MRes in Railway Systems Integration

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# Closer Running – Railway Capacity Analysis and Timetable Improvement

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# Executive Summary

With the development of the economy, demand for railway transport tends to grow. However, given the recent 6% annual growth of passenger flows, many railway lines in Britain (e.g., the West Coast Mainline or WCML) will not be able to satisfy public needs in a few years. Taking into consideration the requirement for system resilience and the need for profit, it is impossible to operate as many train services as one might want on a railway line. As a core output of any transport service, railway capacity must therefore be studied and investigated scientifically, well beyond the current level. The present thesis aims to analyse railway capacity from both technical and operational perspectives. Based on the results, practicable solutions and recommendations will be provided.

It is well known that the railway is an interdisciplinary engineering system with high variability and diversity. To avoid misunderstanding and to clear the scope of application, the technical background and industry environment of Britain’s mainline railway are reviewed at the beginning of the thesis. This is followed by an analysis of railway capacity. The compression method is the general method to assess railway capacity. A mathematical tool for analysing railway capacity is also introduced in the literature review.

The minimum technical headway is the critical determinant of railway capacity from a technical point of view. Based on a set of technical data, a single-variable analysis is conducted to evaluate the relationship between each parameter and headway. From an operational point of view, operating trains at different speeds and with different stopping patterns are defined as two analysable strategies. The stopping pattern is a complicated but manageable factor of capacity. To identify the headway change by different stopping patterns and manage them logically, a novel algorithm connecting stopping patterns and headway times is constructed. Furthermore, based on the minimum technical headway model, an optimality analysis helps the railway industry to manage railways efficiently and a sensitivity analysis is performed to show the importance order of each parameter.

Nevertheless, technical parameters are hard to change once a railway is in the operations stage. So, based on the stopping pattern analysis, a general timetabling method is proposed to improve service capacity performance. The WCML was chosen as the case study to apply the method in detail. To improve practicability, the real requirements and limitations of the route are all respected. It should be noted that before conducting a timetable improvement project, passenger demand and the existing service capability should be investigated.

The results of the timetable improvement project show that there are 2 and 4 potential extra service stops for Watford Junction and Rugby respectively. However, although the

railway infrastructure manager has allowed the London Midland services to be operated on the fast line between Euston and Milton Keynes, in order to improve track usage rate, the situation is that the route between Euston and Rugby has nearly reached its maximum line capacity. Because there is not enough adjustable space for increasing capacity through operational means, the technical approach must be considered to meet future demands on the WCML.

From another technical point of view of capacity, updating railway signalling systems is a potential shortcut to achieve satisfactory results. The merits and pitfalls of the relative braking distance approach and moving block signalling systems is discussed. Combining them, an advanced signalling system concept is introduced, namely, the Optimised Headway Distance Moving Block (OHDMB). Based on the operational concept of this proposed system, six realistic braking scenarios are examined to identify the minimum headway distance for each of these. The simulation shows that reducing the technical headway in line with the principles of OHDMB could increase capacity by nearly 60% compared to the traditional moving block system. However, without a further need for railway capacity beyond the capability of ETCS Level 3, the research on new signalling systems should stay at the conceptual stage.

In conclusion, sufficient railway capacity can deliver enhanced reliability, customer experience and better revenue outcomes. Unfortunately, however, it is not appropriate to try to improve capacity by changing train speed and braking rate as they are both limited by physics. Also, train length has a minor negative impact on the maximum number of trains that can travel on a railway line in a given period of time, even though passenger capacity can be increased significantly by coupling more carriages. So, optimising operational strategy is the reasonable and achievable approach to line capacity improvement. While running at different speeds is an organisational problem without any upside, the development of an effective stopping pattern strategy is an underdeveloped factor with potential benefits. Therefore, a stopping pattern algorithm and timetabling method are proposed in this thesis. These tools provide a possibility for dynamic (re-)scheduling. For future applications, it is recommended that a smart and scientific re-scheduling system could be constructed to handle unexpected delays and failures rapidly in a heavily trafficked area.

# Acknowledgements

First and foremost, I would like to show my deepest appreciation to my lead supervisor, Professor Felix Schmid. From the beginning to the end of my MRes studies, Felix has provided me with abundant railway knowledge and learning methods. He also offered me lots of opportunities to participate in BCRRE activities that brought me many valuable experiences with the railway industry and academic teaching. Without his guidance, enthusiasm and encouragement, I could not have completed my study satisfactorily. In my heart, he is the most knowledgeable person in the railway domain. Being his student is one of my most valuable treasures.

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# Glossary of Terms / List of Abbreviations

| **Term** | **Explanation / Meaning / Definition** |
|---|---|
| ADBM | Absolute Distance Braking Mode |
| AHT | Average Headway Time |
| ANOVA | Analysis of Variance |
| ATC | Automatic Train Control |
| ATP | Automatic Train Protection |
| ATR | Automatic Train Regulation |
| CBTC | Communications-Based Train Control |
| C-DAS | Connected Driver Advisory System |
| DAS | Connected Driver Advisory System |
| ET | Extra Time |
| ETCS-3 | European Train Control System Level 3 |
| GDP | Gross Domestic Product, a measure of economic performance |
| GPS | Global Positioning System by satellite |
| GSAT | Global Sensitivity Analysis Toolbox |
| GSM-R | Global System for Mobile Communication - Railway |
| LC | Line Capacity |
| LM | London Midland (now London North Western Railway) |
| LTE | Long Term Evolution (a mobile telephone technology) |
| MA | Movement Authority |
| MK | Milton Keynes |
| OHDMB | Optimised Headway Distance Moving Block |
| PTC | Positive Train Control |
| RB | Rugby |
| RBC | Radio Block Centre |
| RDBM | Relative Distance Braking Mode |
| RDBM-MB | Relative Distance Braking Mode Moving Block |
| RSSB | Rail Safety and Standard Board |
| TMS | Traffic Management System |
| TPH / tph | Trains per Hour |
| UIC | Union Internationale des Chemins de fer (International Union of Railways) |
| UK | United Kingdom (Great Britain and Northern Ireland) |
| VT | Virgin Train |

| Term | Explanation / Meaning / Definition |
|---|---|
| WCML | West Coast Mainline |
| WJ | Watford Junction |

# 1 Introduction

## 1.1 Background

The railway is a popular mode of transportation that is widely developed around the world. It has become the backbone of the public transport system in Britain. The whole country was connected closely by the railway network, in social, political and economic terms. For example, people could travel further in a short time for their work; political movement could be spread faster; regional products could be delivered throughout the country at low cost and with good timeliness.

Compared to other types of transportation, the railway is characterised by high capacity, high reliability, often high speed, energy efficiency and low unit cost when large volumes are transported. With gradually improving living standards, the demand for railway transport is increasing, both for passengers and freight. People need railway services not only for commuting purposes but also for leisure travel and business purposes. Therefore, railway stakeholders have proposed four areas that should be targeted to improve railway performance: customer satisfaction, capacity increase, cost reduction and carbon reduction (RSSB, 2012). Among these, capacity increase is an essential demand since the fundamental goal of transportation is to transport people or goods from one place to another.

