Reducing land take and energy use of high-speed railways through the robust design of operations

by

Daisuke Hasegawa

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Department of Electronic, Electrical and Systems Engineering

College of Engineering and Physical Sciences

The University of Birmingham

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Abstract

High-speed railways provide fast inter-city passenger transport, which is credited with delivering high capacity, short journey times, excellent safety, punctuality and good environmental performance. The first true high-speed railway in the world was the Tokaido Shinkansen from Tokyo to Osaka, which started revenue operation in 1964. It has carried over 5.6 billion passenger, so far, without a single fatal accident due to a derailment or collision. Following the success of the Shinkansen, several countries have already constructed high-speed railways and other countries plan to construct such railways in the context of growing concerns about travel demand and climate change. However, the success of both existing and new high-speed railways is not guaranteed because the high capital cost of their construction is not easily covered by commercial revenue and socio-economic benefits except in a few cases. In addition, the growing awareness of climate change issues is resulting in the requirement for more energy efficient operations.

In this thesis, I addresses the problem of the high capital cost of high-speed railways and the need to reduce their energy use through the design of robust operations at the planning stage. Given the cost structure and benefits of different solutions, reducing the size of termini and maintaining robust operations in and near the termini is identified as a promising option for cost reduction. Two methodologies from manufacturing industry, namely, the Lean principle for cost reduction and the Taguchi method for robust design, are confirmed as suitable tools to realise the objective of improving the design of high-speed railways. I developed a novel approach that combines Lean and Taguchi techniques to deal with characteristic features of high-speed railways, such as the severe requirement for robust operations. The robustness of different terminus designs has been assessed by means of an original terminus simulator based on the Taguchi method. Thereby, the most important factor for the robustness of a terminus design was identified, which is signalling reaction time. The application of Lean principles to high-speed railway service planning creates an efficient operational concept in terms of resource usage, thanks to a reduction in non-value adding activities. This is achieved by minimising the turnaround times at termini while excess platforms are highlighted through a Value Stream Mapping (VSM) analysis. The Just In Time (JIT) concept is adopted for the timetabling task to reduce the duration of non-value adding steps and energy use for traction. The Single Minute Exchange of Die (SMED) concept has been adopted to realise faster turnarounds at termini.

Finally, the worth of the combined approach has been demonstrated by means of case studies of current British conventional railway practice, current Japanese high-speed railway operations and the planned High Speed Two (HS2) line. The latter work has shown the possibility of a reduction in the proposed number of platforms at Euston Station, the main terminus of HS2 in London, as well as energy saving for traction.

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Glossary of Terms / List of Abbreviations

AGV	Automotrice à Grande Vitesse (High Speed Multiple Unit)
ANOVA	Analysis of Variance
ATO	Automatic Train Control system
AUTOMAIN	Augmented Usage of Track by Optimisation of Maintenance, Allocation and Inspection of railway Networks
AVE	Alta Velocidad Española (Spanish high speed railway)
C-DAS	Connected Driver Advisory System: See DAS.
CED	Cumulative Energy Demand
DAS	Driver Advisory System: a system installed in train cabs to advise train drivers to drive trains economically, punctually or safely. There are two variants, depending on whether there are real-time updates (see C-DAS).
HS1	High Speed One (Ashford to London in Britain)
HS2	High Speed Two (London to Birmingham and the North in Britain)
HST	High Speed Train, a British high-speed train
ICE	Intercity Express, a German high-speed train
JIT	Just In Time: a Lean concept for eliminating waste by optimising the timing of each process and step of production (Ohno, 1988)
KTX	Korea Train Express
LCA	Lifecycle Cost Assessment / Life Cycle Cost Analysis
Lean	A philosophy that reduces cost and improve quality of product originated from Toyota's production methods (Womack and Jones, 1996).
LGV	Ligne à Grande Vitesse, the French equivalent to the Japanese dedicated high-speed lines, which uses conventional lines to access city centres.
MAGLEV	Magnetic Levitation
NRT	National Rail Timetable
NVA	Non-value added: an activity that does not add value to a product, process or service.
ON-TIME	Optimal Networks for Train Integration Management across Europe, a European Union supported research project.
Pkm	passenger-kilometre; 1 pkm means that a passenger has been carried for a distance of 1 km.
PKT	Passenger Kilometer Transported (American): unit of transport measurement; 1 PKT means that a passenger has been carried a distance of 1 km.
PPM	Public Performance Measure
RPIAP	Railway Possession and Isolation Authorisation Process
S&C	Switches and Crossings

SMED	Single Minute Exchange of Die: a Lean concept developed to improve the efficiency of manufacturing by reducing the changeover time of machine dies (Shingo, 1985).
TALGO	Tren Articulado Ligero Goicoechea Oriol (Goicoechea-Oriol light articulated train), a Spanish high-speed train
TGV	Train à Grande Vitesse (a French high speed train)
UIC	Union Internationale des Chemins de fer (International Union of Railways)
VA	Value added: an activity that adds value to a product, process or service.
VSM	Value Stream Mapping: a tool that helps to identify value added and non-value added activities in order to eliminate waste from whole production process (Rother and Shook, 2003).
WTT	Working Timetable

1 Introduction

In the introduction I present the rationale for undertaking my research and the background to my PhD studies. I also state my hypothesis and I provide my aims and objectives. I define the scope and limitations of the research and I suggest a number of research questions before concluding with the structure of the thesis.

1.1 Background

This thesis and the underpinning research address cost and resource use reduction for high-speed railways. The high-speed railway is a mode of transport for fast inter-city passenger travel and, in a few cases, rapid freight transport. Its most important features are high capacity and speed, robust safety, good punctuality and sound environmental performance. The first operational service of this type was implemented in Japan in 1964 for the Tokyo Olympic Games. This line, the Tokaido Shinkansen, which connects Tokyo and Osaka, has been in successful revenue operation for 50 years with not a single fatal accident caused by a derailment or collision. It carried 163 million passenger with an average delay of 0.2 minutes in the fiscal year 2015. Recognising the success of this first line, several countries in Europe and the Far East have also constructed high-speed railways and countries in the Americas, Africa, Middle East and Asia are planning to construct new lines in the context of growing travel demand, economic development and concerns about climate change.

However, the success of the Tokaido Shinkansen was an exceptional case, only mirrored in Europe by the Paris to Lyon high-speed railway or Ligne à Grande Vitesse (LGV), inaugurated in 1981. High-speed railways require high capital investment for land acquisition, construction of the infrastructure and the procurement of rolling stock. Due to this high capital cost, it is reported that other than the Tokaido Shinkansen, only four lines in the world, namely, the Sanyo Shinkansen in Japan, TGV Sud Est in France and the Jinan-Qingdao line in China, are profitable, currently. Even when including socio-economic benefits alongside the commercial revenues, it is still difficult to justify the initial cost of high-speed railways in most cases. In this situation, the construction of new lines is difficult to justify by officials and citizens, e.g., in the case of High Speed Two in Britain.

Prior to my research, cost reduction for high-speed rail has been examined extensively in the areas of maintenance and operations but less so in terms of the first cost of the whole system. This might be attributed to the requirement to ensure a high level of system reliability at the construction stage of high-speed railways, resulting in a trend to build systems that are potentially more capable than necessary. By their nature high-speed railway systems are large and complex so that without a well-considered approach at the planning and design stages, it is easy to over-engineer. Thus, any reduction in the first cost must be achieved in a sophisticated manner, so as not to affect the robustness of operations.

1.2 Research hypothesis

In this thesis, I shall report on the testing of the following research hypothesis:

The application of Taguchi and Lean techniques can improve the planning and design of high-speed railway operations and thereby reduce the cost of construction and the energy use during operations, while maintaining a robust operational performance.

1.3 Aim and objectives

The aim of the research undertaken for this thesis has been to improve the design of high-speed railway infrastructure and operations in order to reduce land take and energy use. To achieve this overarching aim, the following objectives had to be satisfied:

- Identify methodologies that can be used to achieve the aim through a literature review;
- Develop an enhancement approach based on the methodologies and develop a simulation tool to assess its performance;
- Assess the benefits and disadvantages of adopting the approach;
- Confirm the robustness of the enhanced operations by means of the simulator.

Each of the objectives was addressed on its own and within the context of the overall aim of the research project.

1.4 Scope

The scope of the research conducted for this thesis has been defined as follows:

- The study is focused on the design of termini and plain line operations;
- Energy use is studied only in terms of traction energy consumption;
- Land take is studied in terms of the number of platforms required for typical termini;
- Operational robustness is addressed in terms of small delays. Major delays, e.g., those caused by significant infrastructure and rolling stock failures, natural disasters, accident resulting in injuries and so on, are not considered.

Thus, the following issues are out of scope:

- Alignment design and its influence on cost, e.g., because of tunnelling;
- Reliability issues of the infrastructure, rolling stock and other facilities;
- Issues related to the practical implementation of the plans. This is a theoretical study, albeit with practical applications.

I am expecting to provide suggestions for further work, based on the findings of this research.

1.5 Research questions

Based on the objectives and scope of this thesis, the following research questions are to be addressed:

- Do the results of the literature review confirm the Taguchi method as an appropriate approach for ensuring robust operations?
- Do the Lean principles offer a suitable methodology to reduce the land take of termini and energy use during operations?
- Is it possible to develop a novel approach that combines the Taguchi and Lean techniques for ensuring operational robustness, while reducing land take of termini and energy use?
- Is it possible to assess the robustness of terminus designs with different infrastructure and operations options by means of a terminus simulator for use with the Taguchi approach? What is the most important influencing factor for the robustness of a terminus design?
- Can Lean principles be applied to high-speed railway service planning in order to create an efficient operational concept in terms of resource usage, thanks to a reduction in non-value adding activities, e.g., by minimising the turnaround times at termini?
- Can excess platform provision be identified through a Value Stream Mapping (VSM) analysis?
- Can the Just In Time (JIT) concept be applied to the timetabling task to reduce the duration of the non-value adding steps?
- Can the Single Minute Exchange of Die (SMED) concept be applied to realise faster turnarounds at termini?
- Can we develop a case study, which shows the benefits of the approach in terms of the possible reduction in the number of platforms in the termini and the operational energy saving?

- Can suitable case studies of current British turnaround times, current Japanese turnaround times and planned HS2 turnaround be found that show the possibility of a reduction in the proposed number of platforms at Euston HS2 Station, the main terminus of HS2 in London?

It is expected that answering the research questions will lead to a number of contributions to knowledge and railway operations practice that will be summarised in the conclusions.

1.6 Outline of the thesis

The thesis is structured as follows:

- Chapter 1: Introduction;
- Chapter 2: Literature review;
- Chapter 3: Methodology;
- Chapter 4: Robustness assessment by the Taguchi method;
- Chapter 5:Cost reduction through operations and systems design based on the Lean principles;
- Chapter 6: Conclusions and further work.

The background, research hypothesis, aim and objectives of this thesis have been presented in the current chapter. A literature review covering high-speed railways, railway operational planning, the systems engineering approach, the Lean principles and the Taguchi method follows in Chapter 2. In Chapter 3, I develop a general framework for the methodology which tests the research hypothesis. The structure and scope of the application of the approach is presented, focusing on how to manage a trade-off between cost reduction and robustness of operations. In Chapter 4, the Taguchi method is applied to a robustness assessment of the design of terminus stations and operations. The most important factor(s) for robustness will be identified. This chapter is largely derived from a journal paper (Hasegawa et al., 2016). Based on the results of Chapter 4, the Lean principles are applied in Chapter 5 to develop a design approach that minimises the land take and first cost of high-speed railways and reduces the whole life energy cost of train operations by means of an enhanced system design and better control. The chapter builds on three conference papers (Hasegawa et al., 2014a, 2014b, 2015a) and one journal paper (Hasegawa et al., 2015b). A summary of the findings and conclusions is presented in Chapter 6, where further work is also proposed.

2 Literature review

In this chapter, I present a review of some of the literature on high-speed railways focussing on the issues of the great capital cost and the very high expectations placed on their performance in terms of journey times, energy efficiency and robust operations. I then discuss the nature of railway operational planning, from a systems engineering point of view, to identify its potential to contribute to addressing the issues and to satisfying the expectations. I introduce two methodologies aimed at reducing capital cost and operational energy use, while ensuring robustness, namely, the Lean principles and the Taguchi method, which both originated in the manufacturing industry. I discuss their applicability to railway operations and I suggest an approach that combines the two methodologies.

2.1 Definition and classification of high-speed railways

The first purpose designed high-speed railway, the Japanese Shinkansen, started operation in 1964, with a maximum speed of 210 km/h. Since then, the maximum speed of operation of high-speed railways has increased continuously (Figure 1) and they have established a strong presence as a major contributor to satisfying specific transportation needs.

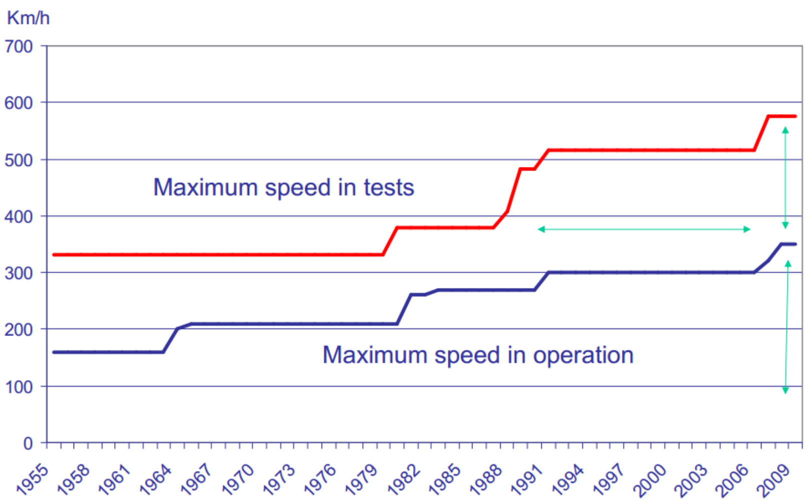

Figure 1 Maximum speed of high-speed railways in tests and operation (UIC, 2009)

The UIC has defined high-speed rolling stock as trains capable of travelling at a speed of at least 250 km/h on new high-speed lines or at a speed of the order of 200 km/h on upgraded conventional lines (UIC, 1996). According to this definition, high-speed railways are already in operation in 15 countries and a further 19 countries have plans to construct or are constructing high-speed railways for important travel corridors that connect major cities (UIC

High Speed Department, 2013). Most of these operations are located in Europe and East Asia, as shown in Figure 2.

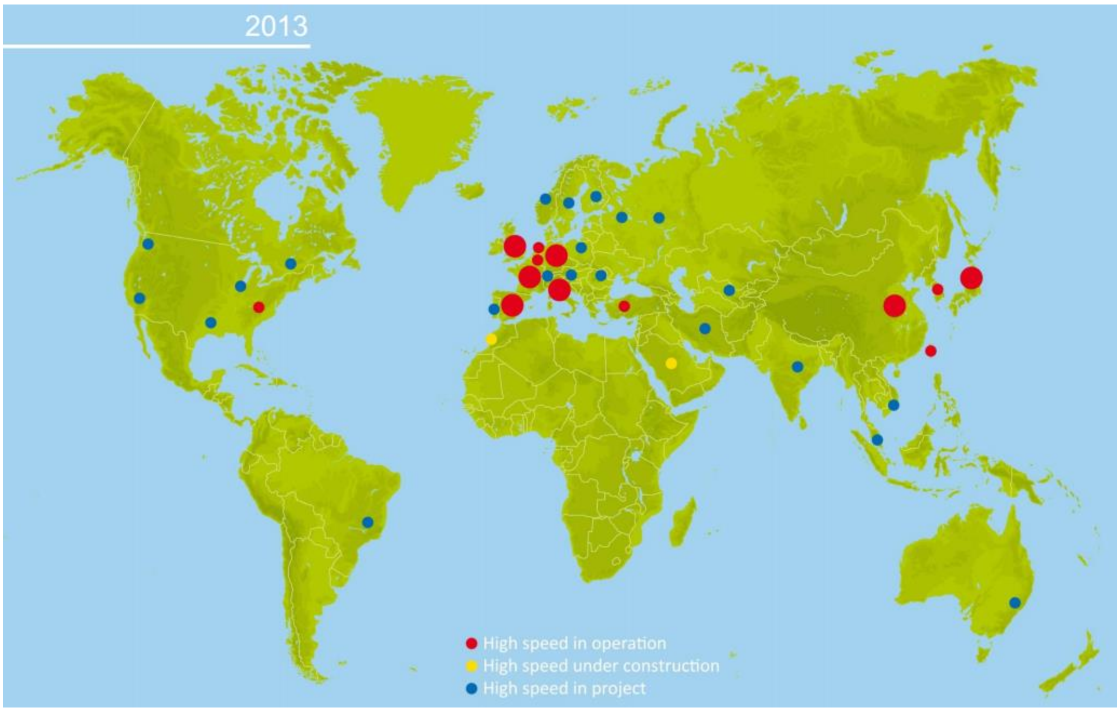

Figure 2 High-speed railways around the world (UIC, 2013a)

Campos et al. classify high-speed railway operations into four types according to their relationship with conventional rail: exclusive exploitation, mixed high-speed, mixed conventional, and fully mixed, as shown in Figure 3 (Campos and de Rus, 2009).

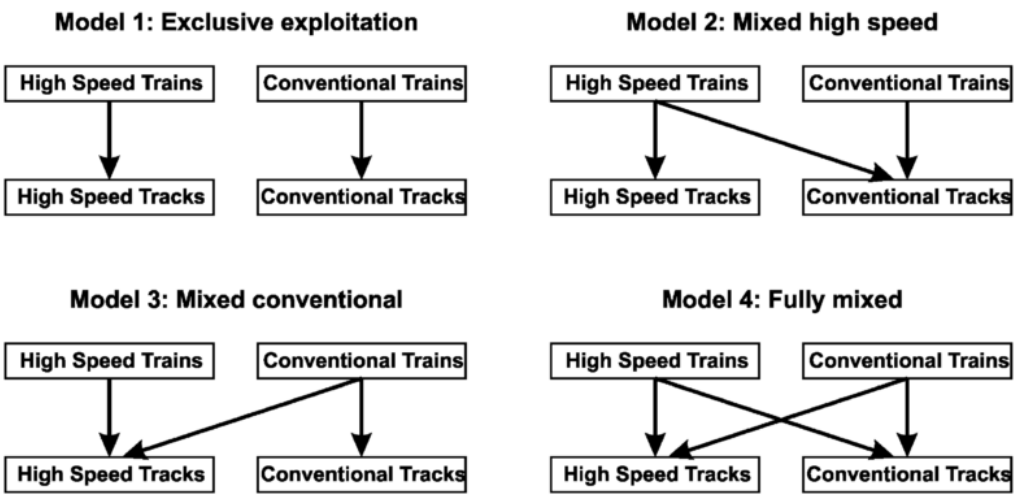

Figure 3 High-speed railway models classified by their relationship with conventional rail (Campos and de Rus, 2009)

Each model has advantages and drawbacks that can be addressed during the design process. As shown in Table 1, there are examples for each model, often the result of a particular historic evolution, e.g., the decision in 1960 to adopt standard gauge (1435 mm) for the Shinkansen lines in Japan.

Table 1 Examples of high-speed railway models (Campos and de Rus, 2009)

Type	*Example*	*Comment*
Model 1	Japanese Shinkansen	Best in high-speed operation. Initial cost is highest.
Model 2	French TGV	Good in high-speed operation. Initial cost is higher.
Model 3	Spanish AVE, TALGO	Lower initial cost where gauge convertible trains and conventional lines are used.
Model 4	German ICE, Italian high-speed rail (Rome - Florence)	Freight trains can use the high-speed line at night.

These models are based on an operational view of high-speed railway services. In the case of Model 2, high-speed trains are designed to run on both high-speed and conventional tracks, but conventional trains cannot enter the high-speed line. This allows the joint use of alignments in sensitive areas, such as city centres. Models 1 and 2 allow a larger number of high-speed services because they do not allow conventional (slow) trains to enter the high-speed tracks. If there is just one slow train on the high-speed tracks, as can be the case for Model 3, the maximum number of high-speed services that can use the line will be reduced significantly (Figure 4).

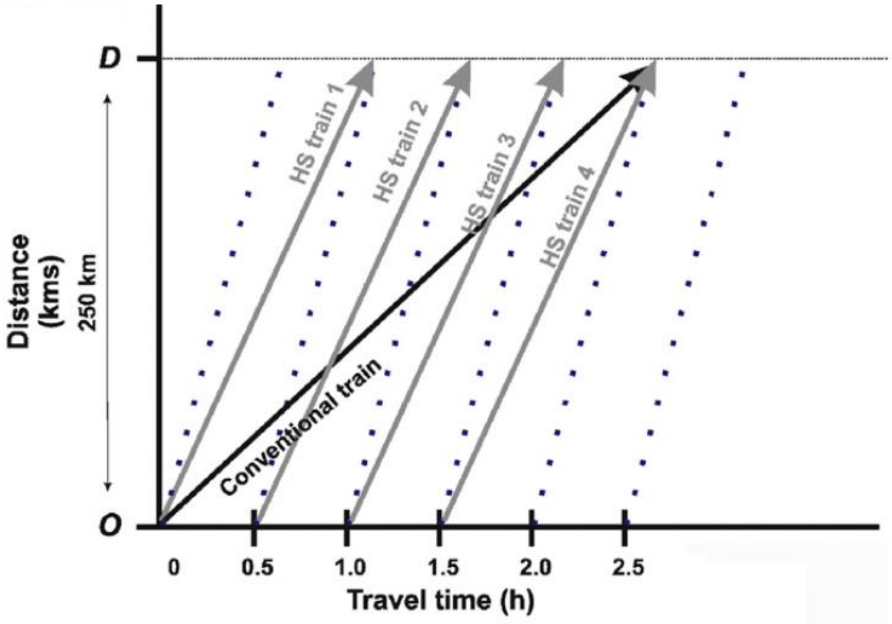

Figure 4 Effect of one slow conventional train (Campos and de Rus, 2009)

However, this use of capacity may be acceptable where paths (a measure of railway capacity) would otherwise not be used at all.

Givoni divided high-speed railways into four types: the Japanese Shinkansen, the TGV, the tilting HST (High-Speed Train), and the MAGLEV (Magnetic Levitation) HST (Givoni, 2006). His classification is based on compatibility, operational speed, and construction cost (Figure 5). The Shinkansen corresponds to Model 1 in the classification by Campos, whereas the TGV, the AVE, and the ICE would all be classified as the same type of high-speed railway by Givoni. The tilting HST can run at elevated speeds on conventional lines due to the tilting function, which allows higher speeds on curves without reducing passenger comfort. The cost of the tilting HST system is therefore lower than that of the other types because it requires no construction costs for new lines. However, tilting HSTs, when adopting operational Model 2, use up more paths on conventional lines, if they are to run unimpeded, as can be deduced similarly from Figure 4. MAGLEV trains use completely different technology from other types of train; its compatibility is therefore low and the initial cost is higher. China has been operating MAGLEV trains in Shanghai at maximum speeds of 430 km/h since 2003 (Yan, 2009). In Japan, Central Japan Railway Company (CJR) plans to start operating SCMAGLEV (super-conducting MAGLEV) trains from Tokyo to Nagoya in 2027 and expects to extend the line to Osaka by 2045 (Fujii, 2010). There is a trade-off relationship between compatibility and construction cost that is based on the premise that railways already exist in a particular corridor or country.

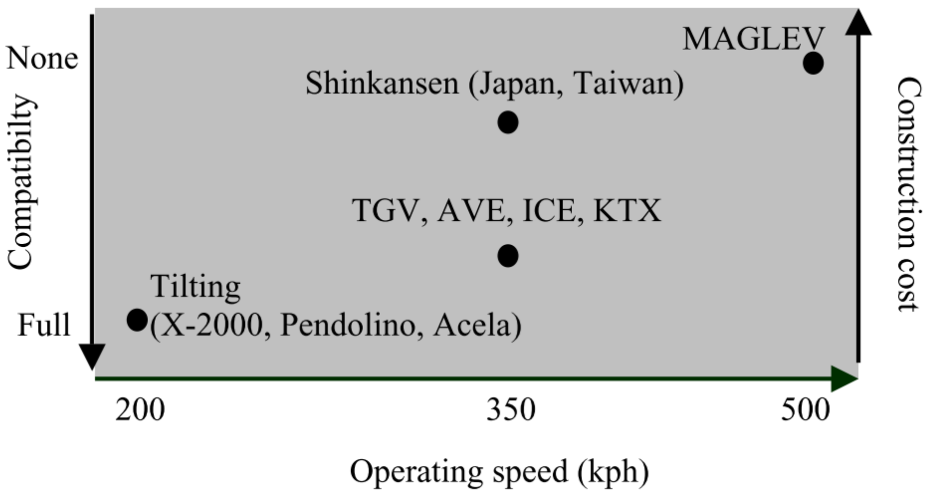

Figure 5 Classification of high-speed railways by compatibility, speed and construction cost (Givoni, 2006)

2.2 Cost and benefit of high-speed railways

The capital cost of high-speed railways is very high, such that most high-speed railway operations in the world are not able to cover their capital cost out of the achievable revenue. According to an ex-post analysis of high-speed railways, there are some exceptions, notably, the Tokaido Shinkansen (Tokyo to Osaka), the Sanyo Shinkansen (Osaka to Hakata) (Kurosaki, 2013) and the TGV Sud Est (Paris to Lyon) (Crozet, 2013). Preston also identified a Chinese high-speed railway line between Jinan and Qingdao that could be financially viable (Preston, 2013).

Construction costs of high-speed railways in different countries, taken from (Nash, 2015) and provided in million Euros per route kilometre, are shown in Table 2. It must be noted that all these figures are greatly affected by the alignment and the resulting line profiles, i.e., the proportion of tunnels and viaducts, gradients and curve radii, and when the lines were constructed. For comparison, the cost of building HS1 in Great Britain, from Folkestone to London St. Pancras was 53.6 million GBP route kilometre (Kable, n.d.), since it was built through one of Britain’s most densely populated areas. Based on the figures in Table 2, Nash argues that high-speed railways with their high first cost can only be justified by large traffic demand and suggests that, solely, linking individual very large cities or chains of large cities can generate enough traffic volume.

Table 2 Construction costs of high-speed rail at 2005 prices (Nash, 2015)

Country	*Million euros per route km*
China	5.7-18.8
Belgium	16.1
France	4.7-18.8
Germany	15-28.8
Italy	25.5
Japan	20-30.9
Korea	34.2
Spain	7.8-20
Taiwan	39.5

Nash also investigated whether there are situations where the benefits exceed the costs and reviewed some of the literature covering French and Spanish studies. He found that, in addition to the examples achieving direct financial success mentioned above, six French LGV lines, including Atlantique, Nord, interconnexion Est, Rhône Alpes and Méditerranée, can be regarded as acceptable if the benefits include socio-economic aspects such as time savings, generated traffic, cost saved on other modes and external cost saved. On the other hand, the total benefits of two Spanish high-speed railway lines, Madrid-Seville and Madrid-Barcelona, are considerably less than their total costs (Nash, 2015).

Due to the concern about their high capital, new high-speed railway projects cannot be approved without political difficulty in the UK and the USA (Preston, 2013). In this situation, reducing cost is important when planning new high-speed railways and renewing existing high-speed lines that are becoming life expired. Within the capital cost, the length of tunnels and new stations are identified as significant (Steer Davies Gleave, 2004). For example, the cost of construction of the stations at Euston, Old Oak Common, Birmingham Interchange and Curzon Street was estimated as 1,675 million GBP against the total construction cost of Phase 1 of HS2 of 6,665 million GBP (HS2 Ltd, 2012a). These factors must be addressed to reduce the capital cost.

While the cost is estimated frequently and can be determined reasonably precisely, the socio-economic benefits of high-speed railways are more difficult to assess because they are subject to the accuracy of ridership forecasts and systems reliability (Chen, 2015). Before starting operations, it is hard to predict the reliability of very complex transportation system, although planners make great efforts to ensure the robustness of operations by means of good design. Ridership is affected not only by demand that is subject to external factors, such as population and economic growth, but also by service reliability. Shrinking the size of stations by reducing the number of platforms can be a good option for decreasing both construction and operations cost. This approach will be investigated in Chapter 5. However, such a reduction may well have a negative impact on the robustness of operations if it is not implemented carefully, an aspect that will be studied in Chapter 4. The ability of high-speed railways to contribute to a region's development is greatly affected by the choice of location for stations (Vickerman, 2015). The very significant land take and technical requirements for large prestige stations limits the potential of high-speed rail because it is difficult to build such stations in congested and highly developed city centres. Raghuram and Udayakumar list options for high-speed railway station construction around city (Raghuram and Udayakumar, 2016). Table 3 is summary of their ideas.

Table 3 Cost of land take and construction and benefit from network for high-speed railway stations

	Cost	*Benefit from HSR Network*
Existing station in city centre	Very High	Best
Existing station at peripheral location	Lowest	Good
New station at peripheral location	High	Worst

If the cost of construction and the land take of station is within an affordable budget and can fulfil the requirements of systems reliability, stations should be built in city centres, ideally co-located with an existing station, to offer convenient access for people who live or work there and passengers from other railway lines and other modes of transport, i.e., bus, tram and underground. This could help to gain higher revenue in comparison with the other cases. Furthermore, locating high-speed rail facilities near existing stations can avoid the problems that arise when building a new railway line into an existing city centre by using an existing route for the last few kilometres of high-speed lines, e.g., the use of conventional lines by the TGVs travelling into Paris from the end-points of the LGVs. However, this option is still expensive and it becomes very costly as the new or expanded station becomes larger. If it is required to reduce cost while keeping certain levels of connectivity of the network, an existing station in peripheral locations is worth considering. Other options are to build new stations in peripheral locations. Needless to say, the cost is likely to be high and benefit from building the network tends to be lower. Thus, capital cost, economic benefit and reliability of service are inter-related. Sophisticated ways of planning to reduce cost without damaging attractiveness and robustness of services are required for new high-speed lines and the replacement of existing ones.

2.3 Robustness of high-speed railway operations

As mentioned above, the reliability and punctuality of the services and, thus, the robustness of the operation of the railway, are important for transport systems and networks. Passengers choose the mode and buy their tickets basing their decision on the timetabled arrival time at their destination as well as the journey's duration, amongst other factors. For example, the former Chief Executive of HS1 Ltd, Nicola Shaw, stated that improvements in the punctuality of HS1 directly increased the number of passengers *(Railway Gazette TV, 2015)*. Trains must thus be operated in a punctual manner and high-speed railways generally perform well in this respect. Table 4 shows a comparison between the punctuality of the airlines and that of the Eurostar high-speed rail service, for the London to Paris and London to Brussels corridors in 2014, where the competing airlines included Air France, British Airways, City Jet and EasyJet for London to Paris and British Airways, Brussels Airlines and EasyJet for London to Brussels. Average delay data for the Eurostar is not available; however, the indicator of arrivals within 15 minutes of schedule is available for both the airlines and the Eurostar service. Eurostar has a better performance in terms of punctuality.

Table 4 Comparison of the punctuality of airlines and Eurostar for the London to Paris and London to Brussels corridors in 2014 (Eurostar, 2014; Flightontime.info, 2015a, 2015b)

	Average delay (mins)	*Arrivals within 15 mins (%)*
Aeroplanes (London – Paris)	10.77	78.82
Aeroplanes (London – Brussels)	11.25	77.55
Eurostar	Not available	92.2

There are several definitions of the robustness of railway systems, from an operational perspective. A general definition states that robustness is “the ability of a railway system to withstand unexpected variations within its operating environment” (Lu et al., 2013); in more detail, it is described as “the characteristic of a railway infrastructure and timetable combination that reduces the overall delays when real process times deviate slightly from the design values, due to changing passenger loads, different driving styles of each driver and varying weather conditions” (Goverde and Hansen, 2013). Both these definitions are very restrictive as they focus on small variations from the timetable only, that is, they do not consider infrastructure failure or rolling stock failure. For the purposes of the research leading to this thesis I have subdivided the aspects contributing to the robustness of terminus operations as follows; the infrastructure consisting of platforms, switches and crossings (S&C), and signalling facilities, and the timetable consisting of turnaround time and buffer time. I have not considered the role of rolling stock in supporting robust operations (Figure 6).

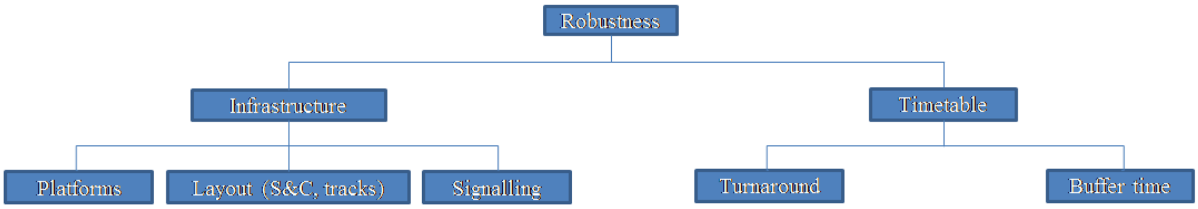

Figure 6 Robustness diagram relating to termini in the railway operations context

From the position of reducing cost, the capabilities of the infrastructure should be designed to fulfil the requirements that arise from the timetable and the growth anticipated in the short to medium term. However, any combination of infrastructure and timetable ceases to be robust once capacity has been consumed to cope with growing demand because there is no longer any buffer for dealing with even small disturbances. In terms of operational planning, the UIC provides recommendations for the percentage of capacity usage by normal operations against a maximum capacity, is fixed by the capability of the infrastructure and trains, which maintains timetable stability (Table 5). The design capacity required in the medium term can be established using this UIC methodology. Additional capacity can later be provided by upgrading infrastructure and trains, meaning that the upper limit for operational capacity consumption can be increased. Therefore, wherever possible, space should be reserved for long term expansion. However, the provision of additional physical facilities and reservation of land for future expansion increase the cost of construction and maintenance. There is thus a trade-off between capacity, robustness of services and the cost of high-speed railway systems.

Table 5 Recommendation for the operational capacity consumption percentage against maximum capacity of infrastructure and vehicle combinations (UIC, 2004)

Type of line	*Peak hour*	*Daily period*
Dedicated suburban passenger traffic	85%	70%
Dedicated high-speed line	75%	60%
Mixed-traffic lines	75%	60%

For a broader view, the most important subsystems of a typical electric railway system, as well as their interfaces and interactions, are shown in Figure 7. The abbreviations have the following meaning: ATP = Automatic Train Protection Interface, VCS = Vehicle Control System and CIS = Customer Information System.

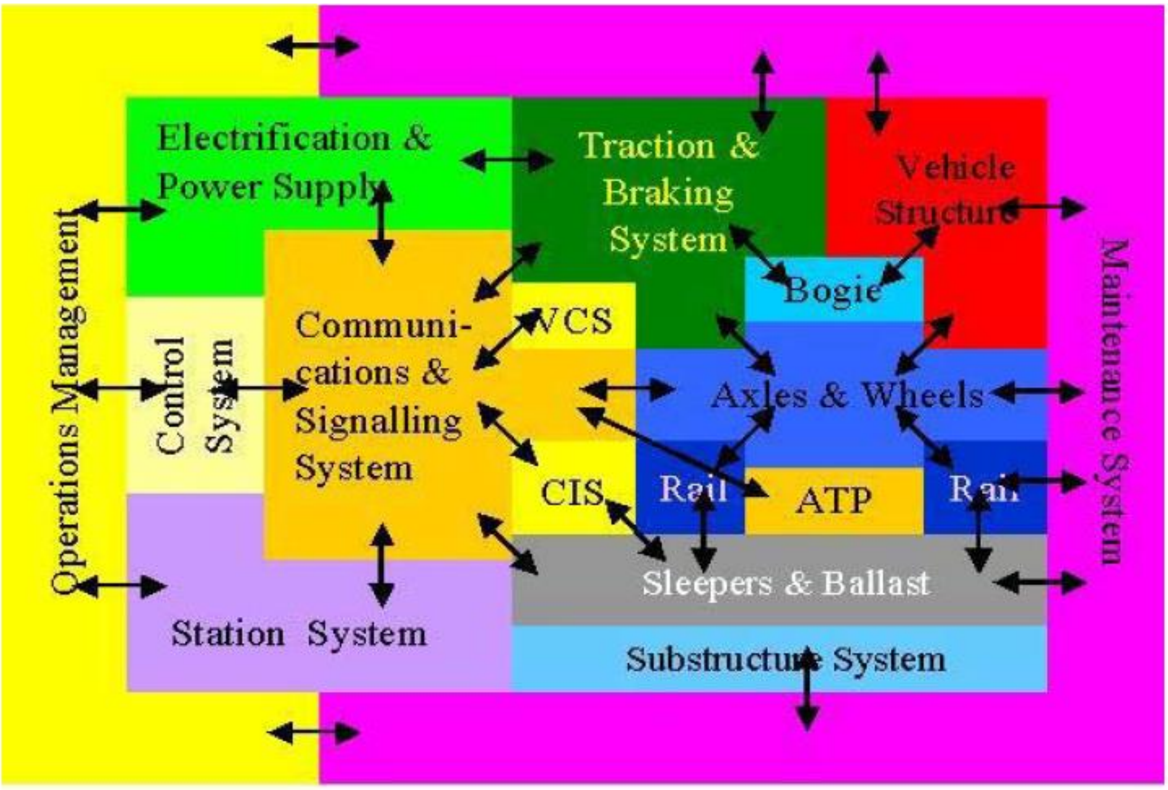

Figure 7 Electric railway subsystems and interfaces systems (Schmid and Goodman, 2009)

As evident from this figure, there are many components and interfaces in electric railway systems and, in order to offer a robust service, every single component has to work correctly and reliably and all interfaces and interactions between the subsystems must be managed strictly to work as a system. This is shown as the operations management function in Figure 7. As introduced above, the operational robustness depends on the ratio of used capacity to available capacity, which is defined by the capabilities of the infrastructure and the rolling stock, e.g., its braking performance. If one of the subsystems fails, for example, one of two tracks cannot be used due to a broken rail, the physical capacity of the railway line is clearly diminished. In this situation, the planned operations would exceed the allowable limit of use of the available capacity and the operations would be disrupted severely. In order to avoid such situations, regular inspections and schedule based maintenance have conventionally been implemented for both rolling stock and infrastructure. This is the maintenance system that is also included in Figure 7. To improve safety and reliability, while reducing cost, condition based maintenance has recently been adopted by a number of railway undertakings. Papaelias et al. developed an online monitoring system for rolling stock wheelsets that uses an acoustic emission sensor for axle bearings (Papaelias et al., 2014). Asada et al. developed an approach for detecting faults in point machines through analysing the data relating to active power that was collected from electric current and voltage sensors in AC point machines (Asada et al., 2013) and DC point machines (Asada and Roberts, 2013). These monitoring systems and methods can find faults that occur between two consecutive maintenance activities, resulting in safety and reliability improvements thanks to early intervention. Conversely, if the monitoring system shows that the condition of facilities is fine, the frequency of maintenance can be reduced safely and, thus, the cost of maintenance is reduced.

If rolling stock and infrastructure are working reliably and at high levels of availability, thanks to appropriate maintenance systems, robustness becomes a matter of operational management. Operations management has several phases from planning, i.e., timetabling and rostering, to everyday activities such as setting routes, driving trains, looking after passengers and controlling people flows in stations. For robust operations, every operational process must work precisely reliably, as must all components of the infrastructure and rolling stock. Umiliacchi et al. have developed an algorithm for the optimisation of the cruising speed of trains on a single track railway line in order to reduce delays and energy consumption, when a single delay occurs (Umiliacchi et al., 2016). The ON-TIME project has developed a framework for the automatic real-time management of traffic perturbation on railway networks and includes case studies from the networks of the UK, the Netherlands and Sweden (Quaglietta et al., 2016).

In this section, a brief review of maintenance and operations management for robustness has been presented. Higher levels of operational planning are studied later.

2.4 Environmental sustainability of high-speed railways

The environmental performance of high-speed railways is another decision aspect that should be considered. Promoters of high-speed railways tend to stress for their low energy consumption and emissions and promote them as a sustainable mode of transport. Sustainability is a widely used term but it is understood in different ways by each person. The most generally accepted definition of sustainability at the time of the appearance of the term was as part of the concept of sustainable development, which Brundtland (Brundtland, 1987) defined as: ”sustainable development is development that meets the need of the present without comprising the ability of future generations to meet their own needs.”. Although her report covers a wide range of issues in the area of development, her most important recommendation is ‘to integrate economic and ecological considerations in decision making’.

This claim set the direction of successive activities in the domain of sustainability. Adams has reviewed the development of the idea of sustainability over a period of more than 30 years, from 1969 to 2006, and points out that there are three dimensions of sustainability, namely, environmental, social and economic sustainability (Adams, 2006). He also notes that the 'greening' of business, that is, considering the environment as part of every business activity, has become a central issue of corporate social responsibility for many companies. However, the environmental aspect of decision making is often made subordinate to financial and political criteria. Cato suggests a different view of economic activity from the conventional one, which ensures that the issue of sustainability is taken more seriously (Cato, 2009). She explains the concept of sustainability by drawing a model with three circles (Figure 8), where the left hand side is based on the conventional view with three circles that are of the same size. The right hand side is based on Cato's perspective, where she suggests that the economy operates within society and society is embedded within the environment. She states that "the economy, society and environment interact but are not interdependent".

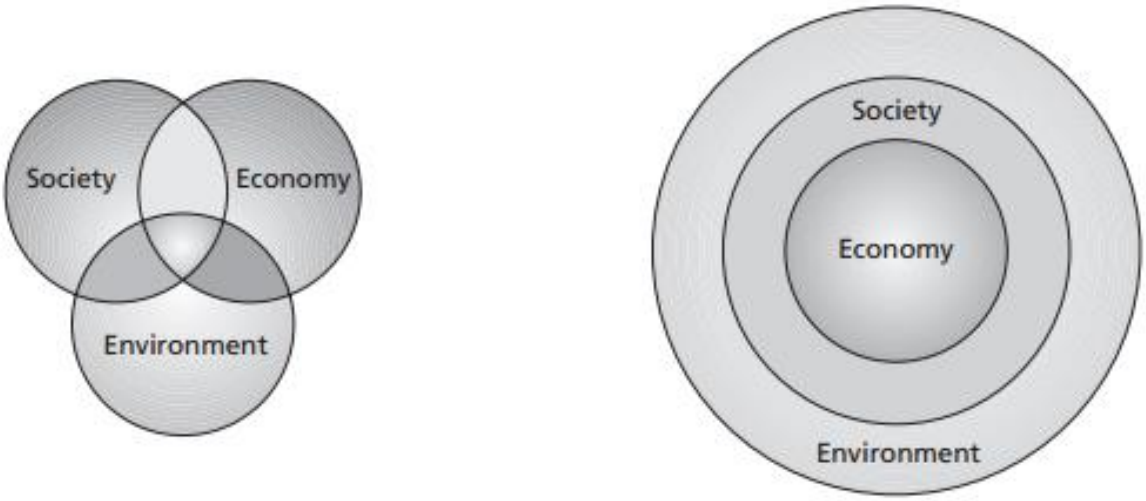

Figure 8 Three circles models of sustainability (Cato, 2009)

As discussed in Section 2.2, many existing high-speed railways are not sustainable in terms of social and economic aspects. However, concerns about climate change have been rising and, thus, the importance of environmental sustainability has becomes greater. The Kyoto Protocol was adopted in Kyoto in 1997 and amended in Doha in 2012. Under this protocol, a targets for the reduction of emissions of Green House Gasses (GHG) was set for each country and these are being monitored (United Nations, n.d.). In the UK, The Climate Change Act 2008 fixes the target of a 33% reduction in greenhouse gas emissions compared to 1990 levels, to be achieved by 2020, and an 80% reduction, to be reached by 2050 (Department of

Energy and Climate Change, 2011). Railways must contribute to achieving these targets. Therefore, Network Rail developed a sustainable development strategy for the period 2013 to 2024 and declared their intention to realise energy efficiency and a low carbon procurement strategy: this involves moving to a low carbon supply of energy, maintaining their assets to reduce losses during transmission and distribution, and investing in more energy efficient equipment (Network Rail, 2013a).

Given this context, it is expected that high-speed railways will have to play a crucial role in transport in future because they are generally regarded as the most environment friendly mode of transport in the fast inter-city passenger transportation market (Smith, 2003; Clewlow, 2012), subject to high levels of occupancy, of course. For example, the energy efficiency of high-speed rail compares favourably with that of short haul flights, where these two modes of transport are competitors, e.g., for major origin-destination pairs such as London to Paris, Barcelona to Madrid and Tokyo to Osaka. Essen et al. calculated the energy consumption per seat kilometre of high-speed rail and air transportation based on data in Europe in 2000 (Essen et al., 2003). From this source, the energy efficiency for each transport mode for a 500 km journey is shown in Table 6. This table shows that high-speed rail consumes a third of the energy per seat-km used by short haul aircraft.

Table 6 Energy consumption of transportation modes in Europe in 2000 (Essen et al., 2003)

Transport Mode	Energy consumption (MJ/seat km)
High-speed railway	0.53
Aircraft (500 km flight)	1.80

A comparison of the energy efficiency and emissions of air transport with those of the high-speed Tokaido Shinkansen, which is run by Central Japan Railway Company, are set out in Figure 9, where (*1) is based on the performance of the series N700 Shinkansen train and (*2) stems from the 2011 annual report of All Nippon Airways (Central Japan Railway Company, 2014). Operating at 270 km/h, the Tokaido Shinkansen trains consume one eighth of the energy used by aircraft and cause one twelfth of the carbon dioxide emissions of aircraft, based on the primary fuel mix of Japan.

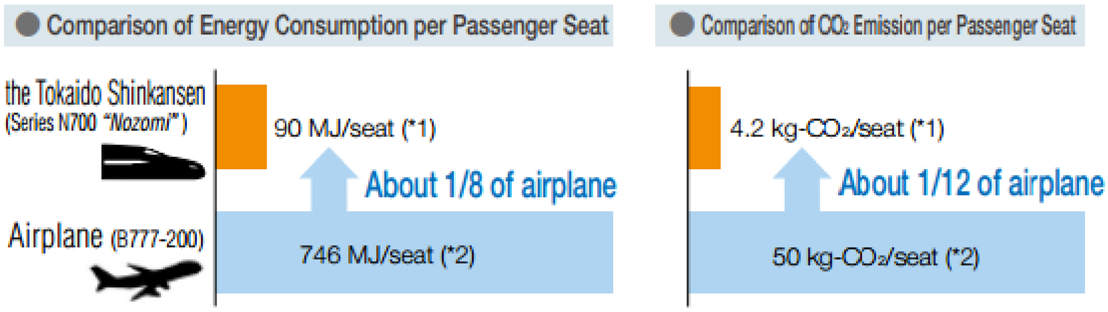

Figure 9 Comparison of the environmental performance of a Japanese high-speed railway and air travel for the corridor between Tokyo and Osaka (Central Japan Railway Company, 2014)

The UIC also comments on the high energy efficiency and low emissions of high-speed railways in comparison with other modes of transport, such as cars and aeroplanes (Table 7). The energy performance of high-speed railways is eight and half times better than that of aircraft and their emissions are just 25% of those of aircraft.

Table 7 Comparison of the environmental performance of high-speed railways and other modes of transport in terms of energy efficiency and emissions (UIC, 2012)

Mode of transport	*Energy efficiency (pkm carried per 1 kWh)*	*CO_2 Emissions (kg CO_2 emissions per 100 pkm)*
High speed railway	170	4
Car	39	14
Aeroplane	20	17

As discussed above, high-speed railways can be said to be an environmentally friendly mode of transport and are expected to contribute to an overall GHG reduction. However, given that high-speed railways generally connect major cities, the distances covered tend to be long, often in the range of 350 km to 1,000 km, while the customers expect short journey times. Therefore, the maximum speed of operation of high-speed rail continues to increase (Figure 1) and, as a consequence, the energy consumption also grows. At speeds above 200 km/h, the aerodynamic resistance increases with the square of the speed and becomes the major contributor to energy use. Moving to higher speeds on railways for such long distance journeys increases the energy use of the system. Thus, energy efficient operation for high-speed rail should be investigated. Central Japan Railway has invested a great deal of effort in limiting its energy use while increasing the operating speed of its Shinkansen trains, from 210 km/h in 1965 to 270 km/h in 1992. This has been achieved by reducing the mass per seat of the trains and by developing better aerodynamic shapes for the ends and smoother surfaces for the sides, roofs and underneath of new trains, as well as improving pantographs (Ueno et al., 2006).

Which aspect of railway operations consumes which proportion of the total input energy? This question should be answered before thinking about energy efficient operations. Railway systems consist of many subsystems and components, such as vehicles, tracks, signals, stations, depots and so on. Each subsystem and each component consumes energy to permit the operation of trains and to deliver all other activities involved in running a railway. Powell et al. investigated the system-wide energy use of the Tyne and Wear Metro in Newcastle and compared its energy use with that of other railway systems in Britain (Powell et al., 2015). This is a relatively modern light metro with short trains that operate mostly above ground. Their analysis showed that energy use for traction was dominant, with an average of more than 70% of overall energy consumption for all railway systems in the UK (Figure 10).

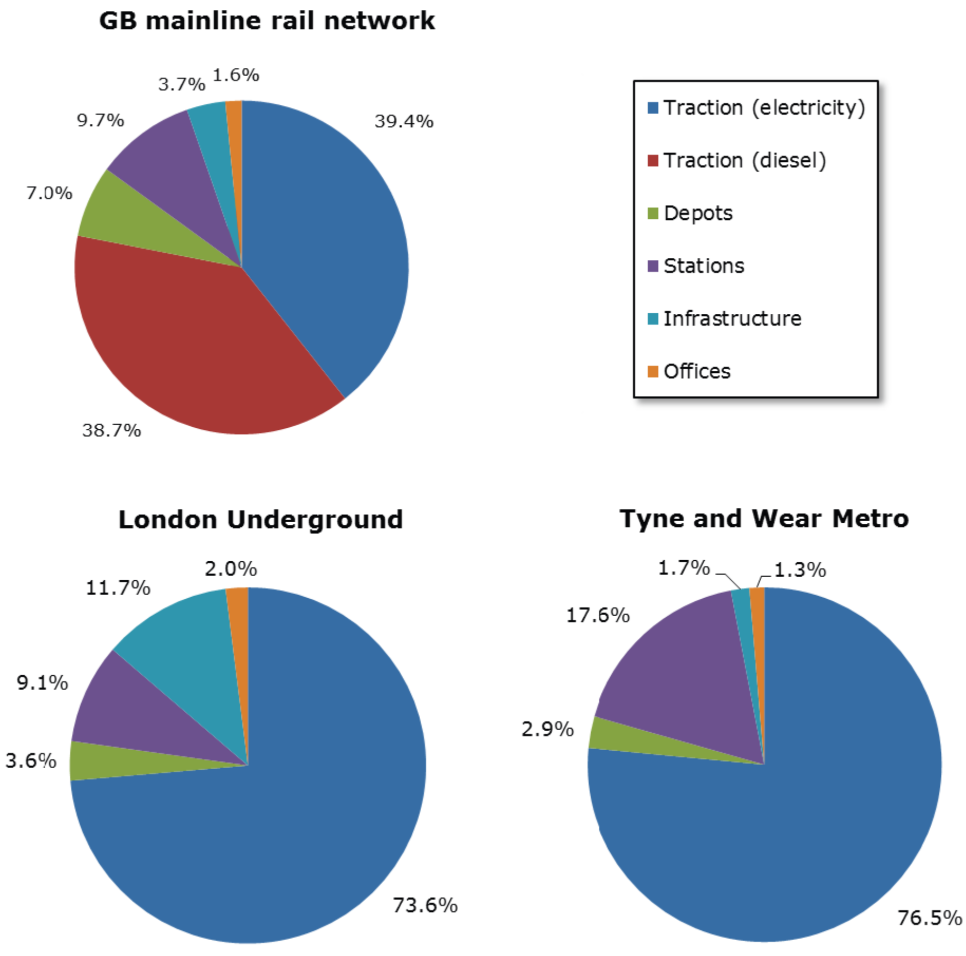

Figure 10 Operational energy use for the GB mainline rail network, London Underground and Tyne and Wear Metro (Powell et al., 2015)

The mainline network has the highest percentage of energy consumption for traction, at 78.1%, using a combination of electricity and diesel. This trend can also be found outside the UK and applies equally to high-speed railways. Roztcki et al. studied the ecological profile of the German high-speed railway route from Hannover to Würzburg, used by the Inter City Express (ICE) (Rozycki et al., 2003). Their work considered the cumulative energy demand (CED) for the lifecycle of the railway system, which includes not only its operation but also its construction. The scope of this study was broader than that of Powell et al. (ibid), however, the contribution of traction energy use is still significant, at 64% (Figure 11).

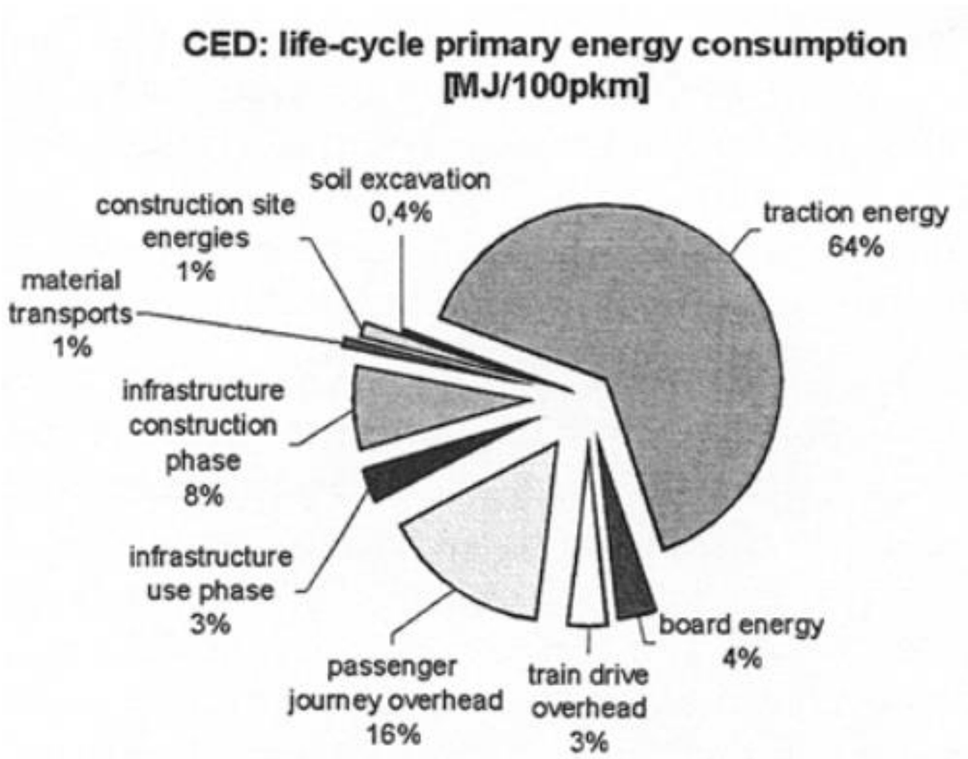

Figure 11 Life-cycle primary energy consumption for the route from Hannover to Würzburg of the German high-speed railway (Rozycki et al., 2003)

As mentioned above, the energy consumption for traction is a major part of the operational energy use of the whole railway system. For high-speed railways, the recent trend to increase the maximum speed of operations could further grow the proportion of total energy consumption used by traction. Recently, many high-speed operations have been introduced where trains run at over 300 km/h and it is planned that the new high-speed railway project in the UK, High Speed Two (HS2), will operate at 330 km/h from 2026 on the route from London to Birmingham (Department for Transport, 2013b). Thus, the energy consumption of high-speed railways is likely to increase above that of conventional railways. Even if the total energy consumption of a corridor can be reduced by replacing aeroplanes with high-speed trains (Givoni and Banister, 2006), it is still worthwhile to consider the energy efficiency of rail, because increasing concerns about environmental and economic issues require more energy efficient operation of all modes, particularly if they are predicted to grow. There is extensive literature focused on the energy efficiency of high-speed railway operations and planning. Hwang presented an approach to optimise the trajectory of a single high-speed train to save energy consumption by utilising a fuzzy model and genetic algorithms (Hwang, 1998). Cucala et al. proposed a joint design approach for realising energy efficient timetables, which combines an energy efficient driving strategy, obtained by simulation and genetic algorithms, with the design of timetables using a fuzzy linear programming model. They conducted a case study for a Spanish high-speed railway line and showed a significant potential for energy saving (Cucala et al., 2012). The energy efficient driving approach was further developed to allow real time recalculation to deal with significant delays (Sicre et al., 2014). Dong et al. highlighted the need for the development of various control algorithms for an automatic train control system (ATO) through a comprehensive review of the development of ATO systems and simulation for high-speed railways in order to reduce energy usage (Dong et al., 2010).

Before conducting detailed research into energy efficiency, a precise understanding of the relationship between energy consumption and the maximum speed of operation of a train service is needed. Previous investigations into this relationship have been conducted as part of the evaluation of performance of transportation modes (Kemp, 1993, 2004; Garcia, 2010), for the planning of specific projects (Watson et al., 2009; Jernbaneverket, 2011; SYSTRA, 2011a) and optimising operations (Feng, 2011; Feng et al., 2012, 2014). Each study was conducted in a different context and, therefore, they are not based on similar conditions and show very different results. In this situation, to understand the relationship between maximum speed and energy consumption correctly, a clear methodological standard for undertaking the analysis is needed. I have developed such a methodology for this type of analysis (Hasegawa et al., 2015b), which I will apply in Section 5.1.5.

For a fuller understanding of the performance of high-speed rail systems, the issue of embedded energy and emissions should also be considered. Other than in the course of operations, energy is consumed and carbon dioxide is emitted during the construction and maintenance phases. When compared with the number of studies addressing operational energy consumption and emissions, embedded energy is not well studied and the understanding of these elements of total energy consumption is still limited (RSSB, 2011).

Chester and Horvath claimed that life-cycle assessments (LCA) of raw materials extraction, manufacturing, construction, operation, maintenance and abandonment of vehicles and infrastructure should be considered by decision-making bodies (Chester and Horvath, 2009). In their paper, they show that operational energy consumption accounts for 24% to 39% of the total energy inputs for railway systems (Figure 12). This figure shows a distribution of energy use that is significantly different from that in Figure 11, especially in terms of infrastructure. Chester and Horvath included stations, power structures and substations, but Roztcki et al. did not. This created differences in the energy consumption of the infrastructure construction aspect and the infrastructure operations part.

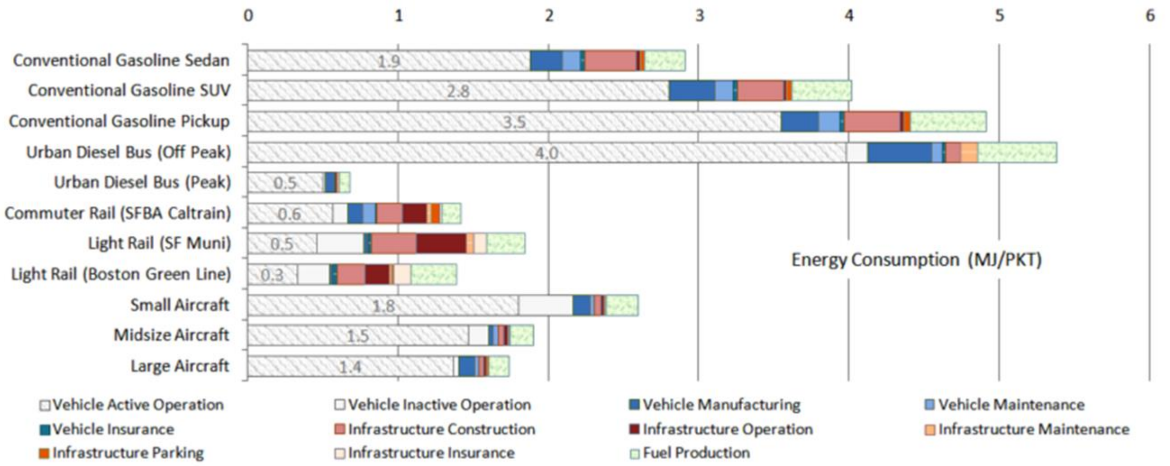

Figure 12 Energy consumption per passenger kilometre transported (PKT), operational energy use components are shown with grey patterns (Chester and Horvath, 2009)

Pritchard investigated the trade-offs between operational energy use and energy embedded in the infrastructure (Pritchard, 2015). He conducted a simulation with three operations scenarios and three different tunnel diameters. A tunnel with a greater diameter creates less aerodynamic drag and, therefore, reduces the operational energy consumption. However, more excavation, earthworks and concrete materials are required to build it, which increases the amount of embedded energy. The optimal diameter thus depends on the operational conditions. As in Pritchard's case study, railway subsystems, such as infrastructure and vehicles, and railway operations cannot be considered separately when assessing whole system energy efficiency.

For the station design, it must be considered that the rolling stock used in high-speed railways is currently between 200 and 400 metres long (UIC, 2013b) and the platforms must be longer than the rolling stock. This directly increases the size of the stations and, thus, the embedded energy and emissions. Correspondingly, the land acquisition and construction costs of high-speed rail termini are very high, often in the hundreds of millions of pounds (HS2 Ltd, 2012a), not least because termini are generally located in the centres of big cities such as London, Paris or Tokyo. In the case of HS2, the cost of the redevelopment of Euston Station alone is expected to be £2.5 billion (Clark, 2017). Therefore, during the construction-planning phase, the question "How many platforms do we need?" must be answered, since this factor determines the width of the footprint of the station. This number must be based on accurate operational planning. Ill-considered planning can further increase the costs and embedded energy and emissions. This aspect will be studied in Chapter 5 because it must be taken into account to ensure that high-speed railways are environmentally sustainable as whole systems.

2.5 Railway operational planning

The objective in designing the infrastructure, rolling stock and operations of new and improved systems is that capital cost, operational cost, operational energy consumption and embedded energy should be reduced whilst maintaining at least the same level of operational robustness as that of existing systems. To achieve this, the operational planning must be conducted carefully. Railway operations are complicated and complex, the former relating to the number and diversity of components and processes and the latter to the unpredictable nature of the environment of the railway and the interactions both within the railway and with other systems (Schmid, 2010). Thus, several independent processes and iterations of activities are involved in operational planning. Vromans et al. (Vromans et al., 2006) show the sequence of the railway planning process (Figure 13). Line planning determines the beginning and end stations of different train services and stopping patterns for intermediate stations that are necessary to satisfy market demand. In the timetabling phase, departure times and arrival times are fixed, taking into account the capability of the infrastructure and the rolling stock, as well as activities like boarding and alighting. These two processes are repeated until the infrastructure and business constraints are met. This iteration process itself is sometimes called timetabling. After the timetabling is completed, rolling stock planning, shunting planning and crew planning are conducted. These activities are often called resource planning (Watson, 2001; Ferreira and Higgins, 1996). Timetables do not contain any information about the use of mobile resources, such as rolling stock and crews. With the resource allocation planning, timetables become feasible plans. Between timetabling and resource planning, there are also several iterations, e.g., timetables are sometimes modified to remove critical constraints and conflicts relating to the resource allocation problem.

Conversely, good timetables in terms of usage of mobile resources can reduce the requirements for rolling stock and crews.

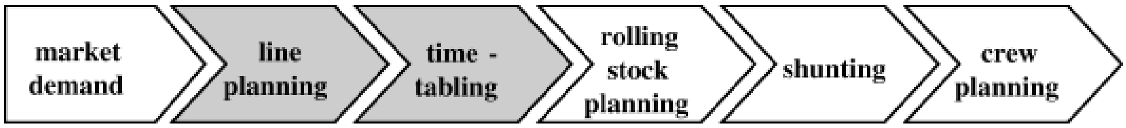

Figure 13 Sequence of railway planning process (Vromans et al., 2006)

For the process described above, infrastructure provision and capability is viewed as being a fixed input. By contrast, Watson (Watson, 2001) categorised the train planning activities of British Rail into three levels in terms of time horizons: strategic, tactical and operational. Strategic planning can consider changes to the infrastructure to allow the enhancement of operations. Tactical planning can consider changes to the allocation of rolling stock and train crews, which is the same as timetabling, scheduling and rostering, mentioned above. Operational planning deals with real time operation, such as perturbations. Strategic planning is conducted based on rough timetables. Harris et al. introduce an example of the Kowloon-Canton railway, which had changed the timetable, the number of trains, the length of the trains and the seat arrangements of the rolling stock from 1983 to 2007, all in order to adapt to the changing market demand (Harris et al., 2007). This example shows that the timetable leads to the specification of rolling stock. Thus, timetabling can be regarded as the centre of operational planning.

2.6 Operational planning with a systems engineering perspective

As described above, operational planning is not only related to the operation itself, but it is also related to the capability of facilities, such as infrastructure and rolling stock. Figure 14 shows the V-model of systems engineering, which is ”an interdisciplinary approach and means to enable the realisation of successful systems” (International Council on Systems Engineering, 2015), or an approach whose ”process involves the use of appropriate technologies and management principles in a synergetic manner” (Blanchard and Fabrycky, 2006b) in order to manage complexity around system development (Stevens et al., 1998a). The V-model shows the life cycle of the development of systems in a systems engineering manner. It is divided into two parts: project definition before implementation and project test and integration after implementation. On the left hand side, the concept of operations delimits the requirements and architecture of the systems and then this is followed by the detailed design activities. On the right hand side, verification and validation is conducted for each step from the bottom to the top, according to the specification developed through the detailed design, requirements and architectures, combined with the concept of operations (Stevens et al., 1998b; Blanchard and Fabrycky, 2006a).

The most important point of this diagram from a railway operations perspective is that the concept of operations of a railway has an important effect on all other activities in the system life cycle because it is at the starting point of the diagram. Thus, a well-considered concept of operations can reduce not only the operational costs but also the first cost. Conversely, it can be said that railway projects become resource greedy with an ill-considered concept of operations. For example, Swiss Federal Railways successfully optimised their timetable and reduced the infrastructure and rolling stock requirements on 6 June 1972, when they introduced their 'Taktfahrplan' or clock-face timetable: optimised arrival times at termini assisted the efficient scheduling of rolling stock and rostering of staff, and the optimised timing of passing trains on single track sections reduced the requirement for double track (Graffagnino, 2013). To ensure the robustness of operations, it is clear that the robustness should be considered at the stage of planning when the concept of operations is being developed.

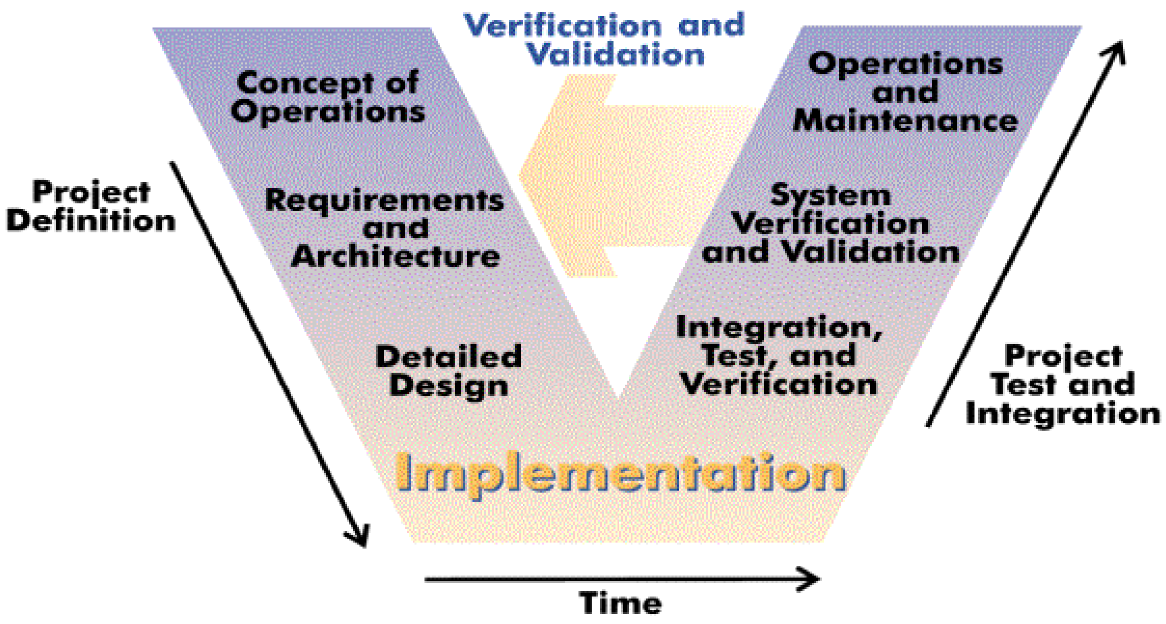

Figure 14 V-model of systems engineering (Federal Highway Administration, 2005)

As discussed so far, in order to achieve the objectives of reducing capital cost, energy consumption and the size of stations, maintaining robustness, the operational planning should be conducted carefully, adopting a systems engineering perspective. Thus, in the following sections, two methodologies from manufacturing industry are introduced, which can be applied to railway operational planning. The first approach is the Lean Principle for reducing cost and waste (Section 2.7) and the second one is the Taguchi method to ensure robustness (Section 2.8).

2.7 Lean principles

Reducing the first cost and the operational cost of production through sophisticated operational concepts is well established in the manufacturing industry. The so-called 'Lean' philosophy has been adopted since the 1960s. The term was introduced following research into the higher production efficiency of the Toyota Motor Corporation, compared with other automobile manufacturing companies (Jones et al., 1990). As a result of further research, the principles of Toyota's production methods were generalised as the Lean principles (Womack and Jones, 1996): these defined the concept of value, allowed the identification and elimination of non-value adding activities and the development of mistake proofing procedures, in a continuing process of improvement. The application of Lean principles to air travel was discussed as an example in a later book by advocates of the method (Womack and Jones, 2006). Suarez-Barraza et al. list a significant amount of literature about the specific applications of lean principles in service industries, such as health, education, banks, airlines and hotels (Suarez-Barraza et al., 2012).

The components of Lean are discussed in the following sections.

2.7.1 Value Stream Mapping (VSM)

As part of the process of continuous improvement which is implemented by adopting the Lean principles, value stream mapping (VSM) can be used to identify value adding (VA) and non-value adding (NVA) activities in the whole production process in its current state (Rother and Shook, 2003). The latter must be eliminated in order to improve the performance of the operation. Figure 15 shows part of the value stream map for the factory production of Matryoshka dolls, where smiling faces mean that the process is value adding, whereas unhappy faces show that the process is non-value adding. This factory creates value for customers who want to buy the dolls. In this value stream, hand painting and assembling are regarded as value-adding steps, because these steps contribute directly to the creation and characteristics of the products. On the other hand, transport from the painting line to the final assembly line and waiting for distribution are regarded as non-value adding steps, because they do not contribute directly to product creation and customer satisfaction. Non-value adding steps create associated waste. In this case, the factory needs to have a warehouse to store the products which are waiting for distribution. Having an unnecessary warehouse requires land and people to manage it. Employing people for a warehouse requires an organisation to manage the people. This negative cycle continues to produce more waste.

Figure 15 Value Stream Mapping and Just In Time concepts with an example from the Matryoshka dolls factory

2.7.2 Just In Time (JIT)

Through the basic value stream mapping analysis conducted above, NVAs and the associated waste were highlighted: waiting times between production processes are regarded as non-value adding steps and these steps always create associated waste. Just In Time (JIT) is an important lean concept for eliminating this waste (Ohno, 1988; Monden, 2011). In the case of the Matryoshka dolls factory (Figure 15), if the distribution of products were to be scheduled to follow immediately after the completion of production, with no delay, the need for storage could be eliminated and then the need for people and an associated management organisation would also be eliminated. This shows that well thought out operations can reduce the initial cost and operating cost of the physical facility.

2.7.3 Single Minute Exchange of Die (SMED)

Single Minute of Exchange of Die (SMED) is a lean concept developed for improving efficiency in manufacturing by reducing the changeover time of machine dies. During the changeover of dies, a press machine has to stop and it cannot manufacture products, which directly decreases the production output of the machine. The inventor of SMED, S. Shingo, analysed the process of the change of dies and developed a method to reduce the setup time significantly (Shingo, 1985). The steps in the method are: 1) observe the whole current setup process, 2) separate the setup steps into internal setup and external setup, and 3) convert internal setup into external setup and optimise the whole setup process. Internal setup requires stopping the machine, while external setup can be done while the machine is in operation. Thus the length of setup time is defined by the duration of the internal setups.

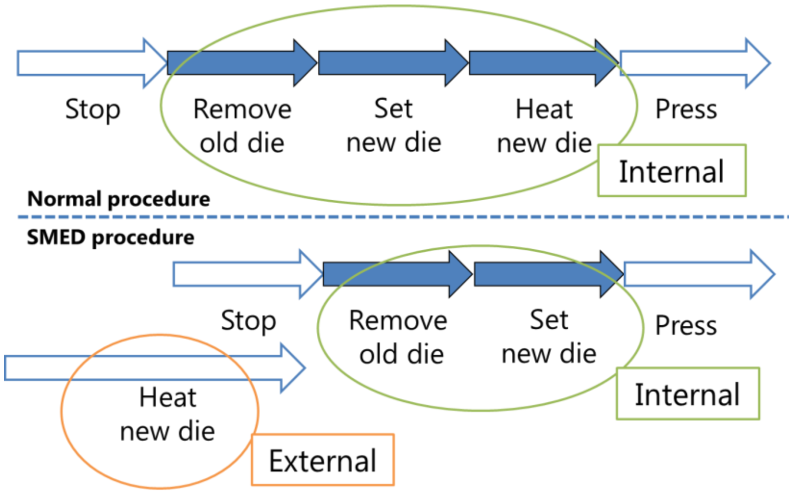

Figure 16 Comparison between the normal procedure and the SMED procedure for changing press machine dies

For example, the non SMED method to change the die of a press machine (upper part of Figure 16) is: stop the machine, remove the old die, set the new die, heat the new die to increase its temperature so that it is hot enough to press the material, and finally restart the machine. In this process the machine is stopped before conducting all setups before restart, so that all three setups are regarded as internal. However, it is not necessary to conduct the heating of a new die while the machine is stopped; this can be done before setting it up. This is a conversion from internal to external setup, leaving only two internal setups in the process (lower side of Figure 16), which results in a reduced setup time and improves the productivity of the production process.

2.7.4 Application of Lean principles to railways in general

In the railway industry, to date, the application of Lean principles has been limited. In the UK, Lean principles have been adopted mainly in manufacturing and in the maintenance area. Garner and Stiles (Garner, 2013; Stiles and Garner, 2015) though investigated the applicability of a Lean approach to the Railway Possession and Isolation Authorisation Process (RPIAP) and developed an adapted version of the Lean methodology that focuses on the differences between the manufacturing and railway industry, the safety and procedures required in railways and the incorporation of the latest information technology. The authors present a leaner and more robust procedure for establishing track possessions with the mock-up of a specialised app for RPIAP that eliminates 6 phone calls between workers and controllers. They suggest the possibility of a reduction of about 30 minutes in the possession taking process. This improvement in each possession could have a large benefit because there are about 93,500 possessions per year on Britain's mainline railway and the total reduction in lost working time would be 2.5 million hours, based on an average involvement of about 50 people in planning, establishing, operating and releasing each possession. The AUTOMAIN project aimed to increase network capacity for freight by reducing track maintenance possessions by adopting Lean principles (Kent et al., 2012). In the USA, the improvement of a freight train classification terminus was studied by adopting Lean principles and more efficient operations with better service reliability were developed (Dirnberger, 2006; Dirnberger and Barkan, 2007).

2.7.5 Application of Lean to railway operations

There are no studies on passenger railway operations in the context of Lean principles, although there are applications in the fields of maintenance and freight, as mentioned in Section 2.7.4. This could be attributed to the characteristics of passenger railway operations, which require a high level of robustness, because delays directly affect passengers and, thus, the culture has to be very conservative. Continuous improvement requires many trials, errors and corrections, which is not an appropriate option for railways, since operations cannot be suspended frequently and the timetables cannot be modified easily. To achieve robustness, railway organisations allow significant amounts of buffer time in the timetable and keep buffer resources within their passenger railway operations, to deal with unforeseen variations from normal service. Improving processes in order to eliminate waste is only one part of lean principles and the implementation is not straightforward. Spear and Bowen point out that only a few manufacturers have successfully implemented the Lean philosophy in their production systems and there is a large gap between Toyota and other companies in terms of workforce development and organisational capability (Spear and Bowen, 1999). Liker discussed his 4P (Philosophy, Process, People and Partners, Problem Solving) model and suggested that most companies fail to adopt Lean in the true sense since they copy only the Process part without understanding the whole system (Liker, 2004).

For these reasons, it seems difficult to adopt Lean principles to railway operations. However, it is still worth considering if the issue of robustness and implementation can be dealt with before adopting Lean principles. Robustness of operations should be addressed first by assessing the important parts of the system with regard to robustness and, then, the operations part of the system can adopt Lean to reduce waste. This will result in applying only a limited selection of the concepts encompassed by Lean in the approach. However, as far as I can ascertain, to date there have been no applications of the complete Lean philosophy to rail operations.

2.8 Robust design

Robustness is an important performance indicator in railway systems. However, there are often conflicts between maintaining robustness and reducing cost. The Taguchi methodology, also known as robust design, was first developed by Genichi Taguchi in the 1950s through the development of a cross-bar switching system for telecommunication (Taguchi et al., 2005a). Since the initial implementation, the Taguchi method has been used in several industries in order to ensure the robustness of production in an economical way (Bendell et al., 1989). A brief introduction to the method and techniques is presented in the following subsections, in comparison with robustness studies for railways.

2.8.1 Definition of robustness in product and process design

In the Taguchi method, the definition of robustness is explained as follows. First, the function of a product or process is defined as its response to a signal factor. By setting control factors appropriately, a 'robust' product or process exhibits a response that is insensitive to noise factors (Figure 17). Products or processes respond to signal factors with control factors employed for dealing with noise factors (Phadke, 1989a).

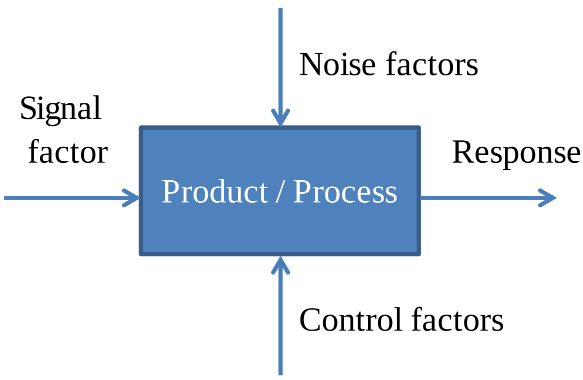

Figure 17 Block diagram used in the Taguchi method

In order to design the product or process in this sense, design and testing activities should be conducted at the same place and time, which is a basic principle of robust design (Taguchi et al., 2005c), although many companies separate these activities.

2.8.2 Quality control activities in different stages

Taguchi also categorised three types of noise factors and four stages of the production process when measures should be taken to cope with noise factors (Table 8). Noise factors are external, internal and unit-to-unit. External noise factors are from outside the product, such as weather conditions. Internal noise factors come from inside the product, such as some subsystems affecting others. Unit-to-unit factors are the variations between instances of each product. Table 8 shows that measures of external noise factors can only be handled during the product design phase and internal noise factors can only be dealt with during the product design and manufacturing process design phases. Thus, these two types of noise factor must be considered off-line, before starting physical operation.

Table 8 Quality counter measures in each production step (Taguchi, 1986; Phadke, 1989a)

	Product realisation step	*Ability to reduce effect of noise factors*		
		External	Internal	Unit-to-unit
Off-line quality control	Product design	Yes	Yes	Yes
	Manufacturing process design	No	Yes	Yes
On-line quality control	Manufacturing	No	No	Yes
	Customer usage	No	No	Yes

2.8.3 Robust design in the railway industry

Table 9 shows a comparison between manufacturing and railway systems. A range of studies into the robustness of timetabling (Cacchiani and Toth, 2012; Yamamura et al., 2014), rostering (Fioole et al., 2006) and operations (Chen, 2012) have been conducted. However, only a small number of studies address the robustness of railway systems at the design level. Landex and Jensen developed a method to analyse the capacity of stations in terms of the need for platform tracks and the complexity of the infrastructure (Landex and Jensen, 2013), which can be used at the system design level. However, their work focused on the improvement of existing systems rather than the creation of new ones. A robustness study for an existing system is basically conducted at the microscopic level and reaches a feasible solution that satisfies many constraints, however, it tends to reach a local optimum for future planning by ignoring options which are difficult to conceive in the context of existing systems.

Fecarotti et al. (Fecarotti et al., 2015) investigated a fault tolerant design for main tracks focusing on huge disruptions due to the failure of facilities such as tracks, signalling and safety systems, power supply systems, switches and crossings, communication systems and civil structure by using Petri nets. The aim of the research was to find an optimal number and position for crossovers between main tracks of uni-direct double track, to cope with huge disruptions by offering additional routing, in terms of the whole cost including initial and maintenance costs.

Table 9 Comparison between manufacturing industry and railway systems

	Manufacturing	*Railway system*
Off-line quality control	Product design	Systems design
	Manufacturing process design	Timetabling, Rostering
On-line quality control	Manufacturing	Operation (Driving, Dispatching)
	Customer usage	Customer usage

2.8.4 Design of experiments

At the design level, possible options with all possible combinations of factors should be assessed in as much detail as possible, in order to reach the global optimum. However, exhaustive experimentation consumes a lot of time and cost due to the large volume of validation work required. Robustness is important for product and service, meaning that validation cannot be compromised; this characteristic makes it more difficult to investigate all possible options explicitly. To cope with this dilemma, the global optimum area of solutions can be obtained via a robustness assessment at macro or mesoscopic level, while validation at the microscopic level can be conducted later within the area of the global optimum. Taguchi suggested the design of experiments using orthogonal arrays and the additive model for approximation, which helps to reduce the number of experiments and conduct analysis concisely, resulting in saving time and cost in the systems design process (Phadke, 1989c). This improves the productivity of the design phase and it enables the assessment of the robustness of products or processes with a broad range of possible design options. For example, the execution of an experiment with 4 control factors and 3 levels (Table 10) and one noise factor requires 81 (3^4) individual tests for a full and exhaustive set of experiments. On the other hand, the equivalent analysis using the Taguchi methodology requires only 9 individual experiments (Table 11).

Table 10 4 control factors and 3 levels

Factors	*Levels*		
	1	2	3
A	1	2	3
B	1	2	3
C	1	2	3
D	1	2	3

Table 11 L9 orthogonal array for 4 control factors and 3 levels

Experiment numbers \ Factors	*A*	*B*	*C*	*D*	*Response*
1	1	1	1	1	R_1
2	1	2	2	2	R_2
3	1	3	3	3	R_3
4	2	1	2	3	R_4
5	2	2	3	1	R_5
6	2	3	1	2	R_6
7	3	1	3	2	R_7
8	3	2	1	3	R_8
9	3	3	2	1	R_9

The analysis of experiments designed with orthogonal arrays is based on the additive model, which is generally known as the additivity of the superposition principle and is given by:

$$F(x_1 + x_2 + x_3 + \cdots) = F(x_1) + F(x_2) + F(x_3) + \cdots. \quad (1)$$

where the formula is based on the assumption that there are no interactions between the elements, i.e. we base our work on the principle of linear superposition effects. Through the designed experiments, the overall mean of responses (*m*) for this example is calculated based on the additive model and is given by:

$$m = \frac{1}{9}\sum_{i=1}^{9} R_i. \quad (2)$$

For factor A, different contributions to responses from each level (m_{A1}, m_{A2}, m_{A3}) are calculated by:

$$m_{A1} = \frac{1}{3}(R_1 + R_2 + R_3), \quad (3)$$

$$m_{A2} = \frac{1}{3}(R_4 + R_5 + R_6), \quad (4)$$

$$m_{A3} = \frac{1}{3}(R_7 + R_8 + R_9). \quad (5)$$

For factor B, different contributions to responses from each level (m_{B1}, m_{B2}, m_{B3}) are calculated by:

$$m_{B1} = \frac{1}{3}(R_1 + R_4 + R_7), \quad (6)$$

$$m_{B2} = \frac{1}{3}(R_2 + R_5 + R_8), \quad (7)$$

$$m_{B3} = \frac{1}{3}(R_3 + R_6 + R_9). \quad (8)$$

The values of factors C and D are calculated in an analogous way. For more control factors and levels, the number of individual experiments in a full set of experiments increases significantly, such that the benefit of reducing the number of experiments by the designed experiment method based on the additive model becomes greater. For the extended cases, the different contributions of each factor to responses are calculated in an analogous way by equations (2) – (8) and equation (2) can be generalised by:

$$m = \frac{1}{N}\sum_{i=1}^{N} R_i. \quad (9)$$

where m is the overall mean of the responses and N is the total number of designed experiments. Equation (3) – (8) is generalised by:

$$m_{jk} = \frac{1}{n}\sum R_{j|k}\ . \quad (10)$$

where m_{jk} is the contribution to the responses from the factor j at level k, n is the number of experiments whose condition includes factor j at level k, $R_{j|k}$ is the subset of responses from the experiments whose conditions include factor j at level k.

2.8.5 Analysis of variance

The contribution of each factor and level which is calculated by equation (10) should be validated by analysis of the variance (ANOVA) (Ross, 1988; Phadke, 1989b; Taguchi et al., 2005b). Based on the additivity described in equation (1), an arbitrary response (R) with a certain combination of control factors can be given with the overall mean (m), the contribution of each factor and level (m_{jk}) and an error factor (e):

$$R = \mathrm{m} + \sum m_{jk} + e, \quad (11)$$

where the summation of m_{jk} is conducted for the given combination of control factors. This equation can be interpreted such that the response can be obtained by the sum of the overall mean, the deviation from the overall mean due to each factor and level, and the deviation from the overall mean due to error. Thus, the deviation due to control factors must be tested whether or not it is significant in comparison with that due to the error. This is called an F-test. Before conducting the test, the calculation of several components is required (Gopalsamy et al., 2009). Total sum squares (SS_T) is given by:

$$SS_T = \sum_{i=1}^{N} R_i^2. \tag{12}$$

This can be given with mean sum squares (SS_m) and error sum squares (SS_e):

$$SS_T = SS_m + SS_e. \tag{13}$$

The mean sum squares (SS_m) is given by:

$$SS_m = \mathrm{N} * m^2, \tag{14}$$

The error sum squares (SS_e) is given by:

$$SS_e = \sum_{i=1}^{N} (R_i - m)^2. \tag{15}$$

The sum squares due to factor *j* is given by:

$$SS_j = \frac{k}{n} \sum_{k=1}^{k\_max} (m_{jk} - m)^2, \tag{16}$$

where *k_max* is the highest level of the factor *j*. The mean square of each control factor (MS_j) is given with the degree of freedom of the control factor (DF_j):

$$MS_j = {SS_j}/{DF_j}, \tag{17}$$

the degree of freedom of the control factor (DF_j) is given by:

$$DF_j = \mathrm{k\_max} - 1 \tag{18}$$

The mean square of error (MS_e) is given with the degree of freedom of the error factor (DF_e):

$$MS_e = {SS_e}/{DF_e}, \tag{19}$$

and the degree of freedom of the error factor (DF_e) is given by:

$$DF_e = \mathrm{N} - \sum(\mathrm{k\_max} - 1), \text{ for all } j, \tag{20}$$

The F-value of the control factor *j* (F_j) finally is given by:

$$F_j = {MS_j}/{MS_e}. \quad (21)$$

By using this F-value, the deviation from the overall mean due to each factor can be tested. The probability density function of the F distribution is given by: (NIST, 2016a)

$$f(x) = \frac{\Gamma\left(\frac{v_1+v_2}{2}\right)\left(\frac{v_1^x}{v_2}\right)^{\frac{v_1}{2}} x^{\frac{v_1}{2}-1}}{\Gamma\left(\frac{v_1}{2}\right)\Gamma\left(\frac{v_2}{2}\right)\left(1+\frac{v_1^x}{v_2}\right)^{\frac{v_1+v_2}{2}}}, \quad (22)$$

where v_1 and v_2 are shape functions. Γ is the gamma function:

$$\Gamma(\mathrm{a}) = \int_0^\infty t^{a-1}e^{-t}dt. \quad (23)$$

F (v_1 = 10, v_2 = 10), F distribution of the degrees of freedom (v_1: the degree of freedom of the numerator and v_2: the degree of freedom of the denominator) is shown in Figure 18. X = 2.98 is the critical value of F of a probability of 0.05, which means that the F values above these points consist of unequal groups with a probability of 0.95. Table 12 shows the critical values for different degrees of freedom. If the F_j is greater than these values, the contribution of each factor j can be regarded as significant. The F-values will be used later in the thesis in Section 4.6.

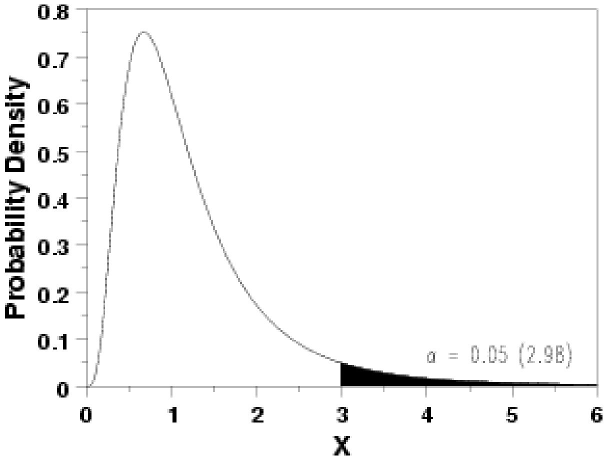

Figure 18 F probability distribution of v_1 = 10, v_2 =10 (NIST, 2016b)

Table 12 Critical F-value table of a probability of 0.05

$v_2 \backslash v_1$	*1*	*2*	*3*	*4*	*5*	*6*
1	161.45	199.50	215.71	224.58	230.16	233.99
2	18.51	19.00	19.16	19.25	19.30	19.33
3	10.13	9.55	9.28	9.12	9.01	8.94
4	7.71	6.94	6.59	6.39	6.26	6.16
5	6.61	5.79	5.41	5.19	5.05	4.95
6	5.99	5.14	4.76	4.53	4.39	4.28
7	5.59	4.74	4.35	4.12	3.97	3.87
8	5.32	4.46	4.07	3.84	3.69	3.58
9	5.12	4.26	3.86	3.63	3.48	3.37
10	4.96	4.10	3.71	3.48	3.33	3.22
11	4.84	3.98	3.59	3.36	3.20	3.09
12	4.75	3.89	3.49	3.26	3.11	3.00
13	4.67	3.81	3.41	3.18	3.03	2.92
14	4.60	3.74	3.34	3.11	2.96	2.85
15	4.54	3.68	3.29	3.06	2.90	2.79
16	4.49	3.63	3.24	3.01	2.85	2.74
17	4.45	3.59	3.20	2.96	2.81	2.70
18	4.41	3.55	3.16	2.93	2.77	2.66
19	4.38	3.52	3.13	2.90	2.74	2.63
20	4.35	3.49	3.10	2.87	2.71	2.60
21	4.32	3.47	3.07	2.84	2.68	2.57
22	4.30	3.44	3.05	2.82	2.66	2.55
23	4.28	3.42	3.03	2.80	2.64	2.53
24	4.26	3.40	3.01	2.78	2.62	2.51
25	4.24	3.39	2.99	2.76	2.60	2.49
26	4.23	3.37	2.98	2.74	2.59	2.47
27	4.21	3.35	2.96	2.73	2.57	2.46
28	4.20	3.34	2.95	2.71	2.56	2.45
29	4.18	3.33	2.93	2.70	2.55	2.43
30	4.17	3.32	2.92	2.69	2.53	2.42
31	4.16	3.30	2.91	2.68	2.52	2.41
32	4.15	3.29	2.90	2.67	2.51	2.40
33	4.14	3.28	2.89	2.66	2.50	2.39
34	4.13	3.28	2.88	2.65	2.49	2.38
35	4.12	3.27	2.87	2.64	2.49	2.37
36	4.11	3.26	2.87	2.63	2.48	2.36
37	4.11	3.25	2.86	2.63	2.47	2.36
38	4.10	3.24	2.85	2.62	2.46	2.35
39	4.09	3.24	2.85	2.61	2.46	2.34
40	4.08	3.23	2.84	2.61	2.45	2.34

2.9 Chapter conclusions

In this chapter, it has been suggested that cost reduction through limiting the size of stations, while not damaging the robustness of operations, is worth considering because the acquisition of the necessary land and the cost of construction account for a large part of the capital cost. Also, choosing good locations for stations is important for the socio-economic development of regions. Reducing the land requirements for stations makes it more likely that stations in good locations in relationship with the existing transport networks and other facilities.

Furthermore, it has been shown that the importance of energy efficient operations is increasing because of growing concerns and pressures about environmental problems, especially climate change.

Based on an investigation of methodologies, the adoption of Lean principles has been suggested since they can be used to reduce cost and waste. The principles highlighted are Value Stream Management (VSM), Just in Time (JIT) and Single Minute Exchange of Dies (SMED). VSM is conducted to identify Non Value Adding Activities (NVAs), while JIT and SMED can be used to reduce the NVAs, resulting in cost reduction. These principles, which originated from manufacturing industry, have already been applied successfully in other industries. However, applications to railway operations situations are rarely found. This could be attributed to concerns about applying experimental principles to railway operations. Also, the characteristics of railway operations make it difficult to adopt the Lean principles unthinkingly. There are strict requirements for service robustness and the railway's culture is very conservative, of necessity.

For dealing with the stringent requirements for operational robustness, another approach has been introduced, namely, the Taguchi method. This method was developed to ensure the robustness of products and their production, at the design stage. This method, which has also been transferred from manufacturing industry, firstly defines the product diagram, which consists of signal factors, noise factors, control factors and response. The product and the associated processes are designed to respond correctly to the signal, while dealing with the effects of noise factors by appropriate setting of control factors. At the design stage, the number of combinations of noise factors and control factors is too great to conduct an exhaustive set of experiments. Therefore, the adoption of the Taguchi approach to the design of experiments is recommended. This reduces the number of experiments that are necessary to choose the values of the control factors that are necessary for ensuring the robustness of products. Studies on the robustness assessment at the design stage are not frequent in railway operations. Thus, it is worth considering adopting Taguchi method and Lean principles together, when designing a new system.

In the next chapter, I show how I developed a methodology that combines the Taguchi method and Lean principles to design a terminus for a high-speed railway operation that realises a capital cost reduction, energy saving and robust operations.

3 Methodology

The aim of the project that led to this thesis was to improve the blueprint of high-speed railway operations in order to minimise land take and energy use, while ensuring robust service delivery. As stated in the introduction, this was to be achieved by optimising the size of the terminus stations and by adjusting the trajectories of the trains running on a line. The literature review suggested that two approaches could be used for achieving the objectives, namely, the Taguchi Method for ensuring operational robustness and the Lean principles for reducing land take and energy use.

The research hypothesis may be stated as ”The application of the Taguchi and Lean techniques can improve high-speed railway operational design and, thereby, reduce land take and energy use, while maintaining operational robustness”. In this chapter, I describe the framework of a methodology that combines the application of the Taguchi Method and Lean principles. It results in an evaluation of the reduction in resource use and the confirmation of the necessary operational robustness. Finally, within the scope of the research, I develop an approach to test the hypothesis and I discuss the requirements for the simulators necessary for the approach.

3.1 General framework of the research approach

In a first step, the framework of the approach is presented, in line with Table 13:

1. Following on from the literature review, I describes the nature and features of railway operations and discusses the concept of operational robustness, as well as the associated theories.
2. Vital control factors for robust operations are identified and then analysed by means of the Taguchi method, with software based simulators developed specifically for this purpose. The results of the simulations are tested by analysing the variance.
3. The identification of non-value adding steps is achieved by Value Stream Mapping (VSM) and compared with the results of the simulations undertaken as part of the Taguchi study, thereby, components can be identified that are not vital for robustness and that are non-value adding.
4. In order to identify feasible approaches to reduce land take and energy use, Just In Time (JIT) and Single Minute Exchange of Die (SMED) concepts are applied to design the operations and associated systems.

5. In order to evaluate the advantages and disadvantages of different designs, the values of selected variables are estimated.
6. Finally, the level of robustness of the operations is assessed by means of the simulator that was developed for the research.

Table 13 Structure of the approach

Step	Aims	Techniques	Remarks
1	Definition of the nature of railway operations and operational robustness	Literature review	
2	Identification of components which are vital for robustness	Input Output Model	Taguchi Method / ANOVA
		Design of experiment	
		Simulation	
		Analysis of variance	
3	Identification of non-value adding steps	Value Stream Mapping (VSM)	Lean principles
4	Design of operations	Just In Time (JIT)	
		Single Minute Exchange of Die (SMED)	
5	Evaluation of the design	Estimation of selected variables	
6	Confirmation of the robustness	Simulation	

3.1.1 Building an input-output model of the Taguchi method

For the identification of the components that have the greatest influence on the robustness of the service, the Taguchi method is adopted in this approach. The Taguchi Method allows the identification of the control factors that exert the greatest influence on the system behaviour and must be considered at the outset when designing the system.

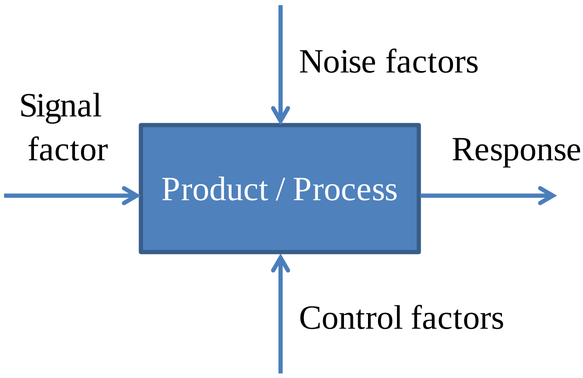

Figure 19 Input-output model of the Taguchi Method

As the first step of using the Taguchi method, a model of the systems must be defined. A generic representation of the type of model used is shown in Figure 19. The model includes signal factors, responses, noise factors and control factors. The function of the system is to respond to signal factors appropriately. Control factors are introduced and set to reduce the effect of noise factors on the responses. For the study of railway operational robustness, the signal factors represent the trains entering the area to be simulated from the outside of the boundary of systems, based on the planned timetables. The responses of the system are the trains leaving from the inside through the boundary of the systems. Ideal responses occur if the trains are able to leave according to timetable, without any delays. Noise factors represent the delays. Delays occur for various reasons, such as congestion in platform track, weather conditions, breakdowns of facilities or mistakes by the operational staffs. Each cause appears with a different probability, so that the extent of the inclusion of the noise factors in the diagram depends on the thinking of stakeholders and other decision making bodies. Control factors include all elements, such as the infrastructure, rolling stock, train crews, station staff, operational rules and operations tactics that can be changed to cope with the noise factors. The degree of freedom of choice depends on each situation as well.

3.1.2 Design of experiments and simulator

To assess the robustness of the different designs, experiments are required. However, for the studies of railway operations, real life experiments are not possible and, therefore, operations simulations are commonly adopted instead. There are several simulators that have been developed to conduct research into operational robustness. OpenTrack is a simulation software that was developed at the Institute for Transport Planning and Systems of the Swiss Federal Institute of Technology (Nash and Hürlimann, 2004), while the Birmingham Railway Virtual Environment (BRaVE) was developed at the Birmingham Centre for Railway Research and Education (BCRRE) of the University of Birmingham (Kirkwood, 2015). Both tools can simulate train movements at the microscopic level, i.e., by modelling responses to signals and generating block section occupation. They calculate the behaviour of the system based on the capability of rolling stock and infrastructure at the second by second level. Although these established simulators are highly suitable for the detailed modelling of services, they do not allow rapid changes to infrastructure and operational conditions as they are being adapted to avoid conflicts during the development of models. Thus, it to be investigated which simulators are appropriate for the case studies and dedicated tools have to be developed, if appropriate simulators are not available.

3.1.3 Analysis of simulator results

The simulation results are analysed based on the calculation of the contribution of each control factor, adopting Taguchi's analysis of variance (ANOVA) approach, in order to assess whether or not the influence of a parameter is significant, be it a control factor or a noise input. If significant values cannot be obtained from the simulation, it must be reviewed in terms of the chosen control factors. Initially, one can just change the levels of the control factors. If this does not work, other control factors may have to be defined and this requires changes to the code of the simulator if it has been developed for that specific case. Through this process, the essential factors for operational robustness may be identified.

3.1.4 Identification of non-value adding steps by Value Stream Mapping

After the identification of the essential factors for operational robustness, the next step is the identification of non-value adding steps or activities by means of Value Stream Mapping (VSM). By comparing the results from the analysis, components which are not vital for robust operations and do not add value are identified, thereby reducing resource use without damaging robustness. Before conducting the VSM analysis, the question must be answered: ”What is the value that the system provides for customers?” In railway operations, the answers to this question depend on the nature and views of the customers. For infrastructure managers like Network Rail, the direct customers would be Train Operating Companies (TOCs) and Freight train Operating Companies (FOCs), while passengers and shippers are indirect customers. For TOCs, the customers are the passengers and regulatory bodies and, for FOCs, customers are the shippers. Different definitions of customers result in different value stream maps. However, in terms of high-speed railway operations, passengers are considered to be the main customers.

3.1.5 Design of operations by Just In Time and Single Minute Exchange of Die

Just In Time (JIT) and Single Minute Exchange of Dies (SMED) are concepts that can be adopted to eliminate waste. Waiting time is a non-value-adding (NVA) step and creates waste through activities such as the storage of part-processed goods between production stages. JIT optimises the duration of manufacturing processes improves their coordination to reduce waiting times. For train operations, NVA steps include trains waiting for a platform outside a station or waiting to be serviced in a platform track. To cope with these NVA steps, more tracks and platforms must be provided than a practical minimum. Thus, it is expected to optimise the movements of multiple trains, resulting in reduced land take for stations, junctions or even for plain line tracks. Provision of double track layouts is common for densely traffic lines, however, if the demand is not significant, single track and passing loops could be cost effective options in terms of land take and construction. Energy saving is expected as an additional because the optimisation of train movements would be done by modifying and harmonising speed distance curves and this directly affects the energy consumption of trains.

Changeover time between products or between variants of products represents non-value adding waiting time for production. The application of SMED reduces the changeover times of machines. Changeover times in train operations occur due to maintain facilities, to prepare for the departure of trains in stations, the procedures involved in setting routes in the signalling boxes or control centres, the procedures applied during rescheduling of trains and so on. These waiting times increase the use of the available capacity and, indirectly, they result in greater land take. By adopting SMED, the waiting time for various situations can be reduced and the land take for train operations can be lessened as well.

3.1.6 Evaluation of the relationships between variables

In the following, the advantages and disadvantages of the operations and systems designed with JIT and SMED are evaluated for variables which are chosen according to the scope. For train operations, the variables for assessment could be journey time, energy use, land take, passenger demand, headway times, capacity, number of trains, number of train crews, number of station staffs, maintenance cost of the rolling stock and infrastructure and construction cost. In this project the variables were limited to journey time, energy use, number of platform faces, headway times and fleet size.

3.1.7 Confirmation of operational robustness

The final step of the approach is the confirmation of the operational robustness. The options proposed with the help of JIT and SMED are tested by simulation. Before the simulation, the threshold for a degree of robustness is fixed which is acceptable for each case. For example, a late arrival within 10 minutes for long distance passenger services in the UK is regarded as on time. In this case, 10 minutes can be set as the threshold.

3.2 Assumptions and constraints

For this thesis, the following assumptions were made and, based on these, an assessment approach for high-speed railways has been developed:

- High-speed railway operations;

  Based on the general framework, the approach has been developed for two models of high-speed railway networks, namely, exclusive exploitation and mixed high-speed, according to the classification of Campos et al. discussed in Section 2.1. For the project underpinning the thesis, I focus on the area around termini because they are commonly the greatest cost and robustness contributors in terms of both stations and plain line in the design and operation of HS lines.

  The evaluation is conducted in terms of journey times, energy consumptions, technical headway times, number of sets of rolling stock, number of platforms. Shorter journey times are generally preferred by passengers. However, to achieve theses requires higher speeds and, thus, increases energy use. Higher speeds also increase the technical headway time, which is defined as the time or distance between for the front end of two consecutive train services that is necessary for safety, because of increase of the braking distance, which follows a square law. Longer technical headway times decrease the capacity of the line and can also damage the robustness of operations. On the positive side, shorter journey times decrease the number of sets of rolling stock required because they reduce the round trip times of rolling stock. An assumption can be made that an increase in the number of platforms will enhance the robustness of the operations around the termini but it also increases the construction cost and land take of termini. The aim of the proposed approach is to reduce the initial cost and energy consumption without damaging operational robustness. Thus, these variables must be evaluated and the details of the calculations will be presented in Chapter 5.

- The operational robustness is studied for small delays, e.g., around 5 minutes, not for big delays caused by significant reliability issues associated with infrastructure and vehicles, natural disasters, injury accident and so on.

  Dealing with big delays is out of scope of this thesis. They must be dealt with by the rescheduling of trains, such as by changing departure or arrival times, changing the order of departures and the cancellation of trains. Addressing big delays by planning fully resilient operations is unrealistic because it requires much greater resources and facilities that are then not used in normal operations. Although small delays are sometimes dealt with rescheduling, this is not considered for the present project and thus allows me to ignore also the rescheduling of resources such as rolling stock and crews. This assumption limits the realism of the simulation. However, it makes the requirements placed on the facilities more severe and results in a more robust planning approach.

3.3 Simulators for a high-speed railway with double track and two termini

Within the scope described above, the general framework of an approach suggested in Section 3.1 is developed further for the case study. The approach requires two simulators to fulfil the aims. In this section, the concepts of each simulator for robustness assessment, evaluation and confirmation are developed.

3.3.1 Terminus simulator

For the identification of the components of high-speed railway operations that are not vital for robustness and can thus be omitted, a simulation is conducted in order to assess the behaviour of the system. The simulator has to satisfy the following requirements:

- The framework of the simulator must be based on the block diagram of the Taguchi method:
  - It must allow flexible inputs of different infrastructure characteristics and operational conditions as control factors;
  - It must allow arbitrary arrival delays and departure delays as noise factors.
- It must be possible to run the simulations based on the design of experiments method:
  - The conditions for each simulation run are set according to the orthogonal arrays;
  - It must be possible to change the facilities for each simulation flexibly.
- The output behaviours of the trains must be based on the interaction of trains and operations:
  - Every single movement of each train must be modelled;
  - Queuing and conflicts of trains must be captured.

Reviewing these requirements, it was found that the existing simulators, such as Open Track and BRaVE, are not suitable because they do not allow flexible changes to the characteristics and states of facilities, which means that it is difficult to adopt the design of experiments approach. Thus, an original simulator would have to be developed for the approach. The detail of the simulator, i.e., the model and pseudo-code are shown in Section 4.2.

3.3.2 Standardised approach by single train simulator

Journey time and energy consumption are variables to be estimated for the evaluation of terminus operations and design. The Birmingham University single train simulator

(Hillmansen and Roberts, 2007) is a proven simulator for calculating these types of variables. Hence a standardised approach for the calculation of tractive energy use will be developed with the simulator (Hasegawa et al., 2015b). The theoretical background and details of the approach are described in Section 5.1.5.

3.4 Chapter conclusions

A general framework for reducing resource use while maintaining robustness has been developed, by combining the Taguchi method and Lean principles. This consists of six steps:

1. Definition of the nature of railway operations and operational robustness by literature review;
2. Identification of the vital control factors for robustness by simulation based on the Taguchi method;
3. Identification of non-value adding steps of the operations by a VSM analysis;
4. Reduction of resource use by JIT and SMED;
5. Evaluation of the variables of systems and operations designed with the approach;
6. Confirmation of robustness by simulation.

Based on this framework, an approach has been developed for enhancing the design of terminus areas of high-speed railways based on assumptions and constraints that limit the scope of the approach to small delays without introducing the rescheduling of trains. Finally, the requirements placed on the framework for simulators have been discussed and it was decided to develop an original terminus simulator for robustness assessment. For the calculation of journey time and energy consumption, the existing standard approach using the single train simulator has been adopted. In the following chapter, case studies are conducted.

4 Robustness assessment by the Taguchi method

In this chapter, the application of the Taguchi method to the assessment of robustness of railway systems is studied. Terminus operations with several options with infrastructure and operational conditions on high-speed railways are discussed as a case study. Through this process, the control factors which are important for robustness are determined, thereby allowing the next step of the approach, the cost reduction by the Lean principles, to be implemented without damaging robustness (the application of the Lean principles is discussed in Chapter 5). A simulator for the experiments, the simulation model and the simulation settings for the experiments are presented in the following sections. This chapter is based on my published paper (Hasegawa et al., 2016).

4.1 Definition of robustness in the context of a railway terminus

Definitions from the Taguchi method (see Section 2.8.1) and the railway industry (see Section 2.3) can be combined and interpreted for railway operations around a terminus as follows: the signal factor is defined as the arrival times of trains and the desired response is regarded as the turning around and timely dispatching of trains. Noise factors are arrival and departure delays, while the control factors are the number of platform tracks, the layout of S&C and tracks, the capability of the signalling equipment, the turnaround time and the buffer time.

4.2 Simulator

I have developed a simulator, which can simulate terminus operations according to the block diagram of the Taguchi method (Figure 20). As discussed above, the function of a terminus can be defined as to receive arriving trains, turn the trains around and allow them to depart on time. The simulator receives as an input the arrival times of trains based on a timetable as a signal factor, has arrival delays and departure delays as noise factors and different infrastructure and operational conditions as control factors. It simulates the queuing of arriving trains, route conflicts between arriving trains and departing trains, and turnaround. It outputs the departure delay of the last departing train in the sequence, the number of times that platform tracks are not available at the time of arrival of a train due to full occupation, and the number of times that conflicts occur between arriving and departing trains (Figure 21). Delays are input based on statistical distributions and each simulation is conducted using the Monte-Carlo simulation methodology (MacKay, 1998).

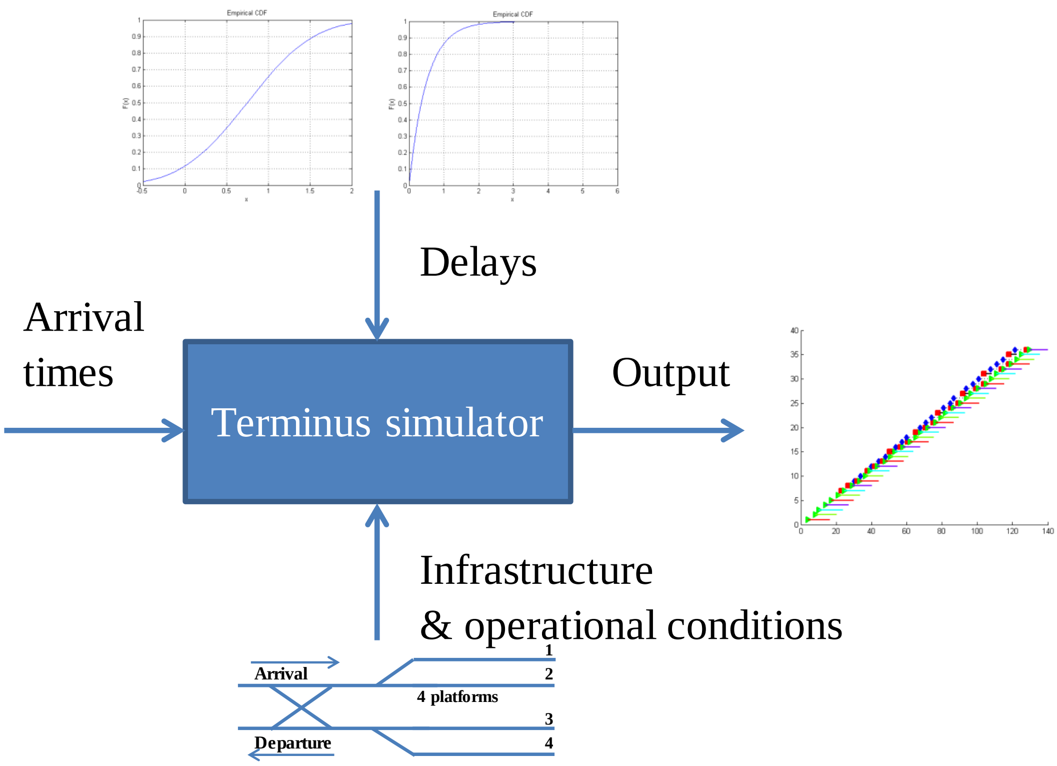

Figure 20 Structure of terminus simulator

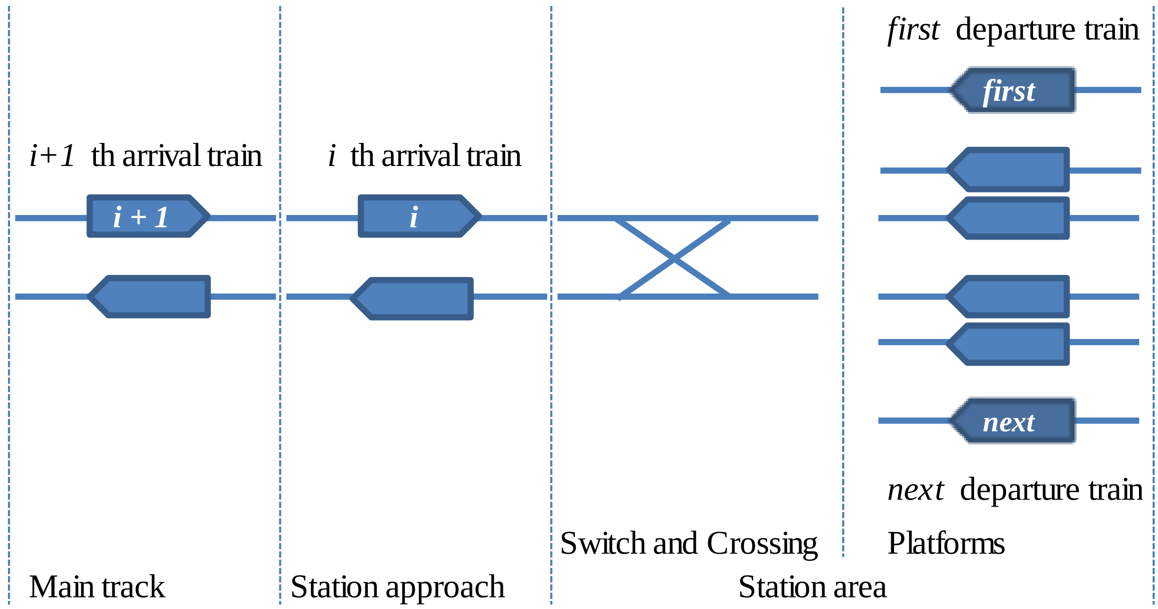

Figure 21 A model of terminus operation consists of arriving trains, departing trains, main track, station approach and station area which includes S&C and platforms

The terminus operation shown in Figure 21 was modelled using the following pseudo-code, where the term 'platform' is shorthand for 'platform track' or 'platform face', 'orthogonal array' delimits combinations of control factors for each simulation experiment (see Section 2.8.4):

READ arrival times, arrival delays, departure times, departure delays, orthogonal array

actual arrival times = arrival times + arrival delays

FOR all simulation experiments

FOR all Monte Carlo simulations

unavailable platforms = 0, conflicts = 0

READ number of platforms, conflict patterns, signalling reaction time, technical headway time, reoccupation time, stop penalty, departure headway time, minimum required turnaround time, according to orthogonal array

platform departure times = departure times (1: number of platforms) + departure delays (1: number of platforms)

first departure time = min (platform departure times)

FOR all arrival trains

IF actual arrival times (i) < first departure time + reoccupation time

actual arrival time (i) = first departure time + reoccupation time

unavailable platforms = unavailable platform +1

IF actual arrival time (i+1) - actual arrival time (i) > technical headway

actual arrival time (i+1) = actual arrival time (i) + stop penalty

ENDIF

ENDIF

actual departure time (i) = actual arrival time (i) + turnaround time

IF actual departure time (i) – departure time (i) < buffer turnaround time

actual departure time (i) = departure time (i) + departure delays (i)

ELSE

actual departure time (i) = actual departure time (i) – buffer turnaround time + departure delays (i)

IF 0 < actual arrival time (i) - next departure train < reoccupation time && conflict == true

next departure time = actual arrival time (i) + signalling reaction time

conflicts = conflicts + 1

ENDIF

departure interval = 3rd departure time - next departure time

WHILE departure interval < departure headway time

3rd departure time = next departure time + departure headway time

departure interval = 4th departure time - 3rd departure time

ENDWHILE

ENDFOR

ENDFOR

ENDFOR

WRITE final departure delay, number of times unavailability platforms occurred, number of times conflicts occurred

4.3 Simulation experiments and settings

For the models in Figure 20 and Figure 21, each factor and the evaluation indicators of the output are fixed. The signal factor (input) is trains arriving with a frequency of 18 per hour for a period of 2 hours. This frequency is indeed a high value for high-speed railways. However, there are some examples: Tokaido Shinkansen in Japan has 18 train arrivals and 18 departures per hour at Tokyo station, while HS2 in the UK aims to operate the same number of trains per hour at London Euston station in phase 2 (HS2 Ltd, 2012b). The desired response is for all of the trains to depart with a 10 minute turnaround time. The success or otherwise is checked by evaluating the departure time of the final train to depart from the terminus, the number of trains that could not be allocated a platform track on arrival and the number of conflicts between arriving and departing trains.

Noise factors are arrival delays and departure delays. For this proposed new infrastructure design, data corresponding to real operations has not been available. However, several fitted delay distribution models have been studied: normal, lognormal, gamma, Weibull and negative exponential (Yuan, 2008). For this simulation, three types of arrival delays (Chen, 2012) and a departure delay distribution (Goverde and Hansen, 2001) are used:

- Arrival delays
  - normal distribution short delay (μ = 0.75 minutes, σ = 0.625 minutes) over [-0.5, 2]
  - normal distribution long delay (μ = 2 minutes, σ = 1.5 minutes) over [-1, 5]
  - negative exponential distribution delay (μ = 1.5 minutes) over [0, 6] for arrival delay
- Departure delays
  - negative exponential distribution (μ = 0.5 minutes) over [0,2]

Table 14 Factors and levels for terminus operation simulation (examples of layout of a, b, c are shown in Figure 22)

Factors	*Levels*		
	1	2	3
A: Number of platform tracks	4	5	6
B: Layout	a	b	c
C: Minimum required turnaround time (mins)	8	7	6
D: Signalling reaction time (seconds)	40	30	20

Four control factors and three levels were assigned (Table 14). The control factors are: A) the number of platform tracks; B) the track layouts (which influence the potential for conflict between arriving and departing trains); C) minimum required turnaround time, consisting of alighting, boarding, handover, checking for the next departure and cleaning work (Hasegawa et al., 2014a), and; D) signalling reaction time. Even at the lowest level the system runs without problems when there is no delay. In the face of noise all will experience knock on delay or conflicts. Looking at level 2 and 3 over level 1 will help determine which investment is valuable in terms of improving robustness. Different numbers of platform tracks (sometimes referred to as platform faces) and layouts which have different conflict patterns are shown in Figure 22. For example, a terminus with 4 platform tracks and layout a is conflict free when the arriving train enters platform track 1 and the departing train departs from platform track 3, while it is not conflict free in the case of an arrival on track 1 and a departure from track 2. Layouts b and c are improved from a, in terms of having fewer conflict patterns, by adding additional platform tracks and S&C: layout b adds one additional access route to platform track 1 for arriving trains and layout c further adds an additional route for departing trains from:

- track 4 of a 4 platform track terminus (Level 1 of factor A),
- track 5 of a 5 platform track terminus (Level 2 of factor A),
- track 6 of a 6 platform track terminus (Level 3 of factor A).

Via the improvement from layout a to b with a 4 platform track terminus, the case of trains arriving on track 1 and departing from track 2 no longer results in a conflict. The conflict matrices in Figure 22 show the conflict patterns between arriving (A) and departing (D) trains. The row and column indices represent the platform track numbers, circle markers show that the combination of a given arrival and departure does not have the potential for a conflict, while a cross marker shows that there is potential for a conflict if the timing is wrong.

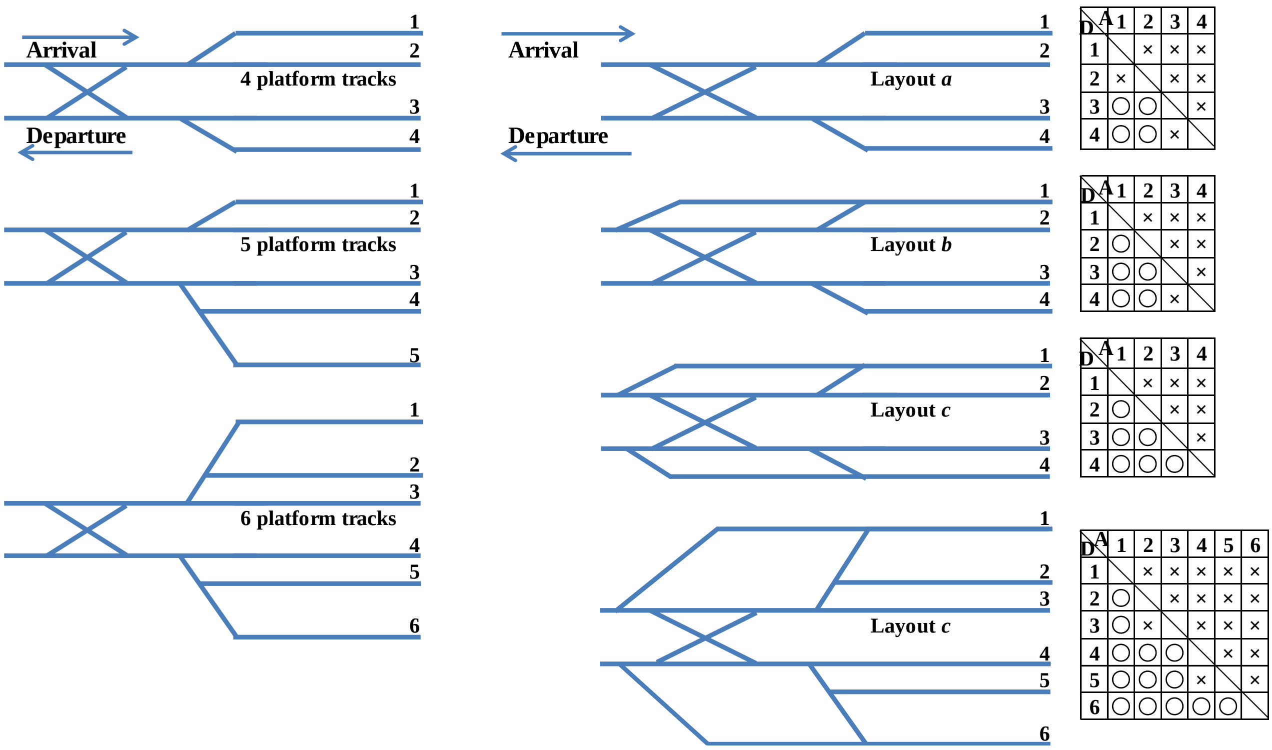

Figure 22 Different numbers of platform faces (4, 5, 6) and different layouts (a, b, c) for 4 platform tracks and layout c for 6 platform tracks

The signalling reaction time consists of train detection, interlocking, S&C movement, driver's response, etc. (see (Mense, 2011) for details of the signalling system), which form part of the technical headway times (see (Pachl, 2014) for details of the technical headway times), none of which are related to a vehicle's properties. All vehicles have the same properties in this simulation, with the running time between platform tracks and station approach (see Figure 21) set at 2 minutes 20 seconds for both directions. If the train stops outside the station before entering the station area, a 1 minute penalty is added to the running time. The technical headway time outside the station area is 2 minutes.

For the four factors and three levels, an L9 orthogonal array was used, as shown in Table 10. A total of 9 sets of 1,000 runs for 4 platforming patterns (ascending order, descending order, odd-even number, and even-odd number) and 3 types of delay scenarios of Monte-Carlo simulation were conducted.

4.4 Validation of the simulator

The terminus simulator had been validated before conducting the simulation experiments, with the output of each simulation being validated separately. The output of the simulator for level one of all control factors, one noise factor of the normal long distribution arrival delay and the negative exponential distribution departure delay is shown in Figure 23. This is the profile for a 4 platform face-terminus operation with an arrival and a departure every 3 minutes and individual arrival and departure delays (Table 15). Green, blue, purple and red bars are the turnaround time on each platform face. Green triangles show the actual arrival time of trains after the calculations to add delays, queuing and conflict. Red squares show the time at which the train stops on approach to the station because of the lack of a vacant platform face. Blue rhombuses show the time at which the train stops on the main track outside the station approach due to delay of a previous train. Black bars show the waiting time duration of a departing train due to a conflict with an arriving train. The grey jagged line shows the number of trains waiting in the queue.

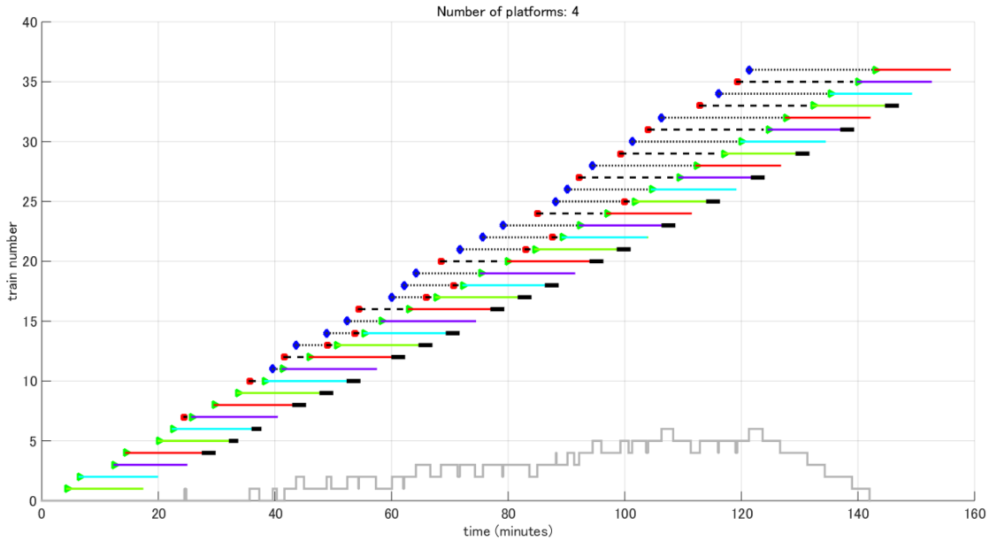

Figure 23 Output of the terminus simulator with level one of all control factors and noise factor of long normal arrival delay and negative exponential departure delay

Table 15 Arrival and departure delays of individual trains from the long normal distribution arrival delay and negative exponential departure delay

Train number	Arrival delay (min)	Departure delay (min)
1	1.03	0.92
2	-0.20	0.11
3	2.49	1.31
4	-0.25	0.04
5	3.41	1.35
6	2.47	0.25
7	0.52	0.11
8	3.01	0.06
9	3.65	0.49
10	0.82	0.43
11	2.95	0.08
12	-0.20	1.98
13	-0.51	0.12
14	2.20	1.71
15	2.40	0.18
16	0.32	0.48
17	3.41	0.55
18	2.17	0.59
19	0.78	0.12
20	1.81	0.21
21	1.72	0.09
22	2.35	3.55
23	2.50	0.26
24	5.00	0.02
25	4.84	0.20
26	2.35	1.18
27	-0.72	0.42
28	1.15	0.51
29	2.59	0.41
30	-0.24	0.10
31	0.69	0.65
32	-0.37	0.01
33	2.88	0.92
34	2.81	0.54
35	2.63	0.39
36	1.27	0.26

The timetabled arrival time of the 36th train is 120 minutes and the departure time is 130 minutes after the start of the simulation. The actual arrival time is 142.98 minutes and the departure time is 155.65 minutes. The corresponding delays are attributed as follows: 18 times there were no empty platform tracks, 20 times there was a conflict between arrival and departure. Thus, the movements and interactions of every single train have been calculated.

The effect of upgrading the control factors was checked through the simulation with three cases (upgrading the control factor levels) and three types of arrival delay. The simulation results should show an improvement. Case 1 is with level one of all control factors, case 2 is with level two of all control factors and case 3 is with level three of all control factors, as shown in Table 16.

Table 16 Case setting for the simulator validation

Case	*Factors and levels*			
	A	B	C	D
Case 1	1	1	1	1
Case 2	2	2	2	2
Case 3	3	3	3	3

As noted in Section 4.3, the terminus with level 2 or level 3 of each control factor has greater capability in terms of robustness than that with level 1. Therefore, the response of case 3 should show the best performance and case 2 should be the second best. The result of the simulation for the simulator validation is shown in Table 17 and plotted in Figure 24, Figure 25 and Figure 26. The responses of the terminus are defined as follows: departure delay (minutes) of the final departing train (O1), the number of times platform tracks are not available on arrival (O2) and the number of times conflicts occur between arriving and departing trains (O3). These responses are obtained for three delay scenarios, namely, normal distribution short delay (Figure 24), normal distribution long delay (Figure 25) and negative exponential delay distribution (Figure 26). As shown in the figures, case 3 shows the best performance, case 2 is the second best and case 1 the worst. With the control factors in the setting of case 3, the terminus can cope with all three delay scenarios almost perfectly; almost no delay on the final trains, no unavailable platform tracks and no conflicts between arrivals and departures. Case 2 shows an improvement in all responses for all delay scenarios in comparison with case 1. This result shows that the simulator can perform the simulation experiments appropriately based on the simulation model developed in Section 4.2.

Table 17 Result of the simulator validation

		Case 1	*Case 2*	*Case 3*
Normal short delay	O1	27.09	16.43	2.05
	O2	21.77	18.34	2.88
	O3	21.69	17.66	3.95
Normal long delay	O1	27.69	16.14	1.26
	O2	21.33	15.71	1.34
	O3	21.30	15.62	1.71
Negative exponential delay	O1	27.66	17.06	1.48
	O2	21.49	17.33	1.68
	O3	21.47	17.06	2.23

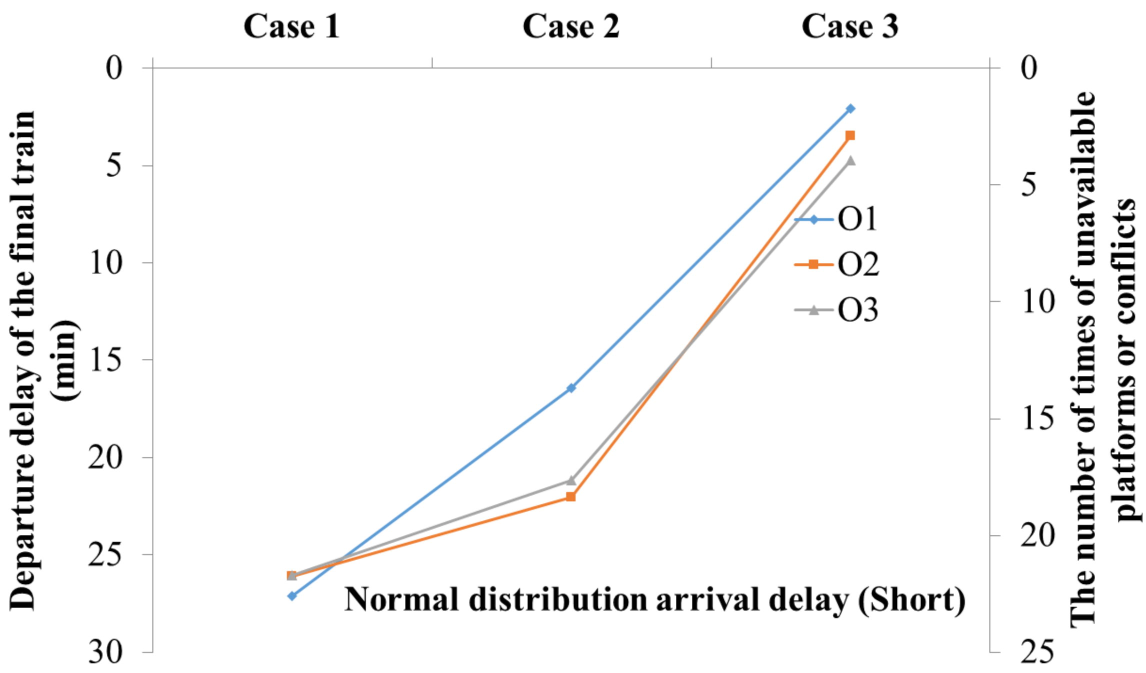

Figure 24 The responses for the three cases with the normal distribution short arrival delay

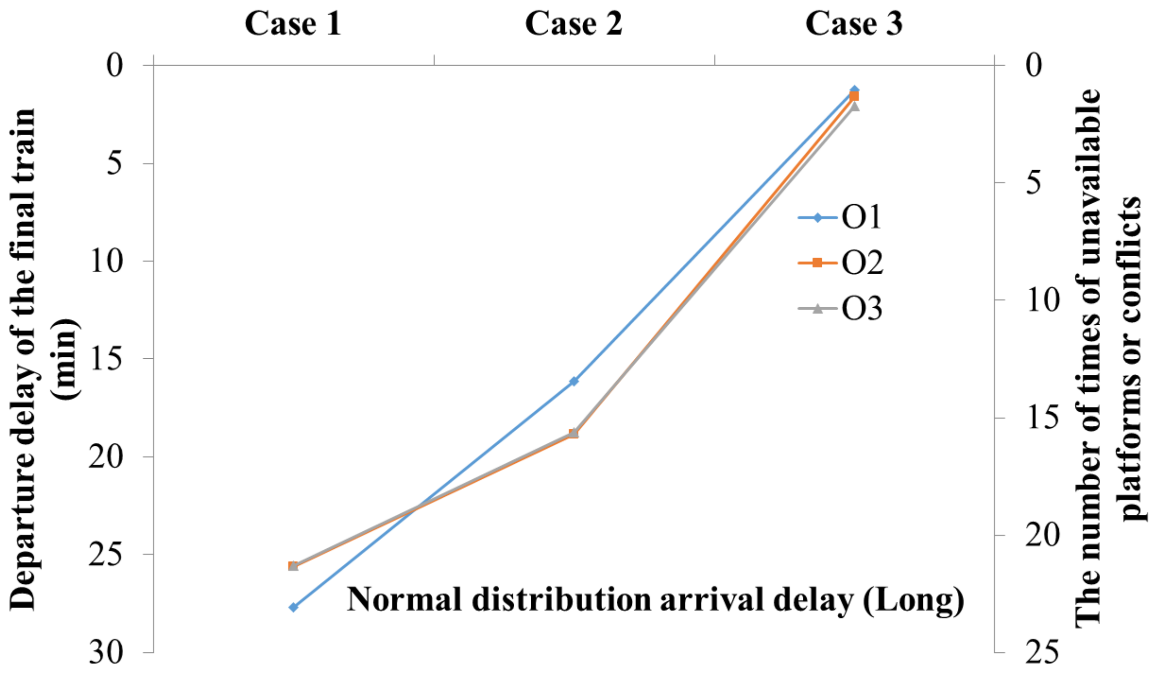

Figure 25 The responses of the three cases with the normal distribution long arrival delay

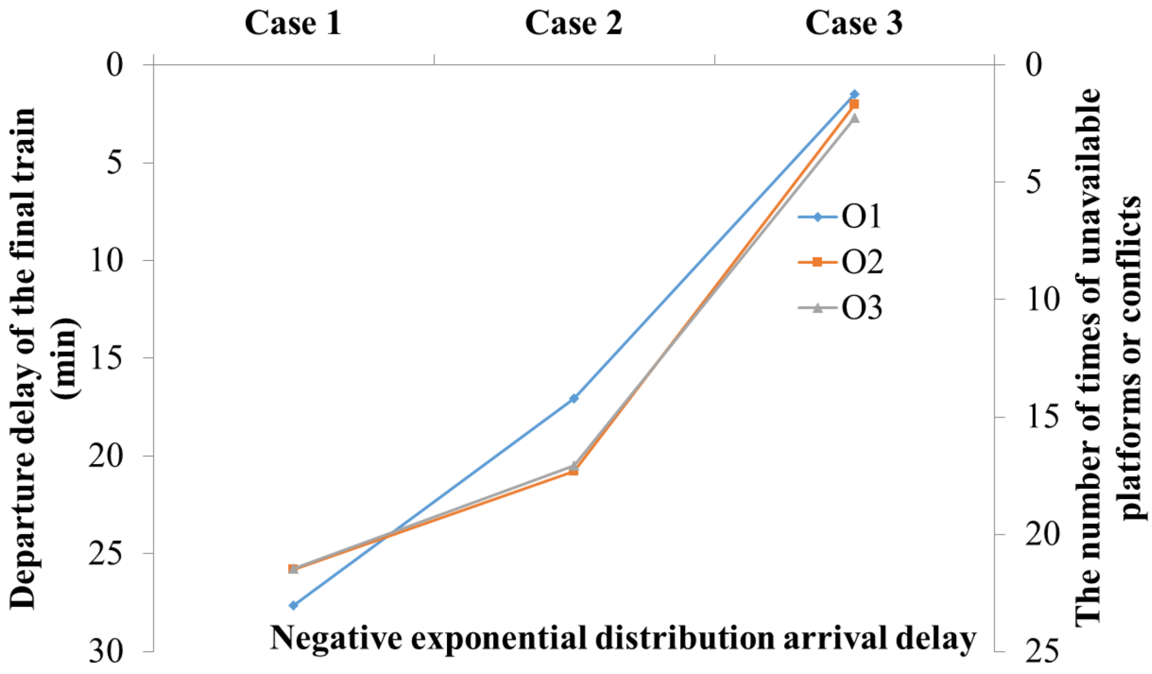

Figure 26 The responses of the three cases with the negative exponential distribution arrival delay

4.5 Simulation results based on the Taguchi method

The simulation experiments designed with the L9 orthogonal array took 3632 seconds, or about 60 minutes, to obtain the results. If the full factorial simulation experiment were to be conducted, it would take about 9 hours because the number of combinations of conditions is 9 times greater than that of the Taguchi designed experiment. The results of the simulation are shown in Table 18. The contribution by each factor and level, calculated from this table using equations (9) – (10), is shown in Table 19 and the overall results are calculated (Table 20). The overall results are plotted in Figure 27. The average of each response is also plotted as a dashed line in the figure.

Table 18 Results of the Taguchi based simulation experiments

Expt. no.	*Control factors*				*Normal short delay*			*Normal long delay*			*Negativee exponential delay*		
	A	B	C	D	O1	O2	O3	O1	O2	O3	O1	O2	O3
1	1	1	1	1	27.09	21.77	21.69	27.69	21.33	21.30	27.66	21.49	21.47
2	1	2	2	2	12.91	21.00	17.73	14.52	20.51	17.94	14.11	20.47	17.73
3	1	3	3	3	1.66	9.61	9.54	2.23	8.71	10.22	2.00	9.36	9.65
4	2	1	2	3	5.36	13.14	15.80	6.40	10.58	13.24	6.81	11.37	14.62
5	2	2	3	1	21.12	18.63	16.30	19.64	15.31	14.07	21.52	17.37	15.71
6	2	3	1	2	12.51	14.83	14.18	12.86	13.92	13.32	13.07	14.45	13.73
7	3	1	3	2	6.98	5.70	6.09	4.98	3.59	3.88	6.43	4.79	5.17
8	3	2	1	3	2.25	3.08	3.63	2.62	2.58	3.14	2.98	2.80	3.61
9	3	3	2	1	7.99	5.53	5.01	7.72	4.63	4.31	9.04	5.60	5.19

Table 19 Contributions of each factor level in the Taguchi experiment for each noise factor

		mA1	*mA2*	*mA3*	*mB1*	*mB2*	*mB3*	*mC1*	*mC2*	*mC3*	*mD1*	*mD2*	*mD3*
Normal short delay	O1	13.89	13.00	5.74	13.14	12.09	7.39	13.95	8.75	9.92	18.73	10.80	3.09
	O2	17.46	15.54	4.77	13.53	14.24	9.99	13.23	13.22	11.31	15.31	13.84	8.61
	O3	16.32	15.43	4.91	14.53	12.56	9.58	13.17	12.85	10.64	14.34	12.66	9.66
Normal long delay	O1	14.81	12.97	5.11	13.02	12.26	7.61	14.39	9.55	8.95	18.35	10.79	3.75
	O2	16.85	13.27	3.60	11.84	12.80	9.09	12.61	11.91	9.21	13.76	12.67	7.29
	O3	16.49	13.54	3.78	12.81	11.72	9.28	12.59	11.83	9.39	13.23	11.71	8.87
Neg. Exp. delay	O1	14.59	13.80	6.15	13.63	12.87	8.04	14.57	9.99	9.98	19.41	11.20	3.93
	O2	17.11	14.40	4.40	12.55	13.55	9.80	12.91	12.48	10.51	14.82	13.24	7.84
	O3	16.28	14.69	4.66	13.75	12.35	9.52	12.94	12.51	10.18	14.12	12.21	9.29

Table 20 Overall result

	Overall		
	O1	O2	O3
m_{A1}	14.43	17.14	16.36
m_{A2}	13.25	14.40	14.55
m_{A3}	5.66	4.26	4.45
m_{B1}	13.27	12.64	13.70
m_{B2}	12.41	13.53	12.21
m_{B3}	7.68	9.63	9.46
m_{C1}	14.30	12.92	12.90
m_{C2}	9.43	12.54	12.40
m_{C3}	9.62	10.34	10.07
m_{D1}	18.83	14.63	13.90
m_{D2}	10.93	13.25	12.19
m_{D3}	3.59	7.91	9.27
Mean	11.12	11.93	11.79

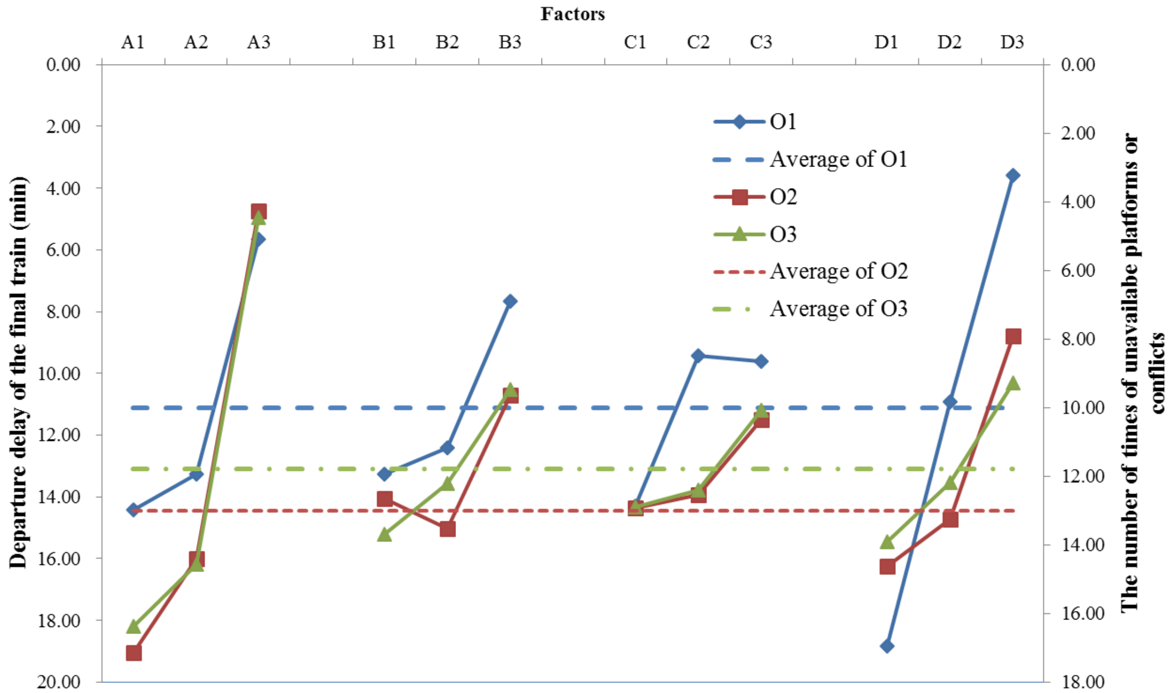

Figure 27 The overall responses

4.6 Analysis of the variance of the simulation results based on Taguchi method

An analysis of the variance (ANOVA) was conducted for the simulation results. From equations (12) – (21) in Section 2.8.5, the sum of the squares and the mean square for all control factors and an error factor for all simulation results were calculated and, finally, F-values for all control factors against an error factor were calculated (Table 21), where DF is a degree of freedom. The critical F value for a probability of 0.05 for $v_1=2$ and $v_2=17$, which is the case for all factors, was 3.56 (see Table 12 for the critical F-value). Then all F-values were tested by the critical F-value and it was found that factor A for O2 and O3, and factor D for O1 were higher than the critical F-value (underlined values in Table 21). This means that the deviation from the overall means due to these factors can be regarded as significant.

Table 21 ANOVA table of the simulation results

Factors	*DF*	*Sum of squares*			*Mean square*			*F-value*		
		O1	O2	O3	O1	O2	O3	O1	O2	O3
A	2	485.04	1076.53	748.00	242.52	538.26	374.00	2.83	**8.99**	**7.32**
B	2	212.48	126.57	101.78	106.24	63.29	50.89	1.24	1.06	1.00
C	2	147.92	60.24	51.12	73.96	30.12	25.56	0.86	0.50	0.50
D	2	784.30	166.38	69.36	392.15	83.19	34.68	**4.57**	1.39	0.68
Error	19	1629.75	1138.19	970.26	85.78	59.90	51.07			
Total	27	3296.37	2605.60	1976.98						

4.7 Discussion based on simulation results with Taguchi method

From the ANOVA conducted above, factor A (the number of platform tracks) for O2 and O3, and factor D (signalling reaction time) for O1 are regarded as significant. The other factors may be regarded as insignificant. For the significant factors, the profiles of each response are worth investigating. Factor A, upgrading the number of platform tracks, shows a clear improvement for all responses, including O1, O2 and O3. In contrast, factor D, upgrading the time related to the technical headway times, improved the response of O1 significantly but not the responses of O2 and O3. It can be inferred that there are two ways of improving the response of O1, indirect and direct ways. Factor A physically changes the terminus and indirectly reduces the final departure delay by avoiding cases of arriving trains which cannot find an available platform track and the conflicts between departing and arriving trains. On the other hand, factor D directly reduces the technical headway times and the final departing delay.

The other more significant factors, B (layout of the terminus), C (minimum turnaround time) did not show a clear improvement when they were upgraded. Factor B improves the physical layout, which could have reduced conflicts. However, the options investigated in this simulation, which were to put an additional access from a main track to platform tracks for arriving trains and an additional access from the platform tracks to a main track, are not enough to have a significant positive effect on the responses. To improve the layout, there are other possible options: Sone and Zhongping (Sone and Zhongping, 2010) suggested an improved layout for Tokyo station in order to reduce the possibility of conflicts occurring (Figure 28). However, as noted in their paper, this is subject to space being available and Tokyo station does not currently have the space to allow additional tracks and junction elements to be built. Factor C appears to have a direct positive effect on the final departure delay by recovering delays thanks to quick turnarounds, however, it does not work directly and independently of the constraints of technical headway times. The recovered departure times are sometimes re-modified due to route conflicts between the arriving and departing trains and the departure time of the previous departing train.

Figure 1: Existing layout. Figure 2: Improved layout.

Table 1: Interference of Fig. 1.

out / in	14	15	16	17	18	19
14	-	x	x	○	○	○
15	x	-	x	○	○	○
16	x	x	-	○	○	○
17	x	x	x	-	x	x
18	x	x	x	x	-	x
19	x	x	x	x	x	-

Table 2: Interference of Fig. 2.

out / in	14	15	16	17	18	19
14	-	○	○	○	○	○
15	x	-	○	○	○	○
16	x	x	-	○	○	○
17	x	x	x	-	○	○
18	x	x	x	x	-	○
19	x	x	x	x	x	-

○ is an interference free route while x route interferes with each other

Figure 28 An option for reducing conflicts at Tokyo station, captured from (Sone and Zhongping, 2010)

4.8 Chapter conclusions

To provide a robustness assessment of railway systems design, the application of the Taguchi method has been presented and a case study demonstrated. From the case study, the components of the technical headway time, such as the signalling reaction time, are found to be the most important for the robustness of terminus operations. Thus, the later step of cost reduction should be conducted without reducing the capability of this component.

This result is also significant for future railway projects with limited budgets, as it may be better to consider signalling reaction time rather than having more physical facilities. It is possible to improve the performance of train service management activities, such as: increasing the computational speed of computers, faster route setting by auto route setting of traffic management systems, reducing the reaction time of the driving function using an ATO system and adopting a moving block signalling system to reduce the track occupation time. Related to the signalling reaction time, the running times between the station approach and the stopping positions at the platform tracks are fixed for the simulation, however, these are also part of the technical headway times. Reducing the minimum running time and including some buffer time can directly reduce the final departing delay. This can be achieved by increasing the acceleration rate, braking rate and the speed limits around the station. In contrast, physical facilities require increased spending on maintenance and require physical space, which is limited in city centres.

The simulation experiments designed with the L9 orthogonal array took 3632 seconds, which is about 60 minutes, to obtain results that are regarded as statistically significant. For the full factorial simulation experiments, the computational time would increase to about 9 hours. This time saving improves the productivity of the design phase.

The model presented in this chapter is relatively simple and a more variable environment should be considered for future work. However, the methodology that has been used to analyse robustness should still be useful with a more detailed model, including different noise factors and additional control factors.

5 Cost reduction through operations and systems design based on the Lean principles

A robustness assessment of terminus turnaround arrangements is studied in the previous chapter. In this chapter, which is the next step of the approach, cost reduction based on the Lean principles is demonstrated through a case study using a model of a simple high-speed railway line expanded from a single terminus in order to see cost reduction activities over a broader range. Firstly, the theoretical background of timetabling is presented in section 5.1.1, with the requirements for infrastructure and energy consumption being identified in sections 5.1.2 and 5.1.5. Next, the application of the Lean principles to the operations and systems design of the model is investigated in Section 5.2. Finally, a lower cost option for the operational factors and the infrastructure conditions, developed by combining the Taguchi method and Lean principles, is assessed in terms of its operational robustness. This chapter is based on my published papers (Hasegawa et al., 2014a, 2014b, 2015a, 2015b).

5.1 Modelling of high-speed railway operations

Railway operations require timetables. The objectives of timetabling are maximizing customer satisfaction and lowering cost while maintaining quality of service. Customers value absolute safety, short travel times, stable and frequent services, comfortable accommodation and low ticket prices. Infrastructure managers and train operating companies seek to operate with absolute safety, minimum infrastructure and rolling stock and low operational cost. There are trade-offs between each objective. In this section, cyclic timetabling and requirements for rolling stock and infrastructure are studied, where the service pattern repeats each cycle time. A cyclic timetable is common in high-speed rail for marketing reasons and because it results in low variation in resource use.

5.1.1 Cyclic timetable

A cyclic timetable repeats the same timetable for every cycle time and intervals between trains are generally the same. For a simple double track high-speed railway network which has two termini (*n*, *m*) and service frequency F in cycle time T at both termini, the time interval between two consecutive departures from terminus *n* is given by:

$$t_d^{i+1}(\text{n}) - t_d^{i}(\text{n}) = T/_F \; (\, i \leq F \in \mathbb{N} \,), \qquad (24)$$

where t_d^i(n) is the departure time of the *i* th train service at terminus *n* in cycle time *T*, t_d^{i+1}(n) is the departure time of the next train at terminus *n*. In the same way, the time interval between two consecutive arrival trains at terminus *n* is given by:

$$t_a^{j+1}(\mathrm{n}) - t_a^j(\mathrm{n}) = {}^T/_F \; (j \leq F \in \mathbb{N}). \tag{25}$$

where $t_a^j(n)$ is the arrival time of the *j* th train service at terminus *n* in cycle time *T*, t_a^{j+1}(n) is the arrival time of the next train service at terminus *n*. Cycle time *T* is generally 60 minutes for high-speed railways and departure time t_d^1(n) is fixed at 0 minutes. The running time of train service *j* from terminus *m* to terminus *n* (RT_{nm}) is given by:

$$RT_{nm} = t_a^j(\mathrm{n}) - t_d^j(\mathrm{m}) \in [l_{nm}\,, u_{nm}], \tag{26}$$

where, l_{nm} and u_{nm} are the lower and upper limits of the running time from terminus *m* to *n*. This time consists of the minimum running time, dwell time at intermediate stations and a running time supplement for robustness. The minimum running time is calculated by the standardised approach presented in Section 5.1.5. For a cyclic timetable, the running time for the opposite direction (RT_{mn}) is fixed as the same:

$$RT_{nm} = RT_{mn} = t_a^i(m) - t_d^i(n) \in [l_{mn}\,, u_{mn}]. \tag{27}$$

Assume that the *j* th train service arrives at terminus *n*, turns around there and departs in the opposite direction to the *i* th train service, the turnaround time at terminus *n* (TT_n) is given by:

$$TT_n = t_d^i(n) - t_a^j(n) \;\in [l_n\,, u_n], \tag{28}$$

where, l_n and u_n are the lower and upper limits of the turnaround time at terminus n (Peeters, 2003).

5.1.2 Requirements for infrastructure and rolling stock

The precise calculation of the required number of platform tracks and sets of rolling stock necessitates a detailed timetable. However, at the planning stage, it is possible to estimate these numbers roughly by using the running time, turnaround time, service frequency and cycle time. If all the platform tracks are fully utilized, the number of platform tracks required at the terminus *n* is given by:

$$NP_n = ceiling\,(\tfrac{TT_n + HT_n}{T/F})\,, \tag{29}$$

where HT_n is the required headway time between arrival and departure of trains at the terminus n due to the layout of the tracks and the signalling set-up. If the sum of turnaround time and technical headway time is less than or equal to *T/F*, the number of platform tracks is only one. The number of rolling stock required is given by:

$$NR = ceiling(\frac{2RT_{nm} + TT_n + TT_m}{T/F}) \text{ ,} \qquad (30)$$

where the numerator of the right hand side of equation (30) is the time required for one train to become available for departure from the origin terminus n, after finishing its round trip. If the time is less than or equal to the train's departure time plus *T/F*, the number of sets of rolling stock required is only one (Peeters, 2003).

5.1.3 Robustness and headway time

To create robust timetables, time supplements and buffer times are added. A time supplement is added to allow running times to let trains recover by themselves. A supplement is also added to turnaround times at termini to cope with the delayed arrival of trains so that the next train departure in the opposite direction can be on time. Buffer time is added between two consecutive trains that share the same track to prevent delay propagation, where an initial delay affects other trains and produces additional delays. In a cyclic timetable, if the time supplements are already included in the running time and turnaround time, the robustness depends on the spacing of consecutive trains sharing the same track (Peeters, 2003). Greater time on space separation between trains increases the amount of buffer time, resulting in higher robustness. However, the required service frequency in the cycle time does not allow the train separation to be arbitrary. In this context, a lower service frequency timetable has better robustness and, for timetables with the same service frequency, the timetable with identical intervals should be the most robust.

5.1.4 Headway time

Headway time is "the minimum time between trains that the signalling will permit, so that the train ahead does not affect a following train" (Woodland, 2004). Headway time is important for both safety and capacity (maximum number of trains per hour for a direction). For the calculation of the capacity of HS2, headway time has been presented in several reports (HS2 Ltd, 2011; Hunyadi, 2011; SYSTRA, 2011b). The theoretical headway time [s], based on the use of Level 2 of the European Train Control System with short train detection sections, is given by:

$$\text{Headway time} = \frac{(L_s+L_t+L_b+BD)}{v} + \text{C}, \quad (31)$$

where L_s, L_t, L_b are the lengths [m] of, respectively, the train detection section, the train and a buffer distance for safety. BD [m] is the braking distance of the following train. C is a constant time which derives from the signalling system behaviour and is of the order of a few seconds. v is the speed of the train [m/s] and BD is given by:

$$\text{BD} = \frac{v^2}{2dec}, \quad (32)$$

where dec is the braking rate [m/s^2]. A smaller headway allows more services, more flexible and robust timetabling.

5.1.5 Journey time and energy consumption

The journey time and energy consumption of the modelled high-speed railway line can be calculated by using the standardised approach which I developed (Hasegawa et al., 2015b). The approach consists of three steps: simulator coding and validation, data collection, simulation and analysis. First, the theoretical background of the simulator is presented. Energy consumption at the wheel and pantograph of a single train is investigated. The efficiency of the pantograph is assumed to be 100% throughout this paper. High-speed railways conventionally adopt an electrical traction system with regenerative braking, so energy is consumed at the wheel to propel the train, regenerated by braking and is also consumed for auxiliary needs such as ventilation. There are certain losses in this electrical traction system from the power stations to the wheel via the pantograph. Thus, the calculation should start from the wheel and then auxiliary power needs and losses in the system should also be considered. The force related to train motion is given as a form of Newton's second law of motion:

$$F_t - F_r - F_g - F_c = M_e a. \quad (33)$$

Each element of equation (33) is as follows: F_t: force provided by traction system, F_r: running resistance force, F_g: resistance force from gradient, F_c: resistance force from curve, M_e: effective mass, a: acceleration. Acceleration requires that the left hand side of equation (33) is positive, while for deceleration it must be negative. The train reaches its maximum achievable speed when tractive force and the three resistance forces (F_r, F_g and F_c) are equal. Tractive force is limited by tractive power and running resistance is a function of velocity. Effective mass is given by:

$$M_e = M_t(1 + \lambda) + M_p, \quad (34)$$

where M_t is tare mass, λ is rotary allowance (typically 5 - 15%), and M_p is payload.

Running resistance is given by:

$$F_r = A + Bv + Cv^2. \quad (35)$$

This equation is known as the Davis equation (Davis, 1926). *A* is the rolling resistance coefficient, *B* is the bearing friction coefficient, *C* is the aerodynamic drag coefficient, and v is velocity. At high speed, the contribution of aerodynamic drag becomes dominant. Resistance from a gradient is given by:

$$F_g = (M_t + M_p)g \sin\alpha \approx (M_t + M_p)g \times n/1000. \quad (36)$$

In reality, α is such a small angle that sin α can be approximated by tan α, which is generally measured as n [m] of rise or fall in one thousand metres, that is, ‰. Resistance from curvature is given by:

$$F_c = (M_t + M_p)g \times 1/1000 \times 700/R, \quad (37)$$

where *R* is the radius of a curve. This equation means that the resistance force of curvature has the same magnitude as a gradient force of 1 % gradient when the radius is 700 m (Hay, 1982; Brunger and Dahlhaus, 2008). In the case of high-speed railways, *R* is large enough to ignore the effect of F_c. The power of the traction system (P_t) and force provided by the traction system (F_t) and velocity (v) have the following relationship:

$$P_t = F_t\, v. \quad (38)$$

Energy consumption at the wheel (EC_{wheel}) and regenerated energy at the wheel (RE_{wheel}) are respectively calculated by the integration of forward force (F_f) and backward force (F_b) with respect to distance (x); journey time (T) is also calculated by the integration of time (t) of each calculation step:

$$\mathrm{EC_{wheel}} = \int \mathrm{F_f dx} = \int \frac{\mathrm{P_t}}{\mathrm{v_f}} \mathrm{dx}, \quad (39)$$

$$RE_{wheel} = \int F_b dx = \int \frac{P_t}{v_b} dx, \quad (40)$$

$$T = \int t dx = \int \frac{x}{v} dx, \quad (41)$$

where forward velocity is $\mathrm{v_f}$, and backward velocity is v_b. The energy consumption by auxiliary power needs (P_a) is a function of journey time (T):

$$EC_{auxiliary} = P_a\, T. \tag{42}$$

Energy consumption at the pantograph of a single train, *EC*, is given in terms of the efficiency of the transformer, κ, $0 \leq \kappa \leq 1$, of the traction system, η, $0 \leq \eta \leq 1$, and the efficiency of regeneration, λ, $0 \leq \lambda \leq 1$.

Using the simplified traction circuit shown in Figure 29, the energy consumption during motoring, EC_m, is:

$$EC_m = \frac{1}{\kappa}\left(\frac{1}{\eta}\, EC_{wheel} + EC_{auxiliary}\right) \tag{43}$$

and the energy consumption during braking, EC_b, is:

$$EC_b = \begin{cases} -\kappa\,(\lambda\, RE_{wheel} - EC_{auxiliary}), if\ \lambda\, RE_{wheel} > EC_{auxiliary} \\ \frac{1}{\kappa}(EC_{auxiliary} - \lambda\, RE_{wheel}), if\ \lambda\, RE_{wheel} \leq EC_{auxiliary} \end{cases} \tag{44}$$

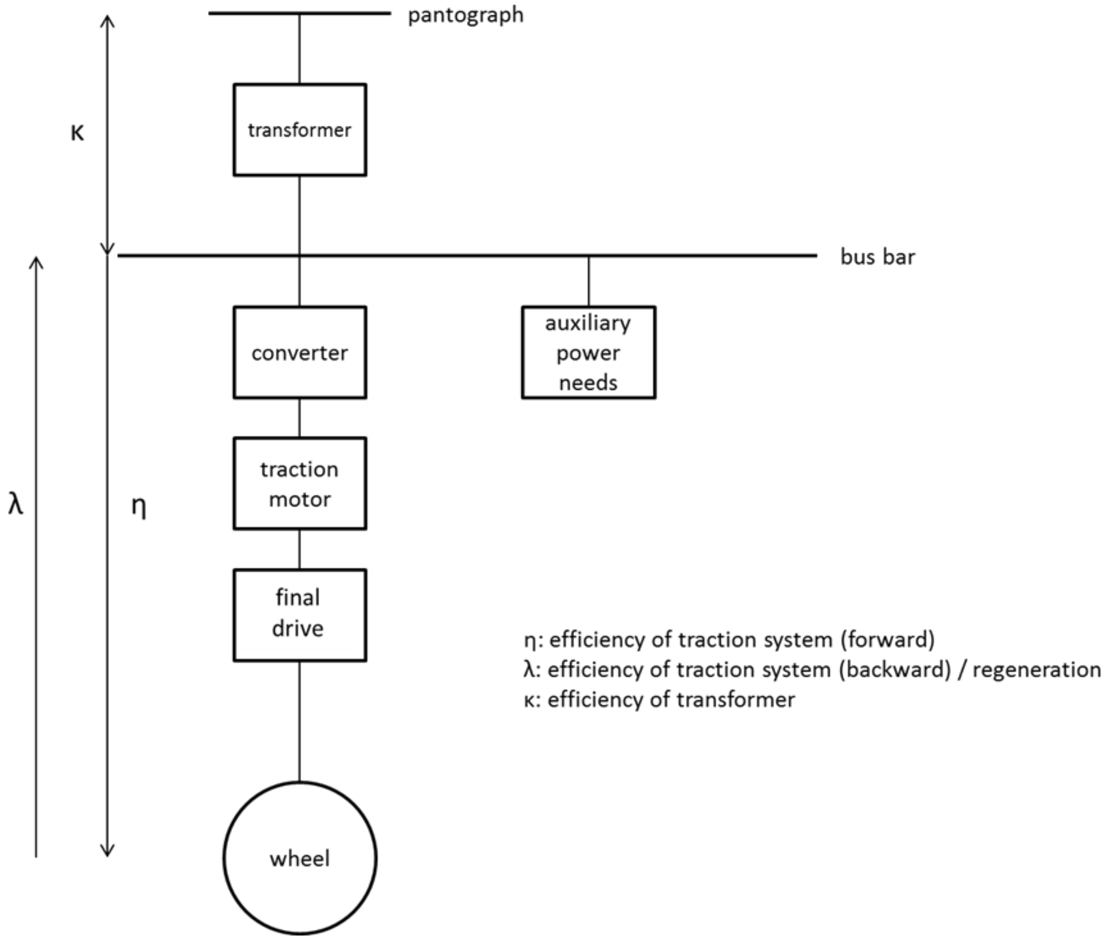

Figure 29 Simplified model of a traction circuit

I also make the following assumptions:

- the losses in the power transmission between the substation and the pantograph are zero;
- the efficiency κ (typically 0.95 to 0.98) of the main transformer is included in the efficiencies of the traction system and of regeneration, respectively η and λ.

Under these conditions, equations (43) and (44) reduce to:

$$EC_m = \frac{1}{\eta} EC_{wheel} + EC_{auxiliary} \quad (45)$$

$$EC_b = EC_{auxiliary} - \lambda RE_{wheel} \quad (46)$$

The main code to simulate single train movement and energy consumption is based on these equations. The following three steps are the standardised approach for the calculation of energy consumption.

5.1.5.1 Simulator coding and validation

The simulator should be validated by comparing the calculation results with those of previous studies and especially experimental data before conducting an original simulation. The specific requirements of the simulator are as follows:

1. Allow the input of arbitrary conditions of the line, vehicle and operation;
2. Repeated computation of continuously changing velocity and force with sufficiently small steps;
3. Calculate energy consumption for each step;
4. Produce a speed – distance curve, traction force and resistance force – speed curve, and altitude – distance curve in order to check whether or not the result is based on appropriate conditions.

5.1.5.2 Data collection

Data required for the simulation are listed in Table 22. They are divided into three categories: lines, vehicles and operations. Each category has the parameters required.

Table 22 Required data for simulation

Feature	Parameter (unit)
Line	Distance (km)
	Gradient (%)
	Speed limit (km/h)
Vehicle	Mass (tonne)
	Davis equation parameters (kN, kNs/m, kNs^2/m^2)
	Maximum traction force (kN)
	Power (kW)
	Auxiliary power needs (kW)
	Regenerative braking efficiency (%)
	Traction system efficiency (%)
	Number of seats
Operation	Maximum speed (km/h)
	Stops
	Braking rate (m/s^2)
	Driving style

5.1.5.3 Simulation and analysis

The purpose of the simulation and parameter settings should be verified before simulation. The result of the calculations should be carefully analysed with the following figures produced.

- Traction force and resistance force – speed curve: find the speed where the two lines cross. Check whether this speed is equal to or higher than the maximum line speed.
- Speed – distance curve: check whether or not the train speed reaches the maximum line speed.
- Altitude – distance curve: check whether or not it exactly matches the simulation conditions.

If these checks are fine, the simulation result can be regarded as a final result. If there is something wrong, each related parameter should be checked (Figure 30). For these three steps, a single-train simulator (STS) (Hillmansen and Roberts, 2007) is adopted. The STS can calculate the energy consumption for an arbitrary vehicle and route. It is also able to output the figures which the standard requires. The approach developed here can be used to assess earlier studies conducted in a different context, which is demonstrated in my published paper (Hasegawa et al., 2015b).

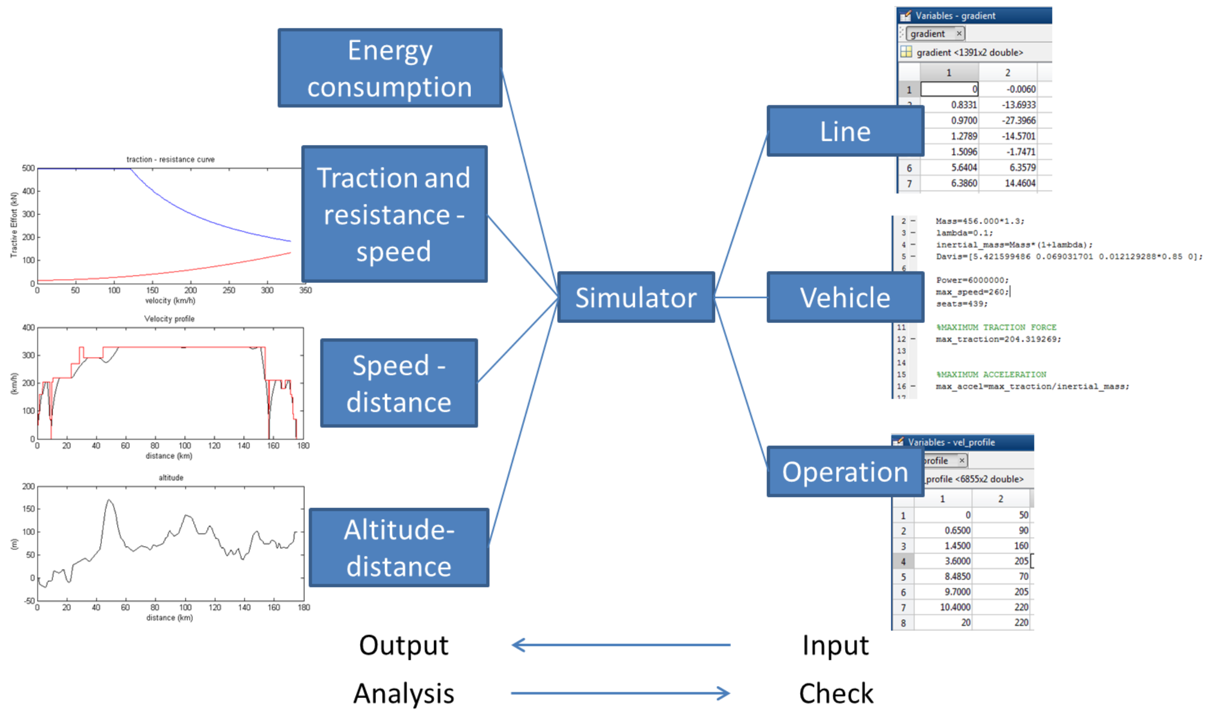

Figure 30 Structure and flow of the methodological standard

5.2 Value Stream Mapping

In this section the application of Value Stream Mapping (VSM) to high-speed railway operations is discussed. Before conducting VSM we need to ask the question, "What is the value for customers?" This helps to diagnose and differentiate the value contributions of different activities (Rother and Shook, 2003) (see Section 2.7.1). Customers use trains to reach a particular destination in safety, on time and quickly. From this analysis, it could be said that trains create value for customers when they are moving with passengers. In contrast, when a train rests at a station or in a depot, it does not create any value. Running times on services between stations are value added (VA) steps, dwell times at stations for boarding and alighting are VA and turnaround time at termini, other than for alighting and boarding are non-value added (NVA) steps. An example of a VSM for one train travelling between two termini is shown in Figure 31.

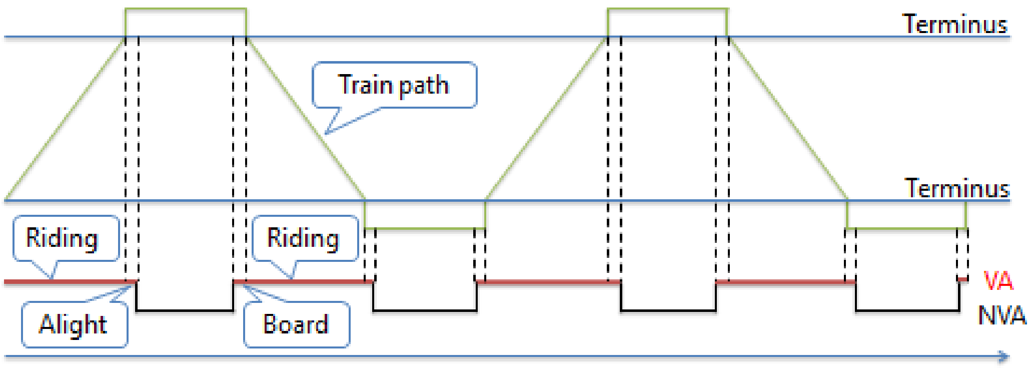

Figure 31 Value stream map for one train operating between two termini

Turnaround time at a terminus consists of time for alighting, handover, restocking of supplies, cleaning, checks for departure and boarding. Within the turnaround time, time for handover, restocking, cleaning and checks for departure are NVA for customers. According to the Lean principles, NVA steps are always considered as waste. In Figure 32, three NVA steps for three trains are shown to take place at the same time, which may increase the number of platform tracks required at the terminus. Currently, high-speed railway rolling stock is typically between 200 m and 400 m long (UIC, 2013b). Longer trains require longer platform lengths, which directly increases the cost of construction and embedded energy. Termini for high-speed railways are generally located in the centre of large cities such as London, Paris and Tokyo, which means that the cost of land take and construction is extremely high. Conversely, if high-speed railway operation is possible with fewer platform tracks at termini, by reducing the NVA steps during the turnaround time for requirements other than alighting and boarding, the initial cost and embedded energy of high-speed railways can be reduced and the non-necessary usage of additional massive quantities of resources can be avoided. From the result of the robustness assessment conducted in the previous chapter, it is suggested that a faster signalling reaction time is most important for the robustness of termini. On the other hand, having more platform tracks does not show a clear benefit for robustness. Thus, the result of VSM analysis can be adopted for cost reduction activities.

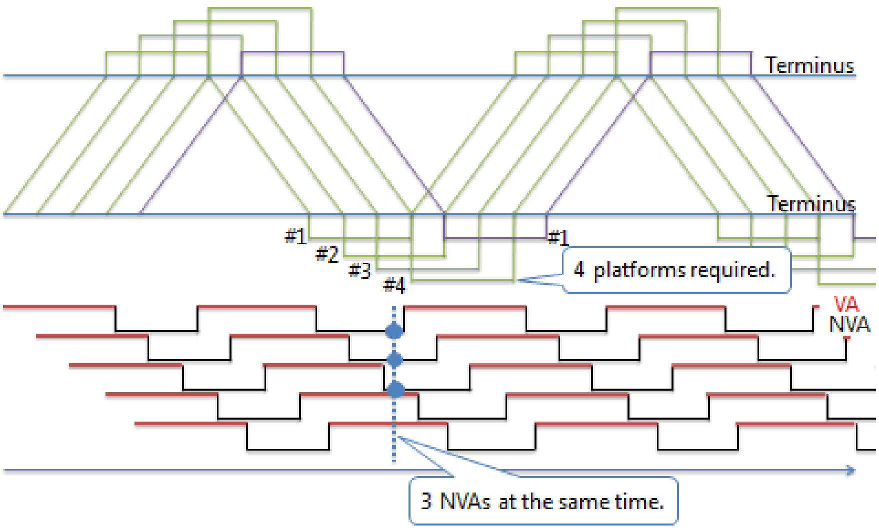

Figure 32 Waste (platforms) associated with NVA (turnaround time used for activities other than alighting and boarding)

5.3 Turnaround

Through the VSM analysis conducted in the previous section, turnaround time for activities other than alighting and boarding is identified as a NVA step and it is found that the cumulative effect of a long turnaround time could affect the number of platform tracks required. The result of the robustness assessment of terminus turnaround arrangements conducted in the previous chapter also shows that the benefit of having additional platform tracks is limited.

The question arises, "Why do we need platforms?”. Figure 33 shows the functional decomposition of occupying a platform and the related physical facilities around a platform (read the diagram from the right-hand side). One of the objectives is to reduce the cost of purchasing rolling stock. To this aim, increasing the efficiency of train use is important and turning a train around at a terminus is a good option, because the same train can be used for the journey in the opposite direction. To conduct turnaround, a train needs to be parked for some time, which requires a dedicated track for the train. Also, passengers need to be unloaded and loaded, so access to a train should be provided, which requires a platform. If the turnaround becomes longer, more dedicated tracks and platforms are required. A longer turnaround time decreases the efficiency of train use, which results in an increase in the number of train sets required. Conversely, if turnaround speed increases, the number of dedicated tracks, platforms and train sets can be reduced (see equation (29) and (30)).

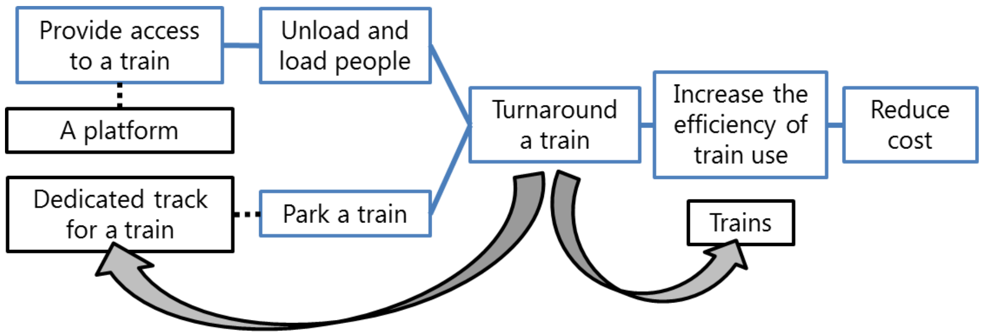

Figure 33 Functional decomposition of occupying a platform and relationship between facilities around a platform.

5.4 Application of the Just In Time concept to running time optimisation

As presented in Section 2.7.2, Just In Time (JIT) is a key concept of the Lean principles. In this section, it is applied to high-speed railway operations in order to realise faster turnaround with fewer platforms.

An example of JIT presented in Section 2.7.2 is as follows: if the distribution of products is scheduled to follow immediately after the completion of production, with no delay, the need for storage is eliminated. This analogy is applicable to turnarounds at termini. Turnaround time is time waiting for the next departure, and the platforms for the waiting trains are the equivalent of the warehouse to store the products. Departure times are fixed for commercial reasons in a cyclic timetable, so shorter turnaround should be realised by shifting the arrival time later in equation (28). To maintain the robustness of the timetable, the amount of time supplement for running and turnaround should be kept at the original level. Thus, the running time should be extended to realise the target faster turnaround time (see Figure 34).

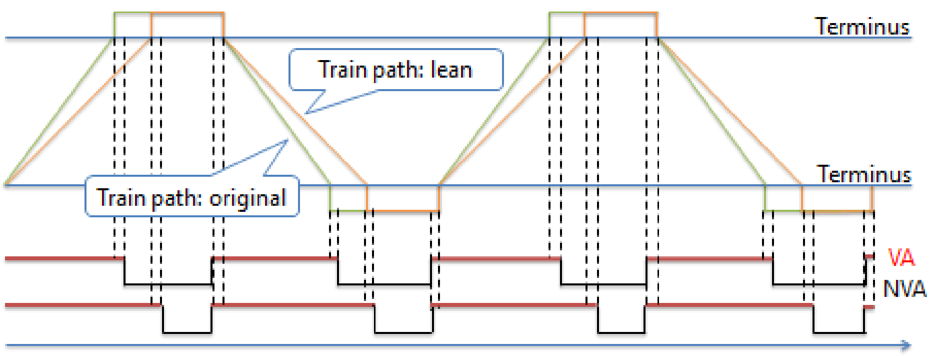

Figure 34 Comparison between the original case and the Lean case with faster turnarounds and longer running time

Clearly, the passengers experience a longer period on board the train but the overall journey time can be held at the same level by reducing the NVA access time, e.g. by providing multiple escalators along the platforms.

An additional benefit of running time optimisation is that propulsion energy is saved, because the operational speed is decreased. This can be regarded as the elimination of unnecessary very high speed. The time supplement for turnaround is for absorbing arrival delays and thus keeping the next train departure on time. If the punctuality of arrivals is improved through an additional running time supplement, decreased supplemental time for turnaround should not have a negative effect on the robustness of the timetable. In fact, the robustness assessment result suggested that having buffer times for the running time between the station approach and platforms is better than for turnaround time. It should also be mentioned that for a high-speed range, such as over 200 km/h, higher speed always increases the required minimum headway between two consecutive trains (see Section 5.5.4 later), so reducing the speed slightly decreases the headway and improves the robustness. This Lean operation can thus reduce the number of platforms required without decreasing the level of robustness (Figure 35), however, from equation (30), the number of trains required is the same as that for the original timetable because the sum of the running time and turnaround is the same as in the original case.

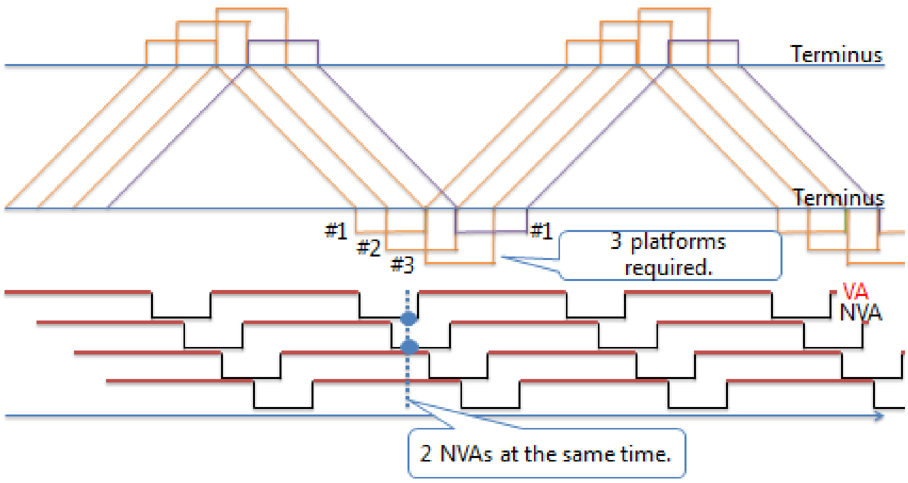

Figure 35 Associated benefit of faster turnarounds (fewer platforms) and running time extensions

5.5 Case study 1: Application of JIT to running time optimisation

A case study of this Lean approach to railway improvement is presented in this section. High Speed Two (HS2) is chosen as a case study. The benefits and disadvantages of reducing the maximum speed are discussed.

5.5.1 High Speed Two (HS2)

High Speed Two (HS2) will start its operation with a maximum speed of 330 km/h from London to Birmingham in 2026 and will be extended to Manchester and Leeds in 2033. It aims to operate 18 trains per hour from London Euston station (HS2 Ltd, 2012b). It is planned that this terminus will have 11 platforms for HS2 (HS2 Ltd, 2013). From these figures and equation (29), if the required headway time between arrival and departure at Euston were to be 3 minutes, the allowable turnaround time at the terminus can be estimated as 33 minutes. For journey time, energy consumption and headway calculation, in HS2 Phase One, the planned maximum operating speed is 330 km/h in order to obtain a margin, while the maximum line speed is 360 km/h. In this section, the route (post public consultation) from London Euston to Birmingham Curzon Street has been simulated for maximum speeds of between 200 km/h and 360 km/h (step: 10 km/h) for two coupled 200 m long Automotrices Grande Vitesse 11 (AGV-11). The journey time and energy consumption of a single train, headway time for plain line, and the number of rolling stock required for each maximum speed are presented. In addition to these results, operational options with lower maximum speeds are discussed.

5.5.2 Turnaround and number of platforms

There are faster turnaround examples of both existing high-speed railways and conventional inter city services: the turnaround for Tohoku, Joetsu and Hokuriku Shinkansen service at Tokyo station takes 12 minutes, while the Tokaido Shinkansen service takes 16 minutes at Tokyo station and the Pendolinos at London Euston station takes 25 minutes. Based on these figures, the number of platforms required for different service frequencies and turnaround times for a cyclic timetable are estimated for the range of turnaround times from 12 minutes to 33 minutes by equation (29) with the required headway time between arrival and departure of 3 minutes. (Table 23). For the planned service frequency of 18 trains per hour, turnaround times of 30, 27, 23, 20, 17 and 13 minutes are thresholds for fewer platforms. For example, by reducing the turnaround time by 3 minutes, 10 platforms become sufficient for the operation of 18 trains per hour. Conversely, in spite of reducing the number of platforms, 11 platforms and 30 minutes of turnaround time could allow the operation of 20 trains per hour.

Table 23 The number of platforms required for different service frequencies (F: trains/hour) and turnaround time (TT: min)

TT \ F	15	16	17	18	19	20
12	4	4	5	5	5	5
13	4	5	5	5	6	6
14	5	5	5	6	6	6
15	5	5	6	6	6	6
16	5	6	6	6	7	7
17	5	6	6	6	7	7
18	6	6	6	7	7	7
19	6	6	7	7	7	8
20	6	7	7	7	8	8
21	6	7	7	8	8	8
22	7	7	8	8	8	9
23	7	7	8	8	9	9
24	7	8	8	9	9	9
25	7	8	8	9	9	10
26	8	8	9	9	10	10
27	8	8	9	9	10	10
28	8	9	9	10	10	11
29	8	9	10	10	11	11
30	9	9	10	10	11	11
31	9	10	10	11	11	12
32	9	10	10	11	12	12
33	9	10	11	11	12	12

5.5.3 Journey time and energy consumption

Journey time and energy consumption are calculated by the proposed standardised approach (see Section 5.1.5). The parameters required by the approach are shown in Table 24. The calculated journey times and energy consumption values are shown in Figure 36. The journey at 330 km/h takes about 49 minutes, which is the same as is given in the project specification of HS2 (HS2 Ltd, 2012b). Journey time decreases and energy consumption increases as the maximum speed increases. Energy consumption is expected to increase in proportion to the square of the speed, however, this profile appears to be linear because the train can only run part of the route at maximum speed (see Figure 37). Thus, changing the maximum speed only affects a very small portion of the journey.

Table 24 Required parameters for the STS of HS2 Phase One from London to Birmingham.

Parameters		Value	Sources
Line	Distance	175.230 km	(ARUP, 2012)
	Gradient	Route after consultation	(Department for Transport, 2013a)
	Speed limit	Route after consultation	(ARUP, 2012; Department for Transport, 2013a)
Vehicle	Mass	820 t (tare) + 82.5 t (passenger)	(ARUP, 2012)
	Davis equation parameters	A=14.4 kN, B=0.084 kNs/m, C= 0.013 kNs^2/m^2	(Jernbaneverket, 2011)
	Maximum tractive force	546 kN	(UIC, 2013b)
	Power	16.8 MW	(UIC, 2013b)
	Auxiliary power needs	1170 kW	(Jernbaneverket, 2011)
	Regenerative braking	80% efficiency	(Watson et al., 2009)
	Traction system efficiency	0.823	(Watson et al., 2009)
	Number of seats	1100	(ARUP, 2012)
Operation	Maximum speed	200 – 360 km/h	Author
	Stops	2 stops, dwell time is 2 min	(ARUP, 2012)
	Braking rate	0.78 m/s^2	(ARUP, 2012)
	Driving style	Flat out	(ARUP, 2012)

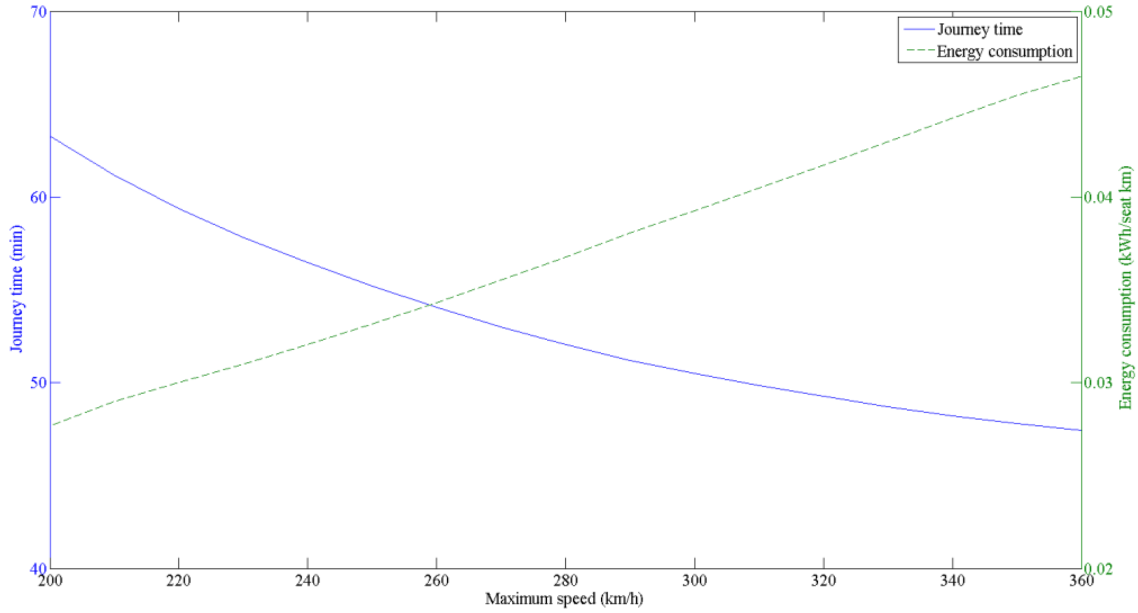

Figure 36 Journey time and energy consumption of HS2 Phase One from London Euston to Birmingham Curzon Street

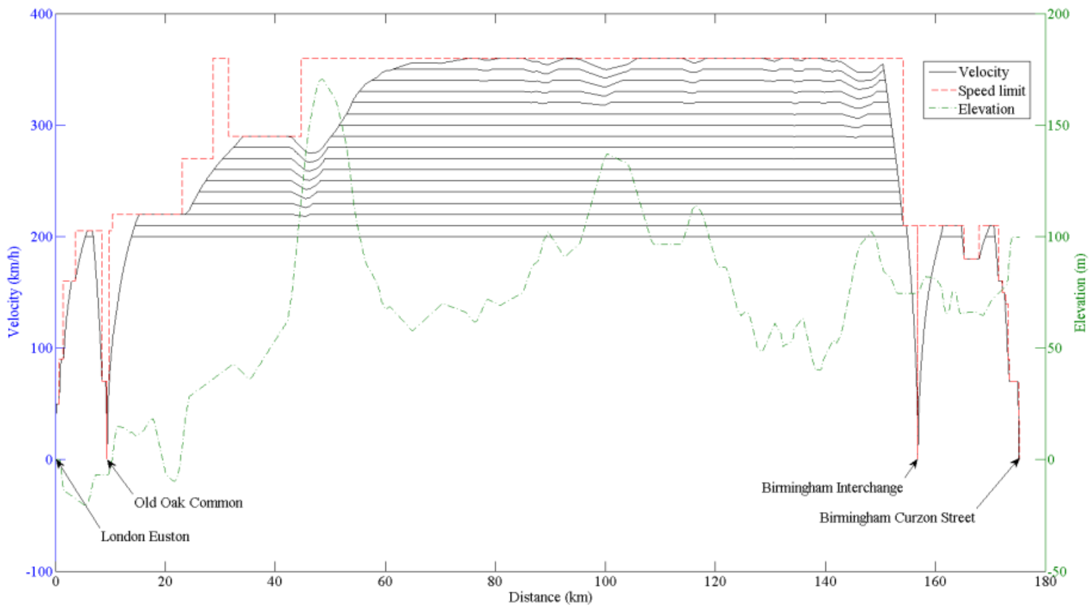

Figure 37 Speed-distance diagram for maximum speeds from 200 km/h to 360 km/h (step-size: 10 km/h) and elevation of the route from London to Birmingham

The speed-distance graph in Figure 37, which shows the route from London Euston to Birmingham Curzon Street, includes two intermediate stops, namely, Old Oak Common and Birmingham Interchange.

5.5.4 Headway time

The parameters needed for headway time calculation are shown in Table 25. They are available in the reports produced by HS2 (HS2 Ltd, 2011), where the headway time for plain line with homogenous operation is given with 1600 m train detection sections. However, the train detection section length has not been finally decided, so headway times for four different detection lengths have been calculated. The calculated headway time on plain line is shown in Figure 38. The headway time at 360 km/h with 1600 m train detection sections is 116 seconds, which is the same as in the HS2 report (HS2 Ltd, 2011).

HS2 Ltd calculated the headway time for the line speed of 360 km/h, even though the normal operating speed is 330 km/h, because the train can run at the higher speed in the case of delays. The calculation of headway time in our research adopts this concept, in which the headway time is used at a speed up to 30 km/h higher than the operational speed. The headway time increases with speed above an optimal value because the braking distance increases with the square of the speed. Shorter train detection sections give rise to shorter headway times; however, this advantage becomes smaller as speed increases.

Table 25 Parameters for the calculation of headway time for HS2 Phase One

Length of train detection section (L_d)	0 m, 400 m, 800 m, 1600 m
Length of train (L_t)	400 m
Length of buffer (L_b)	300 m + 0.02*(L_d + L_t) m (Odometry tolerance is 2%)
Deceleration rate (dec)	0.687 m/s^2
Reaction time of the signalling system (C)	39 s

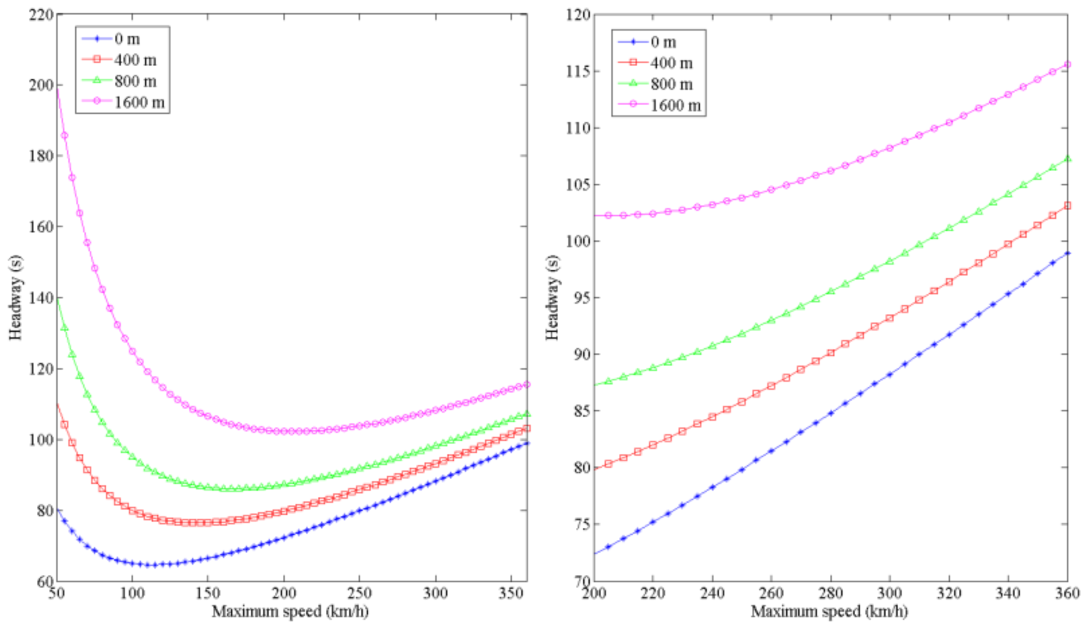

Figure 38 Headway time for plain line for different train detection section lengths

Figure 38 shows the headway times for train detection section lengths of 0 m (equivalent to moving block), 400 m, 800 m and 1600 m for maximum speeds between 50 km/h and 360 km/h (left) and between 200 km/h and 360 km/h (right).

5.5.5 Number of trains required

The proposed service frequency of HS2 Phase One from London Euston to Birmingham Curzon Street is 4 trains per hour at peak times and 3 trains per hour during off-peak times (HS2 Ltd, 2012b). A cyclic timetable at peak times with 15 minutes between departures was modelled as shown in Figure 39: A train departs from each of the terminal stations at 8:00 and turns around at the other terminal, becoming the opposite direction train that departs at 9:15. At a maximum operational speed of 330 km/h, the journey time is 49 minutes, requiring that the turnaround time should be less than 26 minutes in order to realise this timetable with 10 train sets. The allowable turnaround times of this timetable with 10 train sets for different journey times is shown in Figure 40. An increase in journey time directly reduces the allowable turnaround time. Several reference minimum planned turnaround times at terminals are also shown in the figure. Tohoku, Joetsu and Hokuriku Shinkansen turnaround times at Tokyo station are 12 minutes, the Tokaido Shinkansen turnaround time at Tokyo station is 16 minutes and the Pendolino at London Euston station is allowed 25 minutes. If the turnaround time were the same as the lowest amongst the existing high-speed railways, the model timetable with 10 train sets could be realised with lower maximum speeds of operation. On the other hand, if the turnaround time is fixed at 26 minutes, any decrease in operational speed below 330 km/h requires two additional train sets for the timetable to be realised.

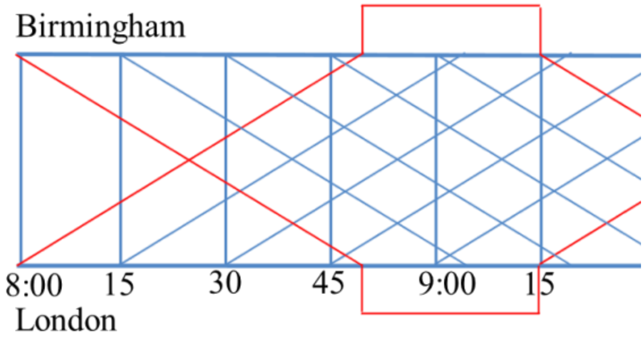

Figure 39 Modelled timetable for the morning peak of HS2 Phase One between London and Birmingham

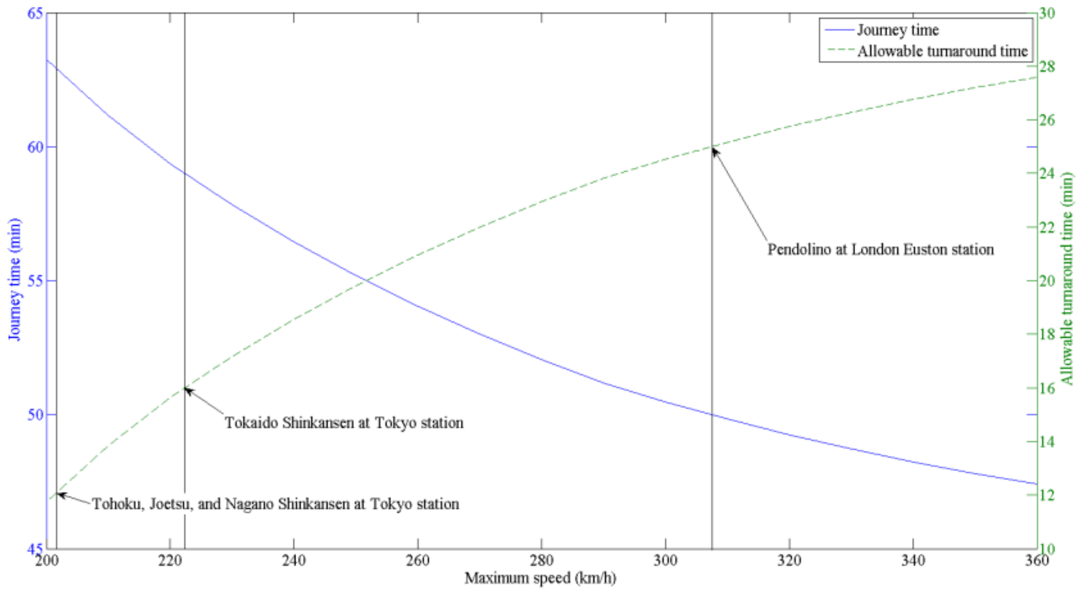

Figure 40 Journey time and allowable turnaround time for the modelled timetable of maximum speeds between 200 km/h and 360 km/h with 10 train sets

In Figure 40, the vertical lines indicate reference turnaround times of the Tohoku, Joetsu, and Hokuriku Shinkansen services at Tokyo station, those of the Tokaido Shinkansen at Tokyo station and the Pendolino services at London Euston station.

5.5.6 Analysis of operational options

Figure 41 shows a summary of the effects of changing the maximum operating speed for HS2 Phase One on the performance indicators of journey time, energy consumption, headway time and allowable turnaround time for 4 trains per hour with 10 train sets. The performance indicators are presented as a percentage of their value when operating at the current planned HS2 maximum speed of operation, that is, 330 km/h. As mentioned in Section 5.5.1, for the headway time, the minimum headway at 30 km/h higher than operational speed is adopted.

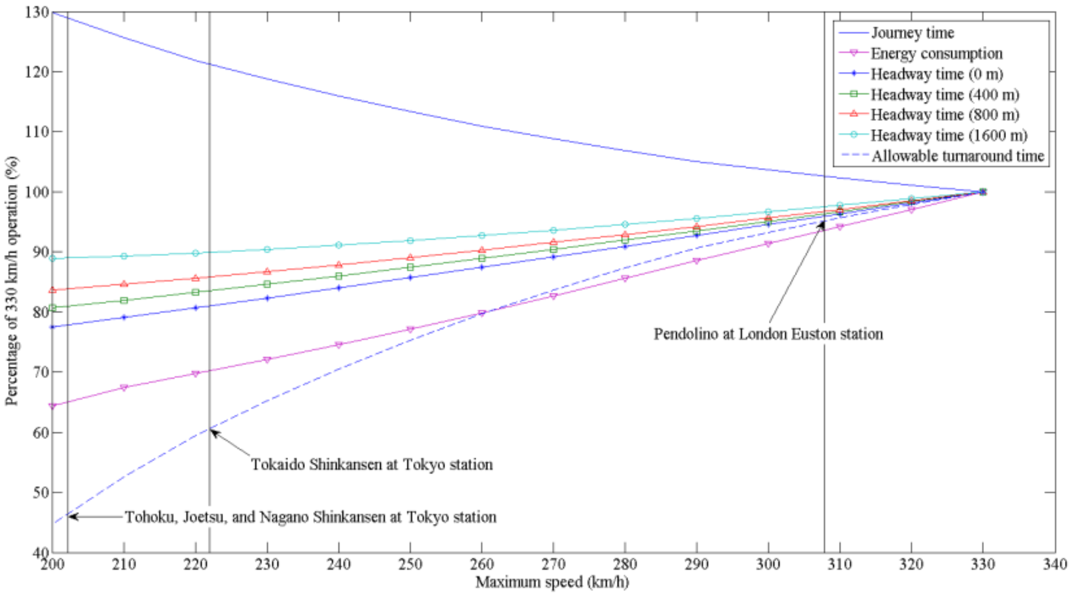

Figure 41 Performance indicators as percentages of values for 330 km/h operation

In Figure 41, the headway times are shown for different lengths of train detection sections (0 m, 400 m, 800 m, 1600 m). Reference turnaround times at terminals for the Tohoku, Joetsu, and Hokuriku Shinkansen services, the Tokaido Shinkansen and Pendolino services are shown as vertical lines. From this, some operational options with different maximum speeds can be suggested.

For example, a maximum speed of 310 km/h increases journey time by 2.3 %, but reduces energy consumption by 5.7 %, it reduces headway times by 2 - 3 % for each train detection section length, and can be realised with the same minimum turnaround time as the Pendolino at London Euston station (25 minutes). A maximum speed of 230 km/h increases journey time by 21.8 %, however, it reduces energy consumption by 27.9 %, headway time by 10 - 20 %, depending on train detection section length, and the timetable for 4 trains per hour with 10 train sets can be realised with the minimum turnaround time of Japanese Shinkansen trains at Tokyo station. Improving turnaround operations can absorb the effects of decreases in maximum speed, and allows the realisation of lower speed operation with less energy use and headway time without requiring more train sets.

5.5.7 Implications of shorter journey time

How does an extended running time affect customer satisfaction? A widely accepted premise of transportation planning is that journey time is wasted time and, hence, that reducing journey time increases demand (Jara-Diaz, 2000). However, the benefit of reducing journey time has recently become a topic of discussion. Lyons and Urry (Lyons and Urry, 2005) question the traditional approach of travel demand analysis, which is based on the assumption that journey time is completely unproductive, and they show several ways of productive use of the time in order to challenge this assumption. In a subsequent paper, they collected data on the use of the journey time in railway travel by age for Great Britain and showed that, even in the age range from 16 to 25, only 30% of passengers thought the journey time was wasted time (Lyons et al., 2007). Berry and Hamilton (Berry and Hamilton, 2010) showed the data of mobile phone use by age on trains and on platforms in Melbourne and found that less than 30% of people in the age range from 41 to 60 and less than 20% of people older than 60 had never used a mobile phone during a journey. Other than voice calls, there are several ways to use a mobile phone on the train or platform. Gripsrud and Hjorthol (Gripsrud and Hjorthol, 2012) also criticized the conventional assumption of unproductive journey time by collecting data of journey time use on trains in Norway, which showed that only 10% of passengers did not use the time for any productive purpose at all. In the context of high-speed railways, Givoni and Banister (Givoni and Banister, 2012) point out that the development of high-speed railways in Japan and France did not aim to reduce journey time, but rather the aim was to increase capacity; they question whether Britain will set a new standard for higher speed in order to construct a new high-speed railway. They also suggest an optimal speed for high-speed railways in terms of holistic planning of transport and lower carbon emissions, and recommend the average speed should be about 200 km/h and the route distance should be less than 500 km (Banister and Givoni, 2013). From these studies, it could be said that the benefit of shorter journey time is overestimated. Conversely, extended running time may have a less negative effect on travel demand than we currently assume. However, further research on this topic should be conducted for a detailed quantitative discussion.

5.5.8 A buffer time from the difference between WTT and NRT

In Britain, train schedules include buffer time which can be used for extending journey time and reducing turnaround time. There are two timetables, the working timetable (WTT) and the national rail timetable (NRT). The WTT is used by the railway industry, whereas the NRT is used for passengers as a published timetable. The arrival time appearing in the WTT is generally earlier than that of NRT, so as to obtain a buffer time for maintaining a high public performance measure (PPM) (Network Rail, 2015b). The PPM shows the percentage of trains which arrive at their terminating station on time and, for long distance services, arrivals within ten minutes are regarded as on time (Network Rail, 2015a). When attempting to optimise arrival timing, this buffer time from the difference between the WTT and NRT can be utilised. Passengers buy tickets according to the published NRT, not the WTT, so using this buffer for extending the running time cannot damage passenger demand.

The current practice of railway operation in Britain, which allows early arrival, unnecessarily consumes capacity at stations. For example, if the arrival time in the WTT at the terminus were to be 8:00 and that in the NRT were to be 8:03, the WTT would allow 3 more minutes of (unnecessary) turnaround time at the terminus (Figure 42). This is the same as the case discussed in Section 5.5.6. In real life operations, 49% of trains arrived early in the year 2010-2011 (Figure 43). There is potential to improve the efficiency of capacity usage through training drivers to arrive on time, according to the NRT. Drivers in Britain do not note the passing time of stations which are not stopping stations, whereas drivers in Japan check the passing time for all passing stations. Japanese drivers must arrive on time at stopping stations, because the arrival time of the drivers' timetable is the same as the timetable given to the passengers in terms of minutes. Drivers' timetables also include the unit of seconds so they are more detailed than passengers' timetables. Also, a Driver Advisory System (DAS) can support drivers to control their trains more efficiently (Network Rail, 2013b). With better operation, the amount of required resources will be reduced.

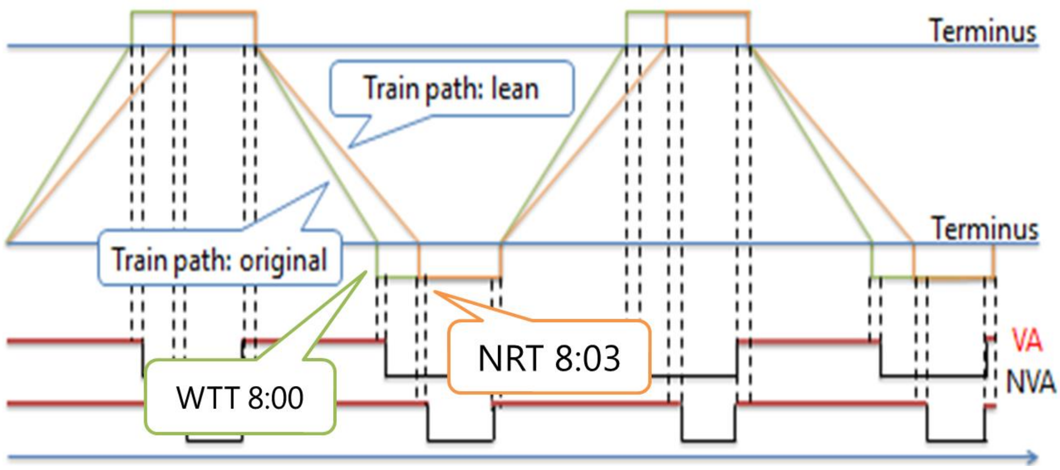

Figure 42 Different turnaround times due to the difference between the arrival times of the WTT and NRT

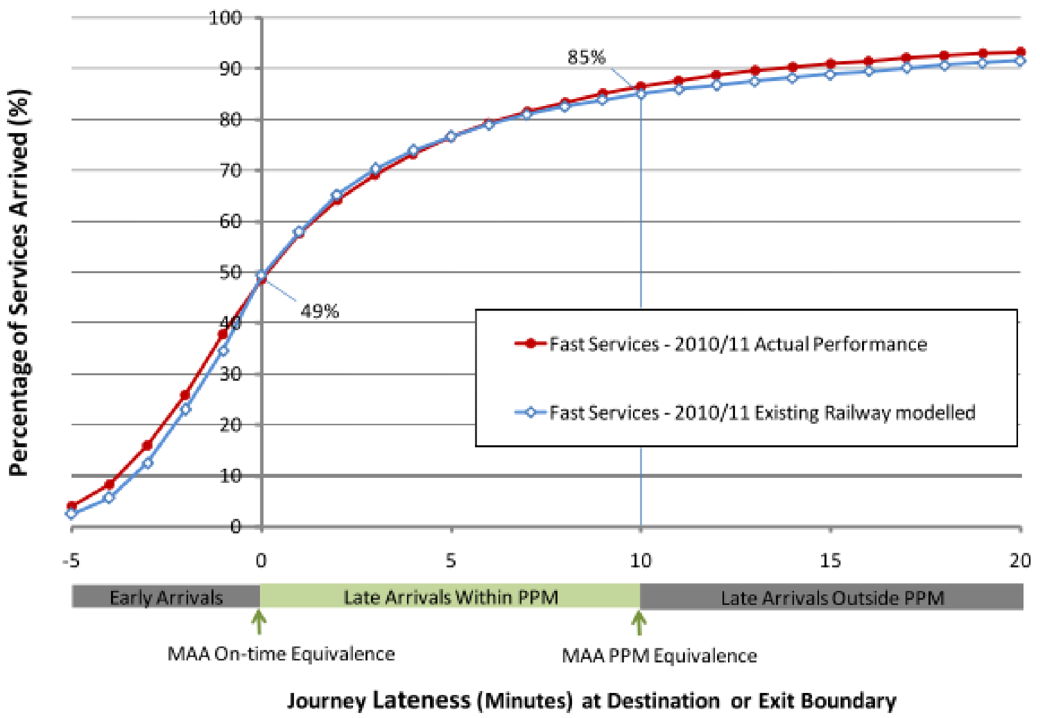

Figure 43 Actual performance of Britain's trains in 2010 – 2011 (Best and Hyland, 2012)

5.5.9 Conclusions of the case study

It is suggested that the optimisation of the running time is preferable to using the minimum running time, in order to support a just-in-time arrival of the train at the station and still maintain the established departure schedule. The combination of an extended running time along with the faster turnaround will maintain the same level of robustness as the original timetable. Furthermore, extending the running time can be regarded as elimination of a wasted speed enhancement on top of the optimal speed and gives the additional benefit of energy saving, which contributes to long term savings of operational cost and resource usage. Shorter headway times could also improve the robustness of the operation. Further study is recommended to resolve the quantitative discussion of the negative effect of the extension of running time on travel demand.

5.6 Single Minute Exchange of Die concept application

The Single Minute Exchange of Die (SMED) concept, widely used in modern manufacturing is applied to the terminus turnaround operations in order to reduce the turnaround time.

5.6.1 Current turnaround

Turnaround consists of the alighting and boarding of passengers, handover and checking for the next departure of train crews, and cleaning, which consists of three tasks: toilet cleaning, wiping tables and collecting rubbish. The activities other than cleaning are internal setup at the initial state (Figure 44). Toilet cleaners only clean toilets, while coach cleaners wipe tables and collect rubbish. At least some of the cleaning work has to be done between alighting and boarding. Handover and checking, which are done during that period, are tasks of relatively shorter duration than cleaning, especially for long rolling stock such as high-speed trains. Thus, reducing the duration of cleaning directly reduces the turnaround time, until its duration becomes shorter than the duration of handover plus checking.

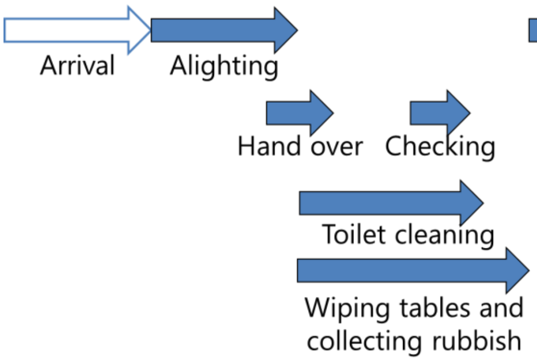

Figure 44 Activities during train turnaround at termini

5.6.2 Application of SMED to the turnaround activity

Turnaround at termini can be regarded as setup for the next departure and the SMED concept can be applied to the turnaround at termini. The next step in SMED is to identify setups that can be converted from internal to external. The alighting and boarding of passengers and handover must be done after the arrival of the train and checking for departure must be done before departure. Toilets should be open for the duration of the journey and tables should not be wiped when passengers are sitting in the seats. These four tasks are hard to turn into external setups. However, collecting rubbish can be done before arrival as an external setup (Figure 45). By doing this, the cleaning tasks of coach cleaners which are conducted as internal setups are reduced from 2 to 1, resulting in a reduction of the cleaning time of the coaches during turnaround. This reduction reduces the overall cleaning time during turnaround until the duration of wiping tables becomes shorter than toilet cleaning. As mentioned in Section 5.6.1, the turnaround time can be reduced by this improvement to cleaning.

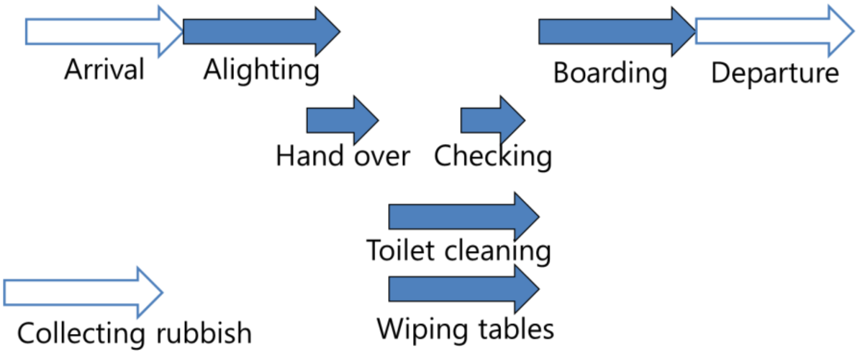

Figure 45 The application of SMED to turnaround at termini

5.7 Case study 2: SMED and the turnaround task

SMED turnaround is already applied in the UK. This good practice is described and compared with the cleaning routine for Japanese high-speed railway trains. Finally, a possible improvement for HS2 is discussed.

5.7.1 On-board cleaner Voith Industrial Service Limited

Voith Industrial Service Limited is the contractor which cleans Virgin Trains Pendolino (Class 390). An on-board cleaner is responsible for collecting rubbish on the train before arriving at the terminus. This method of cleaning is efficient. For instance, an 11 car train from Manchester that arrived at Euston at 11:20 am on 2nd of July 2014 produced 10.5 bags of rubbish, however, 6 of them had already been collected by an on board cleaner before arrival (Figure 46).

Figure 46 Bags of rubbish collected by an on-board cleaner

5.7.1.1 Comparison between Voith and TESSEI

Table 26 shows a comparison between Voith and the Japanese train cleaning company, TESSEI. TESSEI is famous for its very fast turnaround cleaning for Tohoku, Joetsu and Hokuriku Shinkansen trains at Tokyo station: they manage to clean 10-car Shinkansen trains within 7 minutes with 22 cleaners. The time for alighting and boarding is 5 minutes, which makes it possible to turn the train around within 12 minutes (Endo, 2012). On the other hand, Voith cleans 11 car Pendolinos within 15 minutes with 5 cleaners and the time for alighting and boarding is 10 minutes, which allows the train to turn around within 25 minutes. The difference in the time for alighting and boarding is due to the station design and passenger flow management; multiple escalators and stairs are provided at the platforms of Tokyo station and passengers are allowed to wait on the platforms, while Euston station allows passengers to access the platforms via only one end of the platform after the cleaning is finished.

Table 26 Comparison between Voith with 11 car Pendolino and TESSEI with 10 car Shinkansen

	Voith	*TESSEI*
Vehicle	Class 390 (11 cars)	E5 (10 cars)
Train length (m)	265	253
Number of seats	591	731
Turnaround time (min)	25	12
Cleaning time (min)	15	7
Coach cleaners	3	17
Toilet cleaners	1	5
On-board cleaners	1	0

5.7.2 High Speed Two (HS2)

To extrapolate cleaning times for the HS2 case, where the trains are 400 metres long (HS2 Ltd, 2012b), I asked the site manager of Euston to estimate the number of cleaners required for cleaning an imagined 18 car Pendolino within 7 minutes with the normal standard of cleanliness; the answer was compared with a case of cleaning done by TESSEI (Table 27). TESSEI cleans 17 car Shinkansen trains within 7 minutes with 44 cleaners and the train can turnaround within 12 minutes (Endo, 2012; International Hospitality and Conference Service Association, 2013). In contrast, Voith could clean 18 car Pendolinos within 7 minutes with 11 cleaners (Tajni, 2014).

Table 27 Comparison between imagined 18 car Pendolino cleaning case with better station design and passenger flow management and TESSEI with 17 car Shinkansen train

	Voith	*TESSEI*
Vehicle	Class 390 (18 cars)	E5 + E6 (17 cars)
Train length (m)	434	401.7
Number of seats	916	1069
Turnaround time (min)	12	12
Cleaning time (min)	7	7
Coach cleaners	6	35
Toilet cleaners	3	9
On board cleaners	2	0

The figures given by Voith have not yet been validated and the required standard of cleanliness for each case is different, hence, the performance of each company cannot be simply compared. However, the quality of the cleaning done by Voith is enough to satisfy British customers; customer satisfaction regarding the cleanliness inside trains operated by Virgin Trains is 89 %, although the average of all Train Operating Companies (TOCs) is 75% (Passenger Focus, 2014). Thus, it can be said that the cleaning done by Voith works well in the UK, and having on-board cleaners could reduce the time for cleaning significantly and can reduce turnaround time. For the example shown in Section 5.7.1.1, 9 cleaners at Euston and 2 on board cleaners could clean a 400 metre train within 7 minutes, which enables the train to be turned around within 12 minutes, assuming better station design and management of passenger flow. These conditions require only 5 platforms (Table 23).

5.7.3 Conclusions to the SMED case study

To reduce the turnaround time, SMED has already been introduced; a case of good practice in the UK is studied. From the case study, it is shown that having cleaners on board during travel can reduce the cleaning time for coach cleaners during the critical period of turnaround. This allows the overall turnaround time to be reduced until the duration of the cleaning time becomes shorter than the duration of handover plus checking, resulting in a reduction in the number of required platforms. This result suggests that it is worth considering a comparison of the cost of construction of additional platforms and the cost of having additional cleaners at the infrastructure design phase, although this type of comparison is uncommon for such a large construction project.

5.8 Confirmation of operational robustness

Through the approach combining the Taguchi method and the Lean principles, a terminus design with fewer platforms but high capability in terms of signalling reaction time has been suggested. This option is examined by using the simulator developed for the robustness assessment. Four cases of the combination of control factors are set (Table 28) and the simulation results for three noise factors are shown in Table 29.

Table 28 Simulation setting for the confirmation of operational robustness

Case	*Factors and levels*			
	A	B	C	D
Case 1	1	1	1	1
Case 2	1	1	1	2
Case 3	1	1	1	3
Case 4	3	3	3	3

Table 29 Result of the simulation for the confirmation of operational robustness, O1: departure delay of the final train (min), O2: the number of times trains cannot find an available platform, O3: the number of conflicts between arrival and departure trains

		Case 1	*Case 2*	*Case3*	*Case 4*
Normal short delay	O1	27.09	19.48	4.31	2.05
	O2	21.77	21.67	15.84	2.88
	O3	21.69	21.62	16.15	3.95
Normal long delay	O1	27.69	20.19	5.79	1.26
	O2	21.33	21.17	15.60	1.34
	O3	21.30	21.22	16.42	1.71
Negative exponential delay	O1	27.66	20.16	5.78	1.48
	O2	21.49	21.37	15.49	1.68
	O3	21.47	21.39	16.31	2.23

All control factors are level one in case 1. By contrast, all control factors are level three in case 4. A delay of 27 minutes of the final departing train in case one means that the next arriving train cannot arrive within a delay of ten minutes, which is regarded as no delay for long distance service in Britain. In case 4, the delay of the final departing train is 1 to 2 minutes, which means that the next arriving train should arrive within the ten minutes delay window, even if it suffers a delay penalty due to stopping on approach to the station. Cases 2 and 3 are upgraded cases in terms of control factor D, the signalling reaction time. Case 2, which has level 2 of control factor D and level one of the other factors, shows insufficient performance, but case 3, which is upgraded from case 2 in terms of control factor D, shows good performance. Delays of 4 to 5 minutes are small enough to ensure that the next arriving train arrives within the permitted 10 minutes delay. Thus, case 3 is chosen by the approach as it can be said that it is robust enough and better than case 4 because it uses a smaller amount of resources.

5.9 Conclusions for Chapter 5

To reduce the cost of high-speed railways, the applicability of Lean principles has been investigated and they have been applied to the case study of terminus turnaround operations and systems design based on the results of the robustness assessment conducted in the previous chapter. The turnaround time, other than the necessary time for alighting and boarding, is identified as NVA and the related waste, additional platform provision, is highlighted through VSM. Faster turnaround is studied as a possible solution to reduce the waste, with the potential benefit of fewer platforms and thus reduced capital investment, in the initial input of resources. The application of JIT and SMED are demonstrated as tools to reduce the turnaround times indirectly and directly. JIT optimises the running time, resulting in a reduction in track occupation time at the terminus and energy consumption for traction due to a reduced maximum speed. SMED reorganises the tasks during turnaround at the terminus and reduces the turnaround time.

The modified operations and terminus design based on the Taguchi method and the Lean principles were tested with the robustness assessment simulation again and it was found that the option with fewer resources achieved sufficient operational robustness. Thus, it can be said that this approach can reduce the cost without damaging robustness.

Further studies on the negative effect of extended running time on passenger demand for JIT application should be conducted. In addition, the variation in turnaround time due to employing a different number of cleaners should be considered for the robustness assessment simulation.

6 Conclusions and further work

The conclusions of this thesis are presented in terms of findings, an evaluation of the work, recommendations for further work and discussion of the contributions to knowledge.

6.1 Findings of the study

The motivation for this research was to reduce the initial cost and energy use of high-speed railway systems without damaging the robustness of operations. For this thesis, I developed a novel methodology by adopting the Taguchi approach for the robustness assessment and applying the Lean principles for cost reduction. The overall findings are as follows:

- Reducing the size of stations without damaging the robustness of operations is a good option for initial cost reduction because construction and land take are a large part of capital cost. Also, smaller station can be built in better locations in relationship to the existing transport network, which is good for socio-economic development in regions.
- The environmental aspect of high-speed railways attracts concern due to increasing pressure from environmental problems, especially climate change, that are resulting in requirements for more energy efficient operations.
- The applicability of the Lean principles to railway operations was investigated and the possibility of a limited application of the principles to railway operations was identified. The limitations arise because the robustness of operations is a difficult issue due to the characteristics of railway operations, which are different from those applicable to manufacturing industry;
- By considering the characteristics of railway operations, I developed an approach, where I first address the robustness of operations at an operational concept and system design level and then conduct a cost reduction study;
- I discussed and maintained robust operation of the railway using the Taguchi method, one of the tools of quality engineering. I applied the method to a case study of railway terminus infrastructure and operations design, using Taguchi's design of experiments approach with an additive model and an L9 orthogonal array. I undertook a Monte Carlo simulation with statistical distribution delays, which highlighted that the signalling reaction time is the most important factor for operations robustness;
- I conducted a Value Stream Mapping analysis in line with the Lean principles using the same case study with reference to the results of the robustness assessment by the Taguchi method. I identified the main non-value adding activity as the turnaround at

the termini. This only adds value by allowing alighting and boarding and is associated with waste in terms of the number of platforms that are in excess of the basic requirement;

- Faster turnaround has been studied as a possible solution to reducing waste, with the potential benefit of fewer platforms, less land take and, thus, reduced capital investment and initial input of resources;
- Based on my results, I suggest that the optimisation of running time is preferable to using the minimum running time, in order to support a just-in-time arrival of the train at the station for reducing the number of platforms required and to maintain the established departure schedule, while minimising energy consumption;
- I have also discussed SMED as a method for turnaround time reduction and I have studied a case of good practice in the UK. From the case study, it is shown that having cleaners on board the train can reduce the cleaning time, turnaround time and the number of platforms required;
- The robustness of the option with lower resource usage, developed as part of this research has been tested by simulation and the value of the approach has been demonstrated. Although it was not possible to verify the validity of the modelling through practical experiments, I am reasonably confident that the approaches will be of beneficial use in railway.

6.2 Evaluation of the work

Here I evaluate the validity and reliability of my findings:

- The approach developed is useful for train service planning, for the construction of new lines and upgrading (or downgrading) of existing lines. Train planning for these situations is time consuming because it traditionally requires many iterations between design and checking, in order to balance cost and robustness. Train planning by the approach developed as part of my research promises to be productive as it firstly defines the desirable level of operational robustness with clear thresholds and then highlights the most important components to satisfy that level of robustness at the first step, before starting the design of operations. Also, for the assessment of the robustness, the methodology adopts Taguchi's design of experiments approach and reduces the number of combinations of control factors to be checked. Thus, productivity of train planning is improved.

- Improved productivity of train planning allows planners to create robust plans. Ensuring operational robustness is important and must not be compromised, therefore it costs time. With the guidance of the approach, the planners can explore the global optimum from a broader range of options and assess the robustness of each option in a systematic way.

As mentioned above, the approach is useful for reducing cost and time during the planning stage. However, the preparations for using the approach required the following work:

- Special train operations simulators must be developed for each case, because existing simulators do not allow infrastructure arrangements to be modified easily. They restrict the inputs in order to prevent users from developing infrastructure models with in-built conflicts. To adapt the infrastructure from experiment to experiment, requires the simulators to be modified for each situation.
- Thanks to the design of experiments approach of the Taguchi method, the calculation time is reduced significantly. This has made it possible to conduct simulations with more complex models, however, the modelling itself required a great deal of effort. Furthermore, the design of experiments method is based on the premise that there are no interactions between the control factors. Thus, setting up the simulation experiments appropriately requires knowledge of the domain.
- The approach which I developed is intended to deal with the main concerns encountered in railway operations, namely, the operational robustness, through a robustness assessment before conducting the VSM analysis, however, not all issues in the implementation of the Lean principles could be listed and measures for them have not been investigated.

Also, case studies were only conducted for high-speed railways to limit the scope in this research and thesis. The applicability for other cases is discussed in the following:

- The applicability of lean principles to high-speed railways operations has been demonstrated but not applied to conventional railways. Value Stream Management (VSM) is a globally applicable technique so it can be used to analyse conventional lines and to identify waste, e.g., that associated with turnaround times. However, the reduction of the component times will give smaller benefits in terms of energy saving and reducing land take of termini because of the trains' lower speeds and shorter length. Furthermore, it should be noted that turnaround times are already at the minimum for some lines (e.g., at Waterloo) and cannot be reduced by adopting JIT and SMED.

- The Taguchi method was applied to assess the robustness of high-speed railway terminus designs. The components of the simulation model of termini were not derived from the specific characteristics of high-speed railways. Thus, the method will work for conventional lines as well. However, operational robustness was studied only in terms of the response to small delays, such as around 5 minutes. If managing larger delays is to be considered as a requirement for infrastructure design, the results of the assessment will be different. Also, by focusing on small delays, rostering of train crews and trains was not considered. Adopting larger delays requires modelling of rostering.
- Issues relating to the reliability of facilities were out of scope. However, the model developed can include them as noise factors. Arrival and departure delays are generated by probability distributions that are used as noise factors. Thus, noise factors including reliability issues can be generated as the sum or multiplication of probabilities of failure of each facility for different cases.
- By modelling relatively simple operations at the termini, the rostering of rolling stock was not considered. In reality, it is more complex and different from case to case. Thus, the simulation model should be modified for each project.

6.3 Recommendations for Further Work

Based on the evaluation of the findings, recommendations for further studies are presented as follows:

- Applying the approach to conventional railways is worthy of study and will require a VSM analysis from a different perspective. This suggests that different control factors should be investigated and the simulation model can then be developed with different and more control factors, such as braking rate, acceleration rate, driver behaviour and length of train detection sections. The approach can also deal with simulation involving many parameters, thanks to the experimental design methodology adopted, although the computational times increase significantly if full factorial simulation experiments were to be adopted.
- Reliability issues of the facilities should be considered. These can be incorporated by expressing noise factors as the sum or multiplication of probability distributions for

the failure of facilities for different cases. The model used for the approach can be assessed with other noise factors, such as different statistical delay distributions generated by mathematical models or real data, collected from infrastructure and operational conditions, which are similar to the target of the project.

- Scheduling of rolling stock should be included. It will be a critical factor for knock on delay accumulation because rolling stock is not always homogeneous so that some trains cannot be used for certain services and these constraints increase the delays. The equation for the estimation of capacity of termini would have to be modified if this factor were to be considered.
- The rostering of train crews should be studied as well, because like rolling stock, train crews have constraints, such as working hours, which do not always allow the crews to be assigned arbitrarily and thus can cause greater delays.

6.4 Contributions to Knowledge

Finally, I present my contributions to knowledge:

- I have confirmed the Taguchi method as an appropriate approach for ensuring robust operations and Lean principles as a suitable methodology to reduce the land take of termini and energy use of high-speed railways during operations by the results of the literature review;
- I developed a novel approach that combines the Taguchi and Lean techniques for ensuring operational robustness, reducing land take of termini and energy use of high-speed railways;
- I developed a model of terminus operations and design based on input/output diagram of Taguchi method in order to analyse robustness of termini;
- I assessed the robustness of terminus designs with different infrastructure and operational conditions by means of a novel terminus simulator for use with the Taguchi approach and I identified the most important factor for the robustness of a terminus design, namely, signalling reaction time;
- I applied Lean principles to high-speed railway service planning in order to create an efficient operational concept in terms of resource usage, thanks to a reduction in non-value adding activities by minimising the turnaround times at termini;
- I identified excess platforms through a Value Stream Mapping (VSM) analysis;

- I applied the Just In Time (JIT) concept to the timetabling task to reduce the duration of the non-value adding steps and energy use for traction;
- I applied the Single Minute Exchange of Die (SMED) concept to realise faster turnarounds at termini;
- I developed a case study, which shows the benefits of the approach in terms of the possible reduction in the number of platforms in a terminus and the operational energy saving;
- I developed case studies of current British turnaround times, current Japanese turnaround times and planned HS2 turnaround that show the possibility of a reduction in the proposed number of platforms at Euston Station, the main terminus of HS2.

7 Papers published during the PhD studies

I have published the following papers during the course of the PhD:

- D. Hasegawa, G. Nicholson, C. Roberts, and F. Schmid, "The impact of different maximum speeds on journey times, energy use, headway times and the number of trains required for Phase One of Britain's High Speed Two line," in *WIT Transactions on the Built Environment*, 2014, vol. 135, pp. 485–496.
- D. Hasegawa, G. Nicholson, C. Roberts, F. Schmid, and V. Novak, "Lean operation for new high speed railways," in *1964-2064 High Speed Rail: Celebrating Ambition*, 2014.
- D. Hasegawa, G. Nicholson, C. Roberts, F. Schmid, and V. Novak, "Lean principles and sustainable operation of high-speed railways," in *The Stephenson Conference Research for Railways*, 2015, pp. 815–824.
- D. Hasegawa, G. L. Nicholson, C. Roberts, and F. Schmid, "Standardised approach to energy consumption calculations for high-speed rail," *IET Electr. Syst. Transp.*, Oct. 2015.
- D. Hasegawa, G. L. Nicholson, C. Roberts, and F. Schmid, "Analysis of the robustness of terminal turnaround arrangements for railways," *IET Intell. Transp. Syst.*, vol. 10, no. 1, pp. 41–49, Feb. 2016.

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