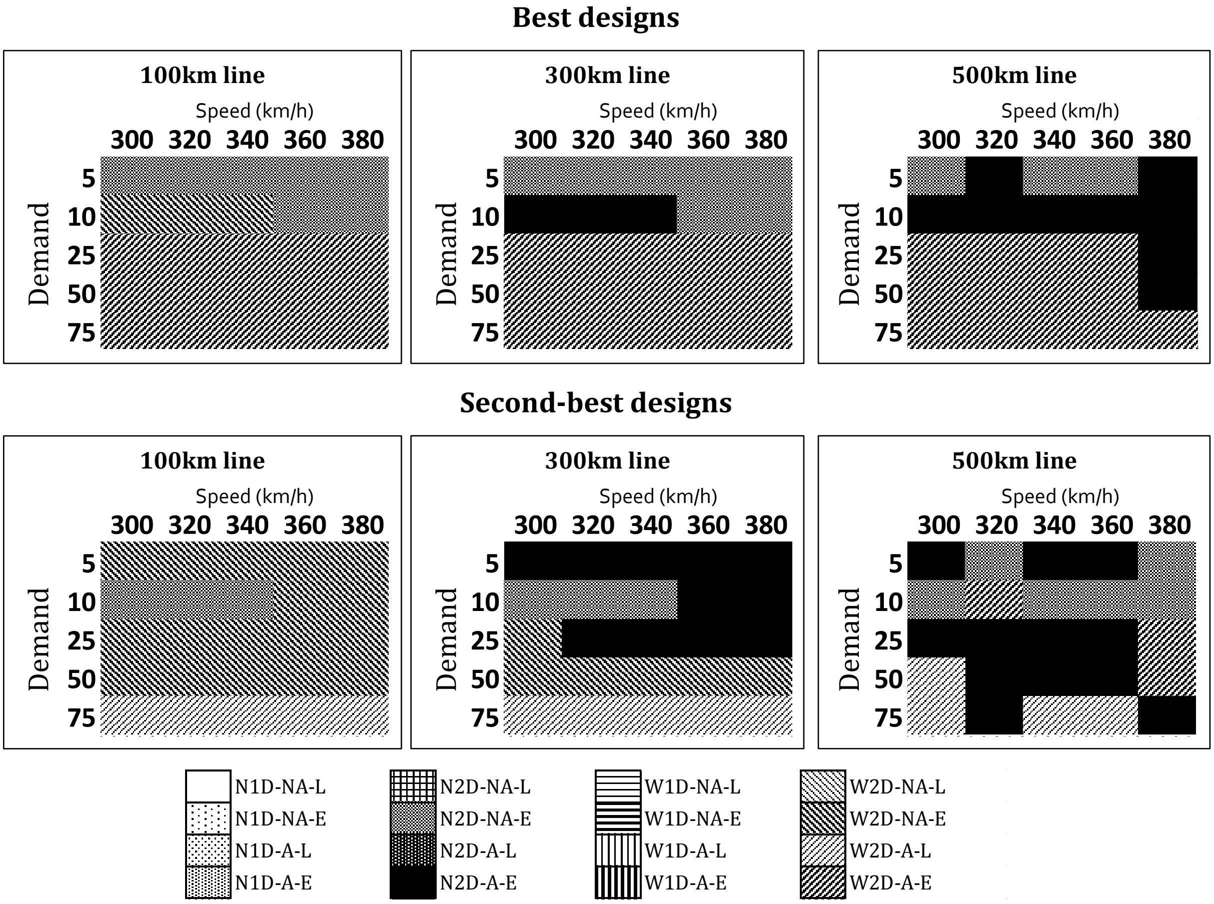


- Omnibus services



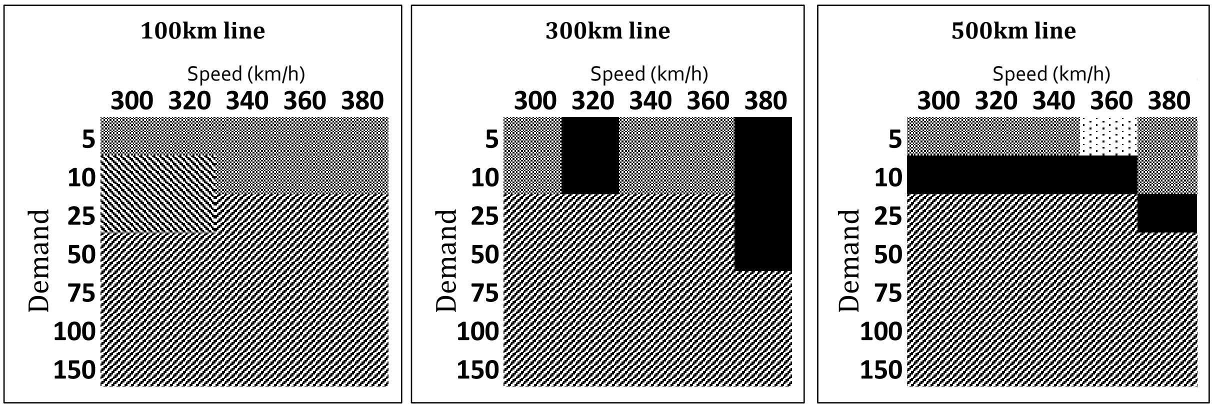
- Demand growth of 2% per year

With the hypothesis and parameters used in this study, no train could accommodate an initial demand 0f 100Mpax or above with a 2% annual growth.

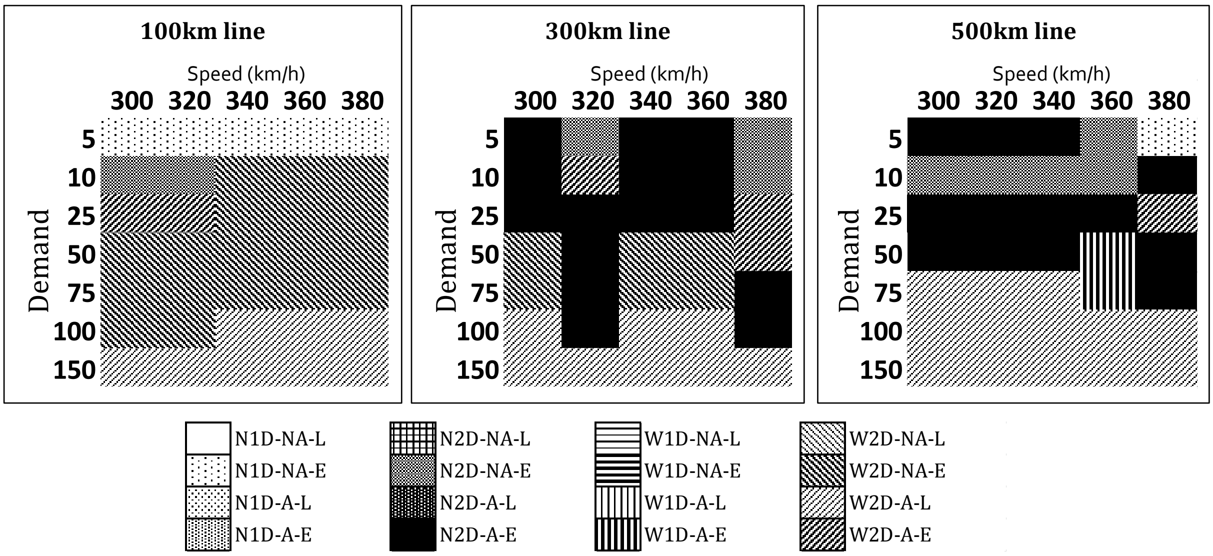


- Operating hours reduced from 18 hours to 14 hours

Best designs

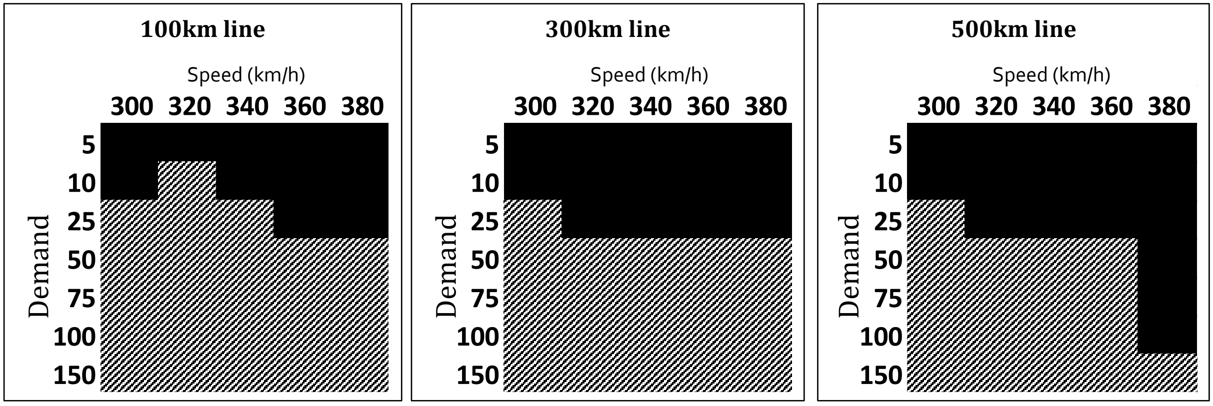


Second-best designs

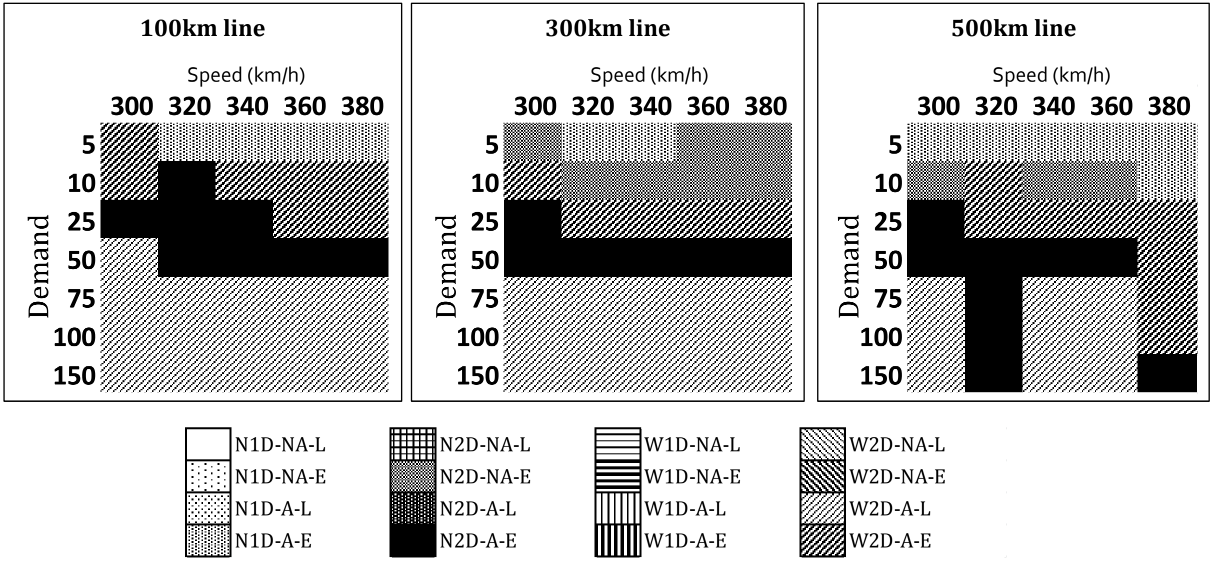


A5.3 Sensitivity case 3: low local costs and high inflation

Best designs

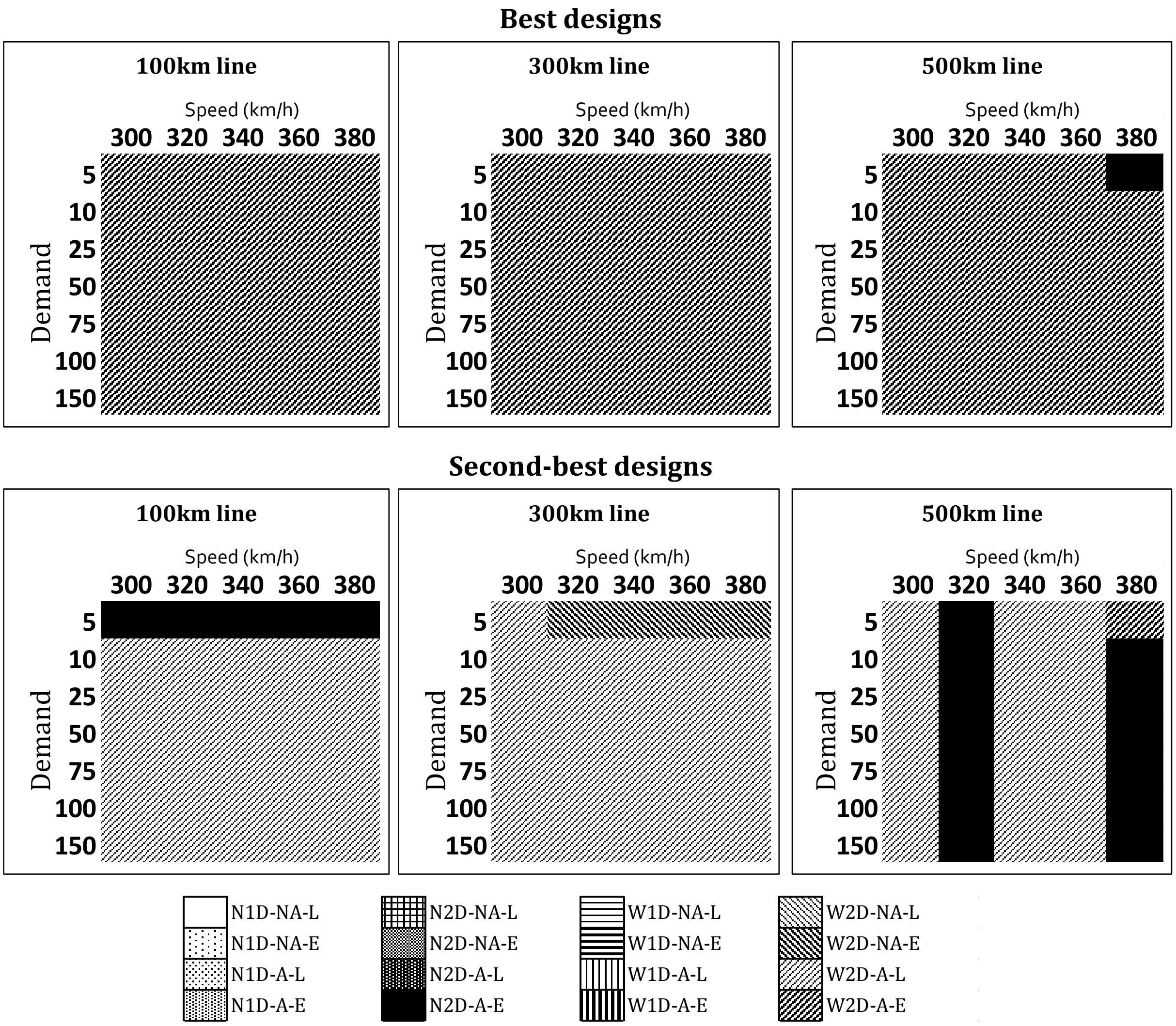


Second-best designs



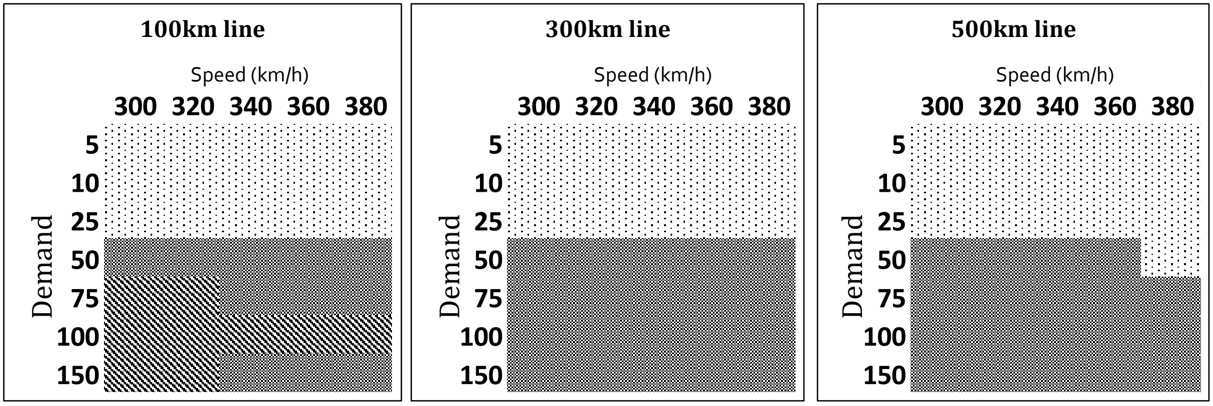
A5.4 Results from vertical separation study

- Operator: operational cost minimization

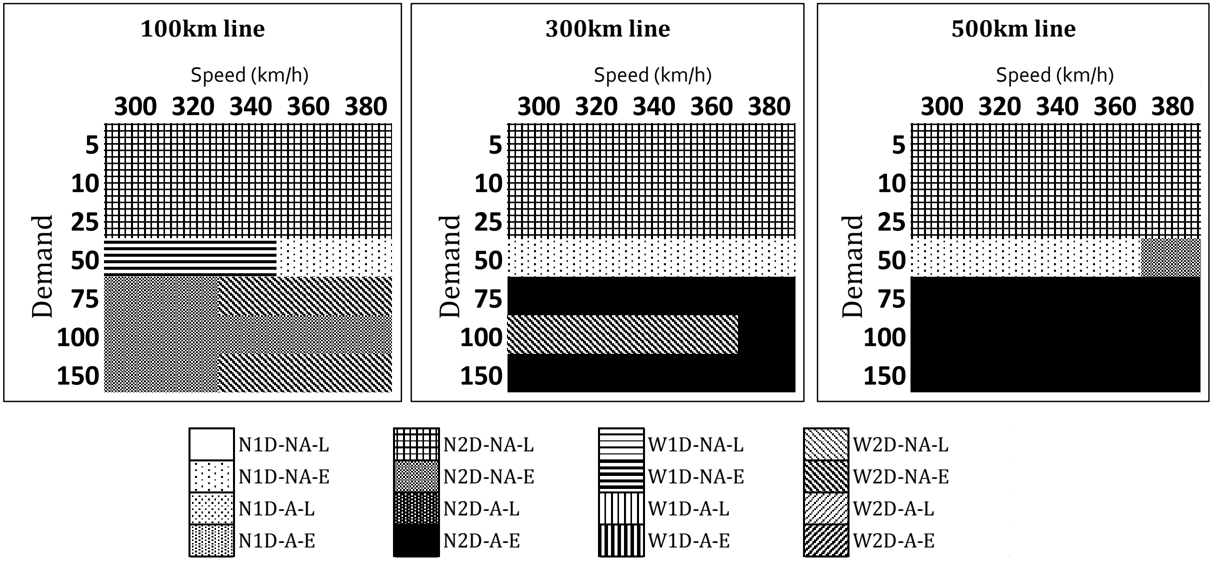


- Infrastructure manager: construction and operational cost minimization

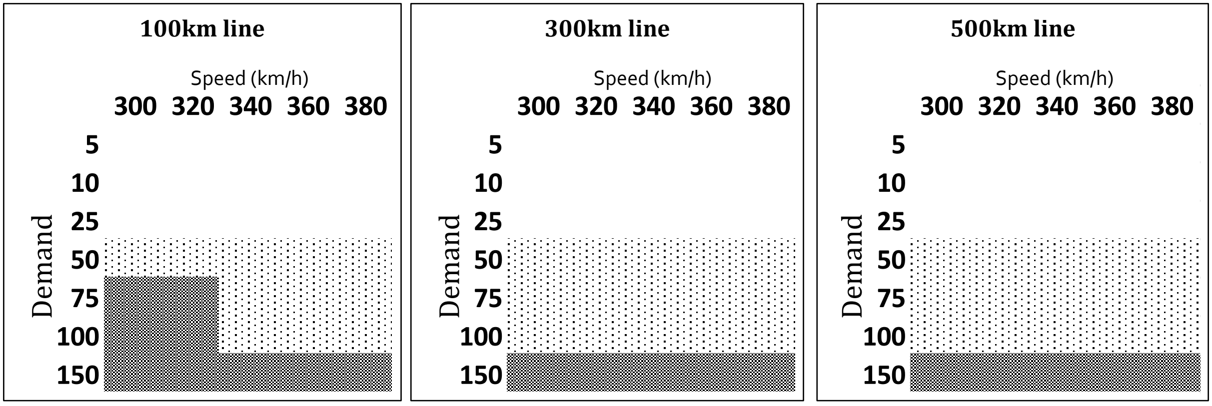
Best designs, “French” case (5% tunnels and viaducts)



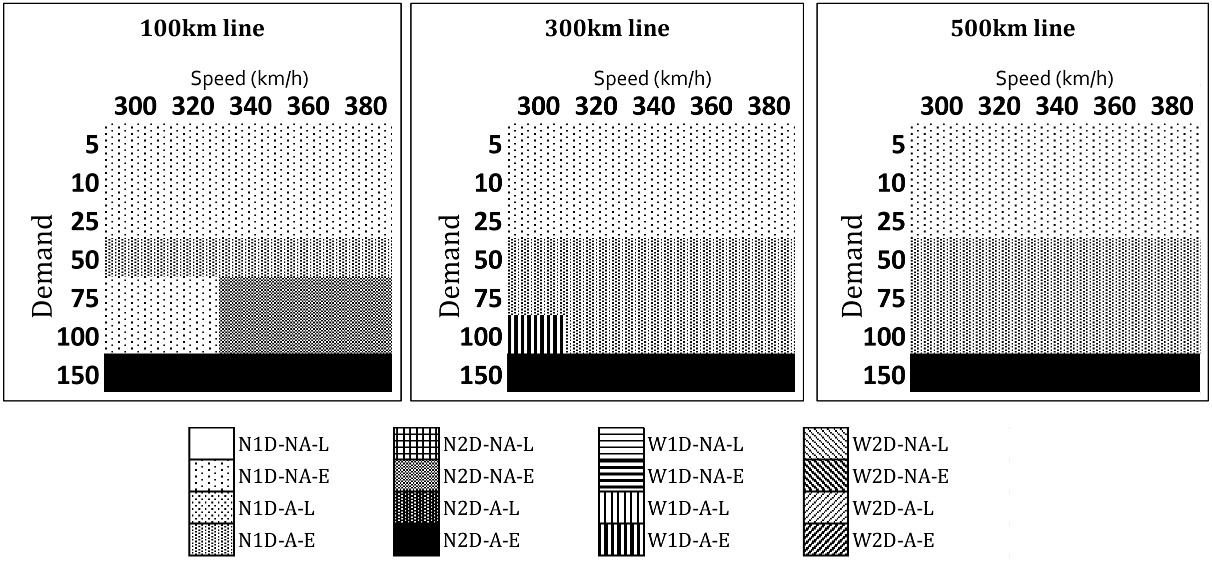
Second-best designs, “French” case (5% tunnels and viaducts)



Best designs, “Japanese” case (45% tunnels and viaducts)

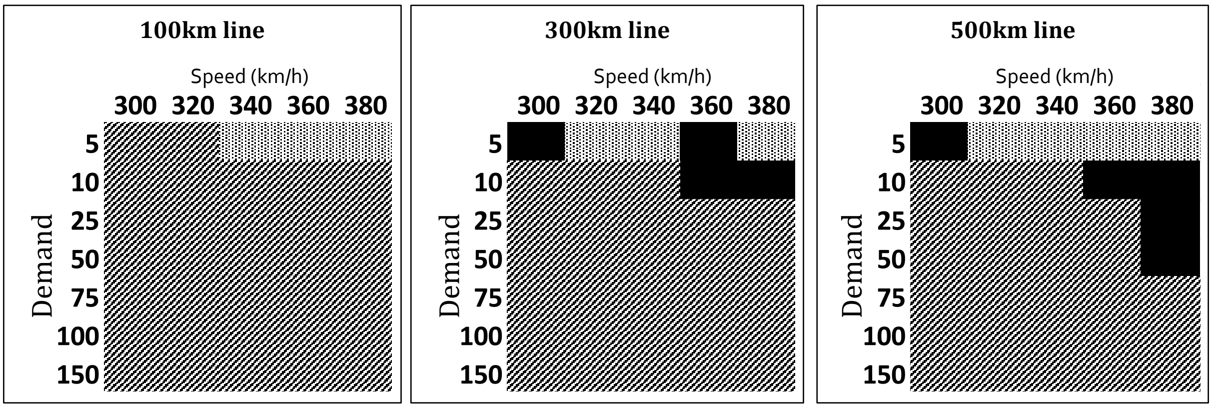


Second-best designs, “Japanese” case (45% tunnels and viaducts)



- Government: environmental impacts minimization

Best designs



Second-best designs