Railway capacity nornally refers to line capacity, which is taken as the number of trains that can operate on a plain unidirectional track (line), given specific operational conditions in a specified period of time (Abril et al., 2008). The unit is trains per hour (tph). According to this definition, two indicators concerning railway capacity are usually used in the domain: maximum technical railway capacity and actual railway capacity. Maximum technical railway capacity is calculated by means of the minimum headway time shown in Eq. (1), while actual railway capacity is planned by railway operators to address system efficiency, robustness of service, revenue and other parameters and it can be calculated by compression method in 2.1.2.

$$Maximum\ Technical\ Capacity = \left\lfloor \frac{60}{Minimum\ Headway\ Time} \right\rfloor \cdots\cdots (1)$$

Headway is the minimum interval time or distance between two successive trains running on a railway line, where the second train is not affected by the behaviour of the first one. This depends on the physical characteristics of the infrastructure, rolling stock and signalling system.

Capacity not only provides seats or space to transport people or goods but has an impact on journey quality and profit of railway companies. This will be discussed in detail in 2.2.

However, in fact, many railway lines have already reached their maximum capability according to companies' reports (NetworkRail, 2018b). For example, passenger growth forecasts on the West Coast Mainline (WCML) suggest that there will be unacceptable levels of crowding on an ever-increasing number of trains (NetworkRail, 2016). Besides infrastructure limitations, mixed traffic on the route and the connectivity requirements between stations constrain the capacity (Department for Transport, 2015). Furthermore, even though it is possible to operate trains at intervals of less than 90 seconds nowadays, as happens on metros, there is still potential demand in heavily populated areas that cannot be satisfied with existing systems.

Railway capacity can be seen as a core output of railway operation, which is defined by the timetable, rolling stock and infrastructure. However, to deliver a satisfactory railway service, balancing the robustness of timetable, the cost of rolling stock and the utilisation of infrastructure is a complicated process. Meanwhile, in addition to those railway assets, the railway operational strategy and human factors also affect the capacity. Stopping patterns, dwell time, and the number of carriages are all variable factors that can affect railway capacity. Furthermore, the variability and diversity of the railway as a system must be respected. For example, while urban railway networks are intended to provide high accessibility and high frequency, touristic lines emphasise passenger travel experiences.

From a technical point of view, the signalling system is a core element of the train control system, and thus has a critical effect on capacity. Without it, trains cannot run sequentially and safely. From about two hundred years ago, when the railway was invented in the UK, to today's high-speed railway that are being constructed all over the world, the form of signalling systems has changed significantly. To meet future demands, the concept of 'Closer Running' has been proposed by signalling engineers. Some operators and engineers propose new signalling systems with higher capacity and reliability, to benefit from trains running closer together.

## 1.2 Aims

Since the provided capacity is a crucial attribute of railway services, it normally requires thorough research throughout the railway lifecycle. The primary aim of the author in this thesis is to analyse how technical and operational parameters affect railway capacity. By means of optimality and sensitivity analyses, the optimal value and importance of each factor's contribution to capacity can be given. Based on the results, the solutions and strategies to improve capacity at both the design and operations stages will be found. In addition, as a direct output of railway planning, the timetable must be managed to deliver a robust and efficient railway service. With the preceding analyses, a general timetabling process can be given to improve capacity. Throughout the thesis, the WCML is chosen as the case study, although there are some simplifications. The recommendations about capacity improvement for the case study will be provided. Furthermore, after reviewing the signalling systems and the related technical context, the thesis will propose an advanced signalling system to meet future demands on railway capacity and reliability, while maintaining adequate levels of safety.

## 1.3 Scope

The referred definitions and concepts in this thesis are based on Great Britain's mainline railway environment, which will be described in some detail in section 2.1, and therefore the result and conclusion only apply to mainline railway lines. The term capacity in this thesis refers to line capacity in tph unless otherwise mentioned. The analysis and timetabling processes are provided for normal operational circumstances where infrastructure, rolling stock, and staff are all well organised and where train services do not suffer any unexpected incidents, such as delays due to passenger crowding. The requirements and limitations of technology for the signalling systems are reviewed in section 2.3.4, but the approaches and specific applications are not provided in detail. Similarly, the specific analysis process for safety analysis methods in section 5.3 is not provided in full. For the case study, the chosen route is the fast double-track section between Rugby and London Euston on the WCML. It is assumed that the route is a well-maintained metro-style line without any junctions or speed limitations.

## 1.4 Methodology

The author aims to analyse and improve railway capacity while considering the practical reality. As the railway is an interdisciplinary, highly complex subject, qualitative and quantitative analysis are both employed in the thesis, assisted by software-based simulations. While the quantitative study provides optimality and sensitivity analysis to capacity from a mathematical perspective in 3.3 and 3.4, the qualitative analysis in 4.3 complies with practical situations and ergonomics. Combining the two approaches, the research could practically achieve scientific and reasonable outcomes.

## 1.5 MRes Thesis Structure

The thesis contains eight chapters. In Chapter 1, a brief introduction is given including the backgrounds, aims, scopes and methodologies of the thesis. Some industry definitions and literature related to capacity analysis and signalling systems are reviewed in Chapter 2. Chapter 3 presents capacity analysis from both the technical and operational points of view, and then optimality and sensitivity analyses are performed. Based on the results of the stopping strategy adopted, a timetable improvement process is introduced in Chapter 4. Chapter 5 proposes an advanced signalling system that could improve railway capacity significantly. The main findings and recommendations are summarised in Chapter 6. Chapter 7 lists the references for the thesis.

# 2 Literature Review

This literature review contains 4 subchapters. Firstly, an international standard document addressing railway capacity is reviewed in section 2.1. Based on the British railway environment, relationships between the railway service and capacity are summarised in the next part, section 2.2. In section 2.3, railway signalling systems and their technical requirements are reviewed. In the last section, 2.4, a mathematical method is suggested for the quantitative analysis of railway capacity.

## 2.1 UIC Code 406

### 2.1.1 Introduction

The International Union of Railways has published a so-called leaflet (a standard) on railway capacity to eliminate misunderstandings between different countries, operators and railway environments. The leaflet provides a series of definitions regarding railway capacity and, based on these definitions, a methodology of calculating capacity for railway lines and networks is proposed (International Union of Railways, 2013).

Thanks to the capacity definitions and the calculation methodology, railway capacity can be assessed in a unified way. Thus, further analysis and research can be conducted to improve the performance of railway services. For example, railway operators can manage their railway assets efficiently according, to demand and a capacity assessment. Through the study of the bottlenecks in a mixed-traffic railway context, an efficient timetable can be planned with high throughput and punctuality. Even in the near future, an advanced traffic management system (TMS) might be applied in the railway industry to improve reliability and save significant amounts of energy (Mazzarello and Ottaviani, 2007).

A significant amount of literature has investigated UIC 406 in detail as the guide to capacity definition and calculation (Abril et al., 2008) (Landex, 2008) (Lindner, 2011). However, besides UIC 406, other methods are applicable with different aims, such as considering priorities between trains and possible delays (Mussone and Wolfler Calvo, 2013) and emphasising the relationship between pricing with capacity (Kozan and Burdett, 2005).

### 2.1.2 Compression Method

The compression method is a means to calculate the actual capacity based on existing or planned railway services. The approach is to compress the timetable and evaluate the number of possible train paths for a line, a node or a corridor (International Union of Railways, 2013). Before conducting the compression method, the line sections must be defined first. Line sections are decided by infrastructure and timetable boundaries and each section should be compressed separately. In this thesis, the chosen WCML section is seen as a uniform complete line section without infrastructure and timetable limitation or change. Therefore, the chosen section can be compressed and analysed as a whole.

In UIC 406, the compression method is summarised in five steps:

- Defining infrastructure and timetable boundaries;
- Defining sections for evaluation;
- Calculating capacity consumption;
- Evaluating capacity consumption;
- Evaluating available capacity.

The compression method can be applied on any railway route in the network, including single track and mixed traffic situations. Considering the scope of the present research, the WCML (Fast) between London Euston and Rugby section is our target line section. Although compressing the departure time between two successive trains on the premise of the interval time between trains is always no less than the minimum technical headway time, a set of services in a defined period could be operated in a shorter period. A schematic diagram is shown Figure 1.

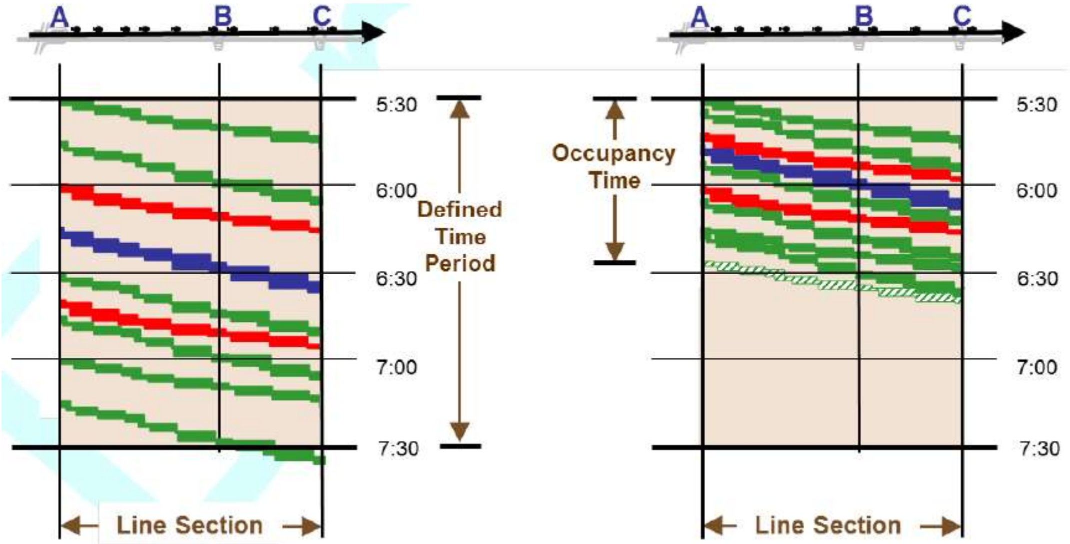

*Figure 1 – The Compression Method (International Union of Railways, 2013)*

After compressing the timetable, the capacity of the defined line can be evaluated as Eq. (2).

$$Occupancy\ Time\ Rate\ (\%) = \frac{Occupancy\ Time}{Defined\ Time\ Period} * 100 \cdots\cdots (2)$$

When planning a timetable for a railway line, the values in Table 1 should be respected to ensure the capability for self-recovery from traffic conflicts.

*Table 1 – Proposed Occupancy Time Rates (International Union of Railways, 2013)*

| Type of Line | Peak Hour | Daily Period |
|---|---|---|
| Dedicated suburban passenger traffic | 85% | 70% |
| Dedicated high-speed lines | 75% | 60% |
| Mixed-traffic lines | 75% | 60% |

In addition, the unoccupied time in the defined period should be added evenly in the timetable. There are two basic methods for decompression, the evenly fixed method and the evenly expanded method.

1. In the evenly fixed method every compressed interval departure time should add a fixed amount time which is derived from the line capacity in the defined period and the occupancy time rate.

$$\begin{aligned} &Interval\ Departure\ Time \\ &\quad = Compressed\ Interval\ Time \\ &\quad + \frac{Defined\ Time\ Period(1 - Occupancy\ Time\ Rate)}{Line\ Capacity} \cdots\cdots (3) \end{aligned}$$

2. In the evenly expanded method every compressed interval departure time should be multiplied by the reciprocal of the occupancy time rate.

$$\begin{aligned} &Interval\ Departure\ Time \\ &\quad = Compressed\ Interval\ Departure\ Time \\ &\quad * \frac{1}{Occupancy\ Time\ Rate} \cdots\cdots (4) \end{aligned}$$

It is relatively convenient for railway operators and staff to apply the evenly fixed method, but the evenly expanded method provides more recovery opportunities for those services following a service with many stops along the route.

Evaluating available capacity is easily carried out by inserting or excluding train services on the railway line.

## 2.2 Capacity and Railway Service

### 2.2.1 **Journey Quality**

From the passenger's point of view, journey quality could be compromised by service disruptions, service delays, lack of security and comfort, and poor quality information (Woodland, 2017).

To quantify the relationship between passenger expectations and service quality, the generalised cost function for rail transport is introduced as Eq. (5) (Connor et al., 2015):

$$Generalised\ Cost = \frac{fare}{a_0} + a_1 * t_j + a_2 * t_a + a_3 * t_w + a_4 * t_d + a_5 * n_c \cdots\cdots (5)$$

$fare$ : Direct cost or fare payable for the journey (£);

$a_0$ : Value of time of the particular traveller or traveller type (£/min);

$a_1 * t_j$: Weighting factor (usually 1) * journey time (min);

$a_2 * t_a$ : Weighting factor (usually 1.5-2) * access time (min);

$a_3 * t_w$ : Weighting factor (usually 1.5-2) * waiting time (min);

$a_4 * t_d$ : Weighting factor (typically 3) * average delay (min);

$a_5 * n_c$ : Inconvenience allowance (min) * number of changes.

The value of $a_1\ to\ a_5$ depends on the respective environment and the person undertaking the journey. The fare-related element may not be required where a third party (employer etc.) pays for the journey.

Railway line capacity affects the generalised cost and, therefore, the journey quality due to the four aspects below:

- When capacity is improved by changing the stopping patterns, the journey time will be changed because of the number of stops;
- Railway line capacity affects the average waiting time directly, which will be discussed in detail in section 4.2;
- The occupancy time ratio introduced in section 2.1.2 indirectly affects the average delay. Usually, low occupancy time rate will bring more capability of self-recovery from traffic conflict and delays. Therefore, it reduces the average delay;
- If there is no direct service between two locations (capacity is 0), the number of changes must be considered.

### 2.2.2 **Revenue and Profit**

Improving railway capacity could provide more seats or spaces for passengers or goods. However, considering the cost, it does not mean the more capacity achieved, the better. The planning of operations for railway capacity must respect demand and potential demand, as the railway is a long-term project and asset.

It is hard for railways to make money (Harris and Godward, 1991). Figure 2 (Schmid and Harris, 2016) is an illustrative comparison between railway and road transport operating cost as a function of transported passengers or goods (in billion passengers/tons kilometres). The main difference is that there is a ladder-shaped complexity cost for rail transport, which is mainly due to the inevitably step-wise investments to meet capacity needs. The fixed cost for railways is higher than that for road transport because of the high operation and maintenance cost for infrastructure, such as stations, tracks and trackside equipment. The slope of the variable cost for railways, by contrast, is relatively shallow. Since the railway is a high-volume and environmentally-friendly mode of public transport, its fuel consumption is competitive compared to that of any other mode of transport, as long as the utilisation is high. Overall, for high capacity demand areas, rail transit is potentially cheaper than road, especially in urban districts. It should be noted that the cost mentioned here excludes the construction and end-of-life decommissioning costs.

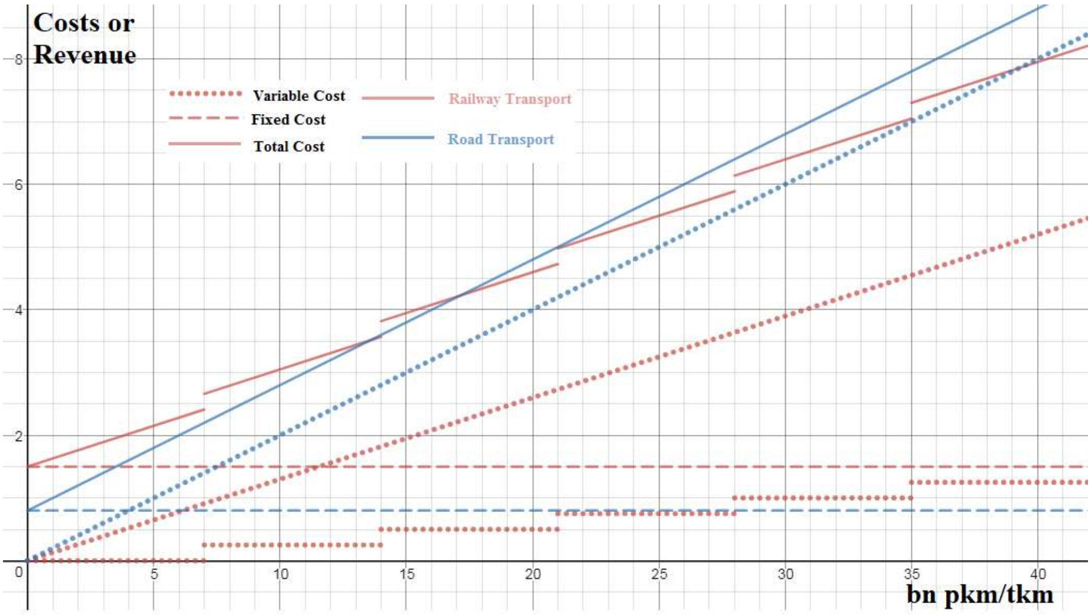

*Figure 2 – The Illustrative Comparison between Railway and Road (Schmid, 2018)*

Figure 3 (Schmid and Harris, 2016) offers an illustration of the relationship between revenue, cost and profit for railway operations. The revenue line is supposed to show how total rail income rises with increasing traffic. In the beginning, people are willing to pay more for limited seats. As the provided number of services increases, the unit revenue tends to reduce, as the demand is finite. The profit is derived from the combination of total cost and revenue. The green line shows that the profit varies as a function of railway capacity. Conventional railway operations rarely make a monetary profit.

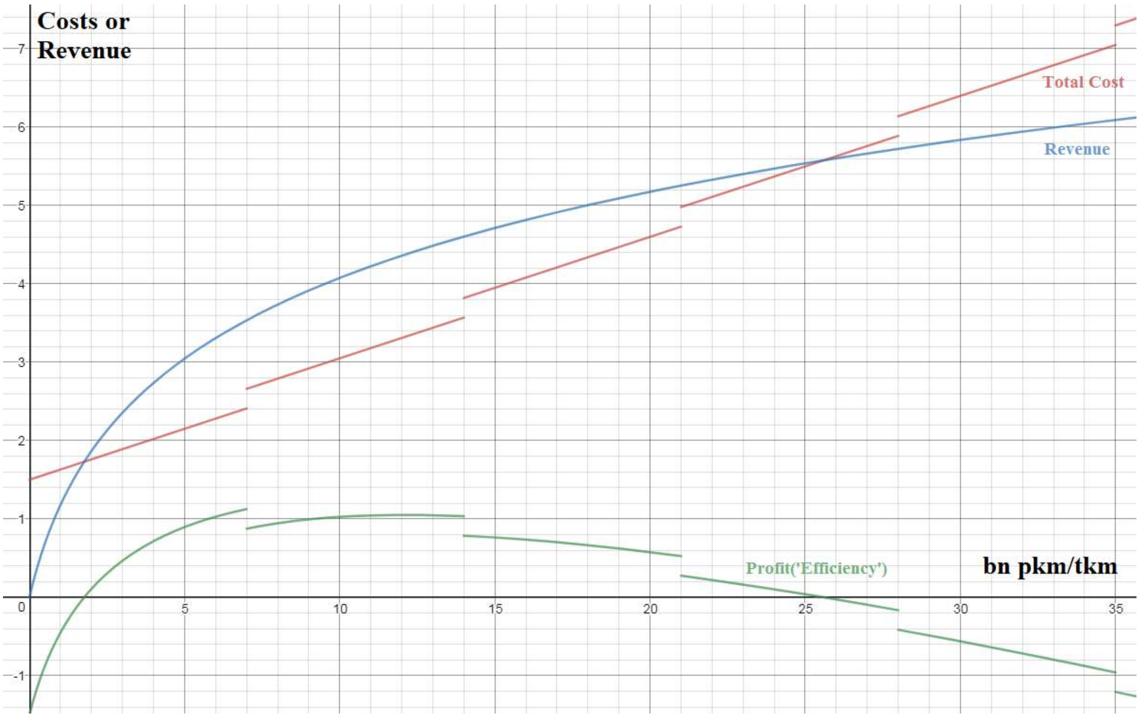

*Figure 3 – The Illustrative Profit Generating Capability of Railways (Schmid, 2018)*

In conclusion, from a point of view of generating profits, the railway capacity provided should respect the demand to find the optimal capacity point. On the other hand, raising ticket fares can also increase revenue and profit, even though the demand might be compromised because of the higher price of tickets. However, the railway is not a purely commercial project, but a social, economic and political necessity for a nation.

## 2.3 Railway Signalling Systems

### 2.3.1 **Fixed Block**

The colour light signal system with fixed blocks and block length is commonly applied on most of the public railway lines in Europe (Gümüşkaya, 2009). Through lineside equipment or a radio block centre (RBC), train drivers acquire the occupation status of the following blocks and then take appropriate action. Separating trains in different physical blocks is the most common method to avoid collisions (RSSB, 2014a). An example of colour light signals is shown Figure 4.

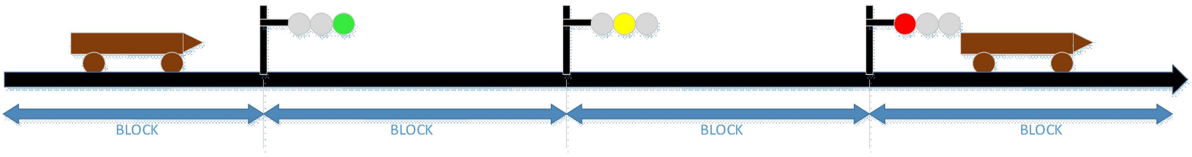

*Figure 4 – Three Aspect Colour Light Signals (Author, 2017)*

The length of block sections limits track utilisation and trackside equipment is also a potential hazard whose failure might cause delays or accidents. On the other hand, trackside equipment is vulnerable to the environment, so maintenance is difficult and costly. In addition, train operation highly depends on driver behaviour as the block information is received by and responded to humans. Therefore, the fixed block is not sufficient for the modern railway which is characterised by high speed, high capacity and high reliability. Furthermore, as other scientific disciplines are developing explosively in the 21st century, the signalling system needs to evolve to follow the new technical environment and social demands. However, a study (Lai and Wang, 2012) indicates that because of the constraints from the station layouts, the benefit of updating signalling systems may not be substantial to capacity improvement, while in our research, as railway lines are treated as metro-style (without any siding), the station's track layout is fixed and will not be discussed.

### 2.3.2 **Moving Block**

The moving block system breaks the physical barriers between blocks. Through continuous radio communication, train location and movement information are collected by the RBC, and then the RBC sends proper movement authorities (MA) to each train to avoid collisions. The movement authority is a permission for a train to move to a specific location with supervision of speed, by which trains can be separated safely on a line. The moving block principle for mainline railway is currently under developed in the shape of the European Train Control System Level 3 (ETCS-3). ETCS is a modern uniform control system to protect trains from collisions and its applications can improve the interoperability of railway network. The schematic diagram of ETCS-3 is shown in Figure 5. A simplified variant of ETCS-3 called ERTMS Regional has been testing in Sweden (Railway Gazette, 2005) and Italy (International Union of Railways, 2017). It intends to provide a cost sensitive system for low-traffic lines, but compared to ETCS-3, it does not use moving block. However, for metros, the moving block principle is widely applied in Communications Based Train Control (CBTC).

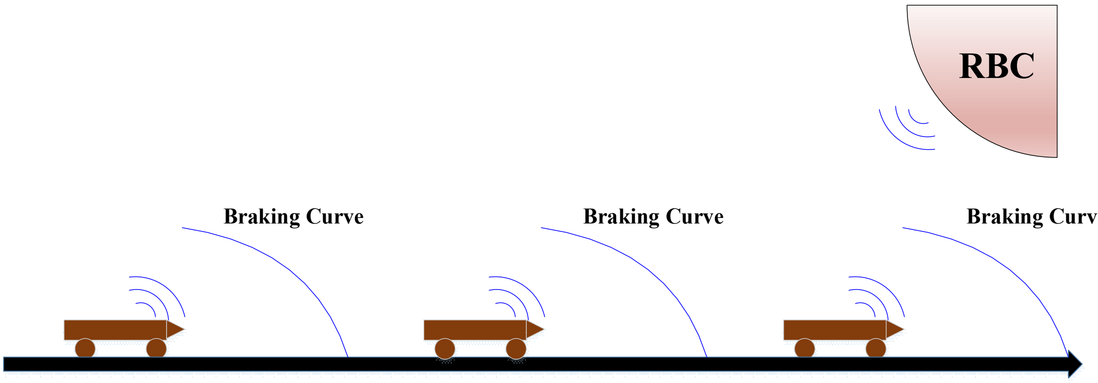

*Figure 5 – European Train Control System Level 3 (Author, 2017)*

The moving block system mentioned above is based on Absolute Distance Braking Mode (ADBM) (Ning, 1998). The interval or distance between trains comprises the braking distance of the second train, the train length of the first train, the communication delay, and the safety margin. It assumes that the first train can stop instantly and the movement authority of the second train is not extended. Based on this assumption, when the leading train suffers unexpected situations (Takeuchi et al., 2003) or communication loss (Zhao and Ioannou, 2015), the following train can take reasonable action to avoid a collision.

Even though this real-time system increases the utilisation of railway tracks, the communication failures and recover behaviours pose another sort of threat (Zimmermann and Hommel, 2003, Zimmermann and Hommel, 2005) to railway operations. From a high-level point of view, the moving block system should be verified continuously through its life circle by different system verification methods (Wang et al., 2014) (Barger et al., 2010). On the other hand, the dynamic headway can cooperate with modern dispatching systems and train control systems to improve efficiency and reliability. Based on the moving block system, Communication-Based Train Control (CBTC) has been applied in many urban railway lines successfully. Nevertheless, CBTC cannot be easily applied in mainline railway, since they are often connected to other networks and feature different types of trains, while metro lines normally operate with a single type of rolling stock and are usually isolated. Also, the client can be locked into one supplier (Fenner, 2016).

To compare the capacity performance between signalling systems operating at different speeds, a comprehensive comparison is shown in Figure 6.

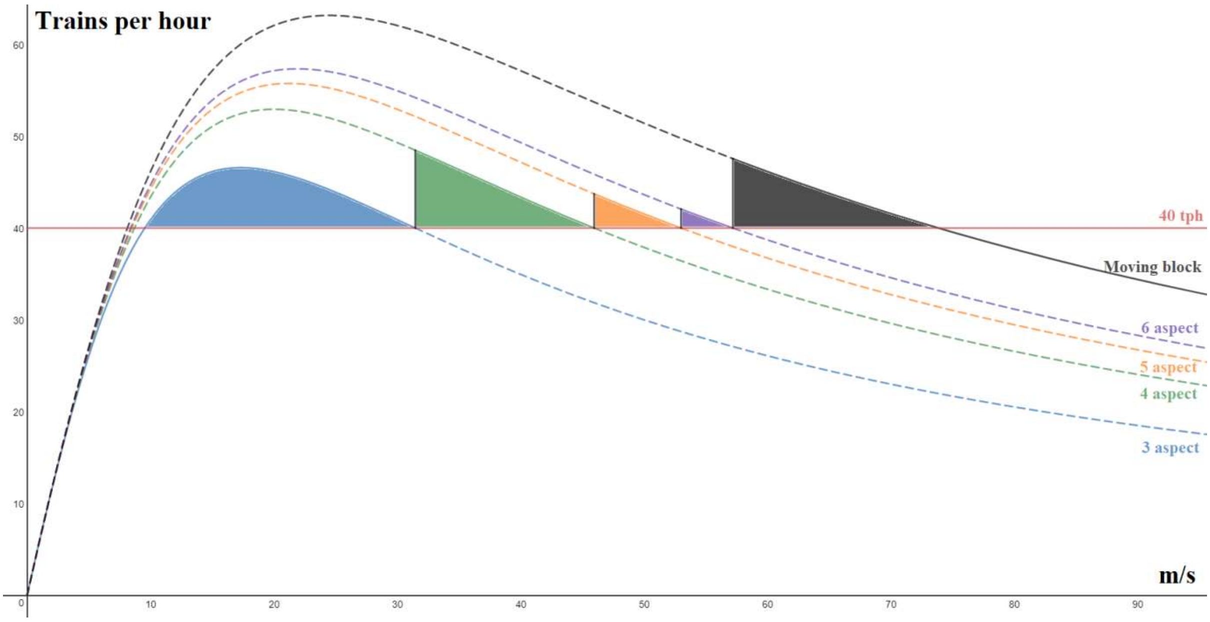

*Figure 6 – The Impact on Capacity of Signalling Systems with Different Speeds (Author, 2018)*

In the low speed range (less than 10 m/s), advanced signalling systems do not have obvious advantages of capacity, because the headway distance in any signalling system must contain a train length and an overlap/margin length, which form the major part of the headway time or distance in this range.

In the normal speed range (more than 10 m/s), moving block shows the best performance as it makes full use of the track and also higher aspect fixed block systems normally bring better results. However, considering implementation and maintenance cost and driver workload, more than 4 aspect systems are not practical. For example, in a 6 aspect signalling system, there are 4 blocks covering the braking distance, which means that there are 5 signal aspects in a braking distance. So, train drivers must respond to instructions all the time without a buffer, leading to cognitive overload. A comparison is shown below.

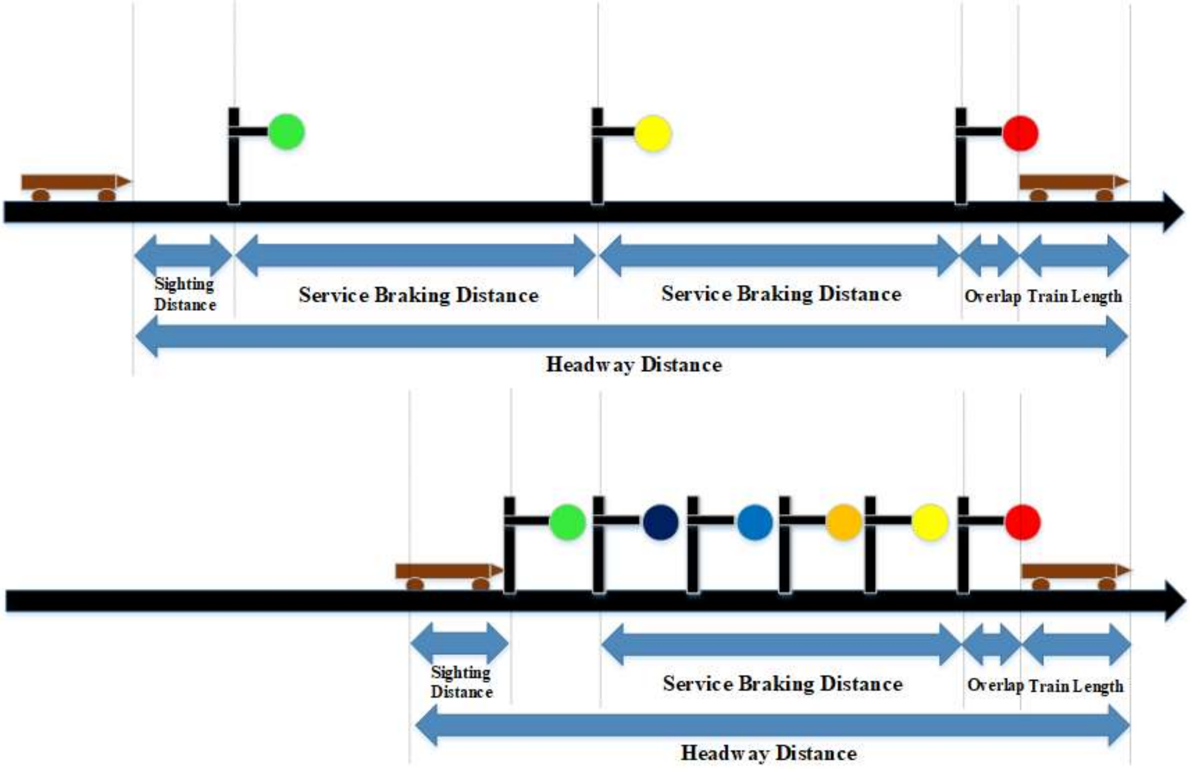

*Figure 7 – The Comparison between 3 and 6 Aspect Signalling Systems (Author, 2018)*

The specific mathematical relationship between signalling systems or train speed and railway capacity will be discussed in detail in section 3.1.1 and 3.1.2 respectively.

### 2.3.3 **'Closer Running' – Future Signalling System**

To meet future demands for reliability and capacity, the 'Closer Running' project has been proposed by British railway engineers (Fenner, 2016). There are two stages to the project:

1. Combining ETCS-3 and advanced communication methods;

2. Breaking the current safety principle that there must be a full braking distance between two trains if the leading train were to crash into a heavy object or a 'wall'.

#### *2.3.3.1 First Stage: Advanced Moving Block System*

In this concept, the provision of information relies on a Vehicle to Vehicle (V2V) communication system (Fenner, 2016) rather than a link between the vehicles and the RBC. Trains share their real-time positions and movement information (such as speed, acceleration, predicted braking distance) with neighbouring ones. The onboard real-time control system can take decentralised actions (Gao et al., 2016), therefore, in a short time. The decentralised approach reduces the response or latency time and avoids information overload at the RBC, which improves track usage rate and system stability (Gao et al., 2015). The concept is shown in Figure 8.

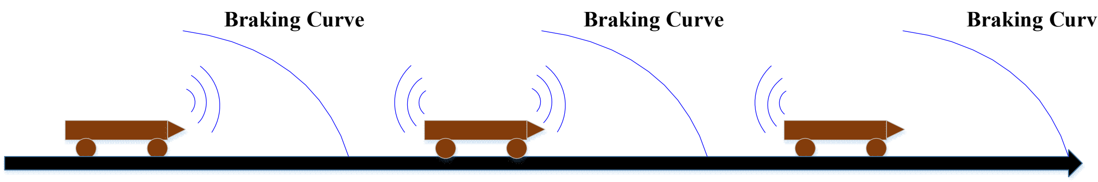

*Figure 8 – Vehicle to Vehicle Communication (Author, 2017)*

To be precise, the advanced moving block system is still an ADBM moving block, except that the communication system and control structure are changed. However, it provides the possibility of achieving other modern signalling concepts, such as the Dynamic-Headway system (Pan and Zheng, 2014) and Motorway-Style Driving (Fenner, 2016).

#### *2.3.3.2 Second Stage: Relative Distance Braking Mode Moving Block*

Relative Distance Braking Mode (RDBM) (Ning, 1998) assumes that, even if the leading train were to hit an obstacle, it would continue to travel forward due to its inertia. Combining RDBM and the moving block system, the technical headway can be reduced significantly. On the premise of being able to handle extreme cases, two successive trains could be operated very closely together. This approach will be referred to as Relative Distance Braking Mode Moving Block (RDBM-MB) in the remainder of this paper.

There are currently two proposed approaches to this controversial system, namely, Motorway-Style Driving and Virtual Coupling, both of which assume that the leading train will not stop instantaneously at any time. Each train in the Motorway-Style Driving system has a high degree of autonomy, while the virtual coupling system provides the possibility of realising fully automatic control and even driverless train operation (Fenner, 2016). In general, an issue brought by the second stage is how trains respond to unpredictable situations.

However, from a system engineering point of view, the realisation of relative distance braking mode moving block is a somewhat meaningless topic. In fact, more conventional modern signalling system concepts should be investigated as a solution to achieving certain capacity or safety targets. Signalling engineers should consider whether the available resources, applied intelligently, can meet the goal first (Dakin, 2017). In his masters dissertation, Dakin (Dakin, 2017) suggests that the unpredictability of the wheel-rail interface in braking is the true obstacle to introducing full RDBM-MB. Moreover, a 'traditional' moving block system for mainline railways is still under developed and is waiting for wider application (Stanley and IRSE, 2011). Without a further need for railway capacity, beyond the capability of ETCS-3, research into new signalling systems could stay at the conceptual stage.

### 2.3.4 **Technical Requirements for Signalling Systems**

#### *2.3.4.1 Braking Performance*

Braking performance is a vital physical parameter of rolling stock. The performance of the braking system decides the braking distance from when a train begins to apply fully braking until it stops. The related parameters and their interactions have been reviewed by Emery (2009). Unfortunately, a recent study has shown that there have been only minor developments in braking performance over the past seven decades (RSSB, 2014b), so it is impractical to put in much effort to reduce braking distance unless there is a breakthrough in the physical area. Moreover, because of the differences between real and ideal braking behaviours, there is a 24% uncertainty margin for single carriage braking performance (RSSB, 2014b), so a reasonable safety margin must be considered for safety and economy (Dakin, 2017).

To model braking distances, tools and methods have been designed to calculate the train braking distance (Barney et al., 2001) (Pugi et al., 2013) and to help operators adopt optimal operation strategies (Balas, 2000) (Balas et al., 2005). However, it is impossible to take all real-world situations and factors into account. In addition, as braking methods and performances vary between different areas of a network, compatibility has to be considered to improve interoperability (Bureika and Mikaliūnas, 2008).

#### *2.3.4.2 Communication Methods*

The Global System for Mobile Communication – Railway (GSM-R) is currently the only broadly adopted railway radio communication system in Europe (European Union Agency for Railways, 2016). To meet the requirements of high-speed railway, a network with a redundant architecture is a feasible approach to improve system stability and reliability (Xun et al., 2010, Lin and Dang, 2012).

However, the future demand for railway operations requires communication methods with higher capacity, reliability, efficiency, computational inexpensiveness and compatibility with future signalling systems (RailEngineer, 2013). Although many novel communication methods have emerged, the main supplier has agreed to support GSM-R at least until 2030 (European Union Agency for Railways, 2016). Afterwards, GSM-R will be replaced by new communication methods, such as LTE.

Long Term Evolution (LTE), known as 4G, is a feasible successor to GSM-R. The two main advantages of LTE are its high capacity and high spectrum efficiency. The data transmission rate can reach up to 150 Mbps while the system delay can be reduced ten times to 10 msec, compared to GSM-R (RailEngineer, 2013). Even though LTE is now used in the mobile communication domain, the challenge is the migration process from GSM-R to LTE. An migration process has been proposed to ensure reliability and stability (Calle-Sánchez et al., 2013).

#### *2.3.4.3 Positioning System*

An accurate positioning system is an essential constituent for any (advanced) moving block system. Typically, trains under the traditional fixed block system are located by trackside equipment, such as track circuits or axle counters (Ngai, 2010). To realise dynamic headways in a moving block system, accurate train position information must be updated frequently and in real-time to ensure safety and efficiency.

The Global Positioning System by satellite (GPS) is a universally available method for real-time train positioning. In America, Positive Train Control (PTC) is used as a standard signalling system, which uses GPS to track train positions, and therefore, dynamic headways can be achieved (Zhao and Ioannou, 2015). However, in Britain, the challenge is that GPS signals cannot easily cover some areas, e.g., inside tunnels and areas with high-rise buildings, so it has only been used for non-safety-critical subsystems. Therefore, fixed block equipment for positioning systems, such as track circuits, might be retained as a back-up system at the beginning stage of using moving block to ensure reliability and accuracy. By on-board control units, operated signalling system can be switched between moving block and fixed block, which can solve signal lost in tunnels and other radio inaccessible areas.

## 2.4 Sensitivity Analysis

### 2.4.1 **Introduction**

Sensitivity analysis is the study of how uncertainty in the output of a model (numerical or otherwise) can be derived from different sources of uncertainty in the model input (Saltelli, 2002). While optimality analysis is focused on the values of the output, sensitivity analysis is a study of the relationship between varying inputs and outputs. Sensitivity analysis is a model-based mathematical method widely used in signal processing, physics, chemistry, medicine and financial areas. The goal of sensitivity analysis is to find the most influential and vital factor contributing to the uncertainty of results (Cannavó, 2012). This approach can be applied in our capacity analysis.

Modelling is the first step in model-based analysis methods and a suitable model can help an analysis to be efficient and precise. Sensitivity analysis is a powerful tool for the analysis of the results of modelling and the method is increasingly being applied in academic articles (Ferretti et al., 2016). However, the process of choosing the input ranges tends to exaggerate the deviation between nature and model, since the possibilities of each value in our ranges of inputs hardly match the real-world possibilities well.

### 2.4.2 **Local Sensitivity Analysis**

Local sensitivity refers to the sensitivity at a fixed point in the parameter space (typically at the optimal fit point for the real data) (Cannavó, 2012). The idea is to change only one factor at a time. However, local sensitivity analysis explores only a small part of the uncertainty space, which sometimes is incomplete. Furthermore, the combined interactions between parameters cannot be assessed by local sensitivity analysis (Saltelli et al., 2007).

Even though local sensitivity analysis is still prevailing, at present, in every scientific domain, global sensitivity analysis could dominate the traditional method in the future (Ferretti et al., 2016).

### 2.4.3 **Global Sensitivity Analysis**

Global sensitivity analysis is based on the entire input parameter space to find the sensitivity value(s) for each parameter. It could help us learn more about the robustness of the model and the variance influence of each parameter (OMB, 2003). Basically, there are two indicators of the result in global sensitivity analysis: first order sensitivity index and total sensitivity index.

First order sensitivity index $S_i$ refers to the variance reduction of output if the factor $X_i$ is fixed.

$$S_i = \frac{V_{x_i}\left(E_{x_{\sim i}}(y|x_i)\right)}{V(y)} \cdots\cdots (6)$$

$E_{x_{\sim i}}(y|x_i)$ is the smoothed curve which is derived from the input space by random sampling. S varies in the range of 0 and 1, and it shows the importance of that factor.

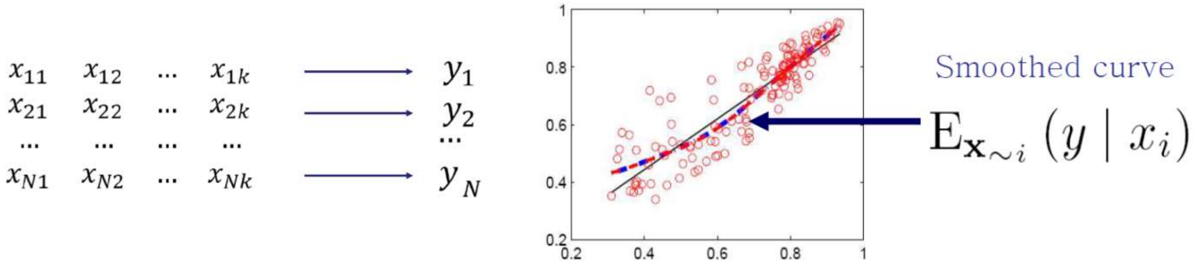

*Figure 9 – Global Sensitivity Analysis (Saltelli, 2017)*

However, first order sensitivity measures only the main contribution of the input *x* to the output variance, neglecting interactions with other input parameters (Cannavó, 2012).

Total sensitivity analysis is based on ANOVA (Analysis of Variance) decomposition: when all factors of the output are independent, the total variance of the output(s) can be decomposed into the main effects of each factor and the interaction effects between them (Saltelli, 2017). If there are three factors to the output, the total variance is calculated by Eq. (7).

$$V = V_1 + V_2 + V_3 + V_{12} + V_{13} + V_{23} + V_{123} \cdots\cdots (7)$$

Hence,

$$1 = S_1 + S_2 + S_3 + S_{12} + S_{13} + S_{23} + S_{123} \cdots\cdots (8)$$

For Factor 1,

$$S_{tot} = S_1 + S_{12} + S_{13} + S_{123} \cdots\cdots (9)$$

The total sensitivity index $S_{tot}$ in Eq. (9) represents the expected percentage that remains if all factors but Factor 1 are fixed.

Consequently,

$$0 \leq S_i \leq S_{i_{tot}} \leq 1 \cdots\cdots (10)$$

Sensitivity analysis can help industry manage limited resources well through adjusting the most influential factor to achieve ideal results. It is also an effective approach to model simplification by fixing the varying factor. $S_{i_{tot}} = 0$ is a necessary and sufficient condition for non-influence, and therefore, Factor *i* can be fixed to reduce the complexity of the model.

# 3 Capacity Analysis

Railway capacity is mainly affected by three factors:

- Minimum technical headway: it is defined by the characteristics of the railway infrastructure and rolling stock in the early stages of design;
- Operational strategy: it depends on the service frequencies, station locations, demands and other practical issues;
- Standards and regulations: these differ between companies and countries.

All the necessary sample data in this thesis is derived from the WCML fast 'down' line from London to Rugby. In the ideal model, the train length is 400 m; the minimum service braking rate is 0.5 m/s$^2$; the emergency braking rate ranges from 0.7 to 1.0 m/s$^2$; the route length is 136 km; the service running speed is 125 mph (200 km/h or 56 m/s). There are four stations on this route: London Euston, Watford Junction, Milton Keynes Central, and Rugby, and they are located at 0, 28.1 km, 80.2 km, 136 km miles on the WCML respectively.

## 3.1 Minimum Technical Headway

The minimum technical headway depends on the type of signalling system installed, the train speed, train length and braking rate.

### 3.1.1 **Signalling System**

Based on the above parameters, typical two, three and four aspect signalling systems and moving block are given as examples to compare their headway and capacity.

For the fixed block system, some parameters are fixed in this thesis, as an example: sighting time 8 s; overlap 200 m.

An illustration of the two aspect signalling system is shown in Figure 10. Considering driver workload and infrastructure cost, the travel time between Main Signal A and Distant Signal B in the classic UK-type two-aspect system should be no less than 15 seconds.

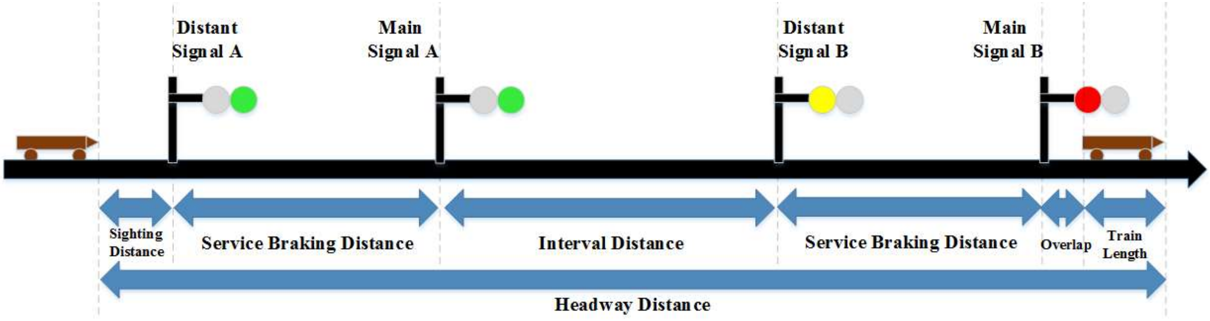

*Figure 10 – Two Aspect Fixed Block Arrangement (Author, 2017)*

$$Headway\ Distance = SD + 2 * BD + ID + OL + TL \cdots\cdots (11)$$

Where

SD: sighting distance obtained by sighting time and running speed;

BD: service braking distance obtained by running speed and braking rate;

ID: interval distance obtained by distance between main signal and next distant signal;

OL: overlap distance;

TL: train length.

Therefore, with parameters previously stated, at a speed of 56 m/s, with a braking rate of 0.5 m/s$^2$, a sighting time of 8 s, an interval time of 15 s, a train length of 400 m, an overlap of 200 m, the headway distance is 8160 m and then headway time is 145.7 s.

A brief description of the three aspect signalling system is shown in Figure 11.

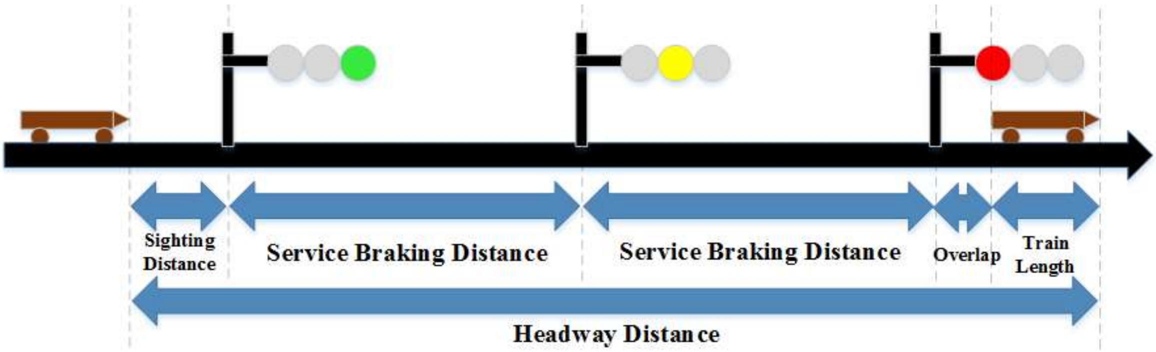

*Figure 11 – Three Aspect Fixed Block Arrangement (Author, 2017)*

$$Headway\ Distance = SD + 2 * BD + OL + TL \cdots\cdots (12)$$

Therefore, with parameters previously stated, the headway distance is 7320 m and then headway time is 130.7 s.

A brief description of the four aspect signalling system is shown in Figure 12.

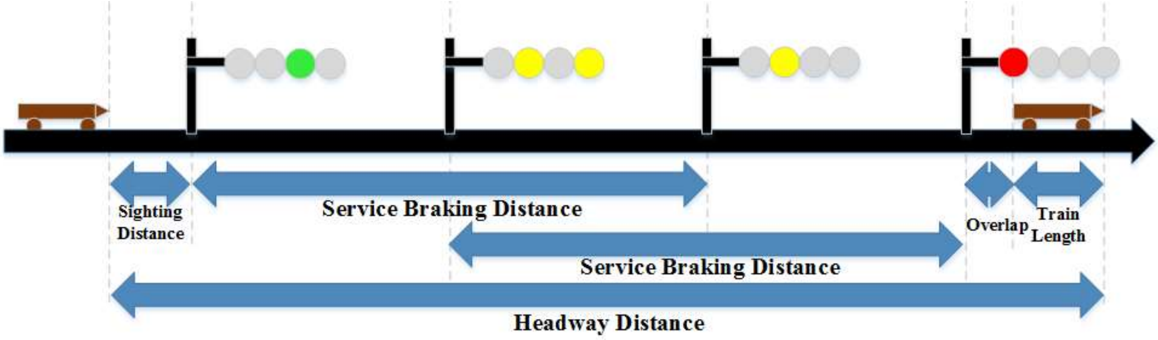

*Figure 12 – Four Aspect Fixed Block Arrangement (Author, 2017)*

$$Headway\ Distance = SD + \frac{3}{2} * BD + OL + TL \cdots\cdots (13)$$

Therefore, with parameters previously stated, the headway distance is 5752 m and then headway time is 102.7 s.

In general, the headway distance and headway time of a conventional *n*-aspect signalling system is Eq. (14). With parameters previously stated, Eq. (15) (16) show the headway results with *n*-aspect signalling system.

$$Headway\ Distance = SD + \frac{n-1}{n-2} * BD + OL + TL \cdots\cdots (14)$$

$$Headway\ Distance = 1048 + \frac{n-1}{n-2} * 3136\ [m] \cdots\cdots (15)$$

$$Headway\ Time = 18.71 + \frac{n-1}{n-2} * 56\ [s] \cdots\cdots (16)$$

For moving block, the latency time (LT) contains the maximum information transmission time and the maximum system delay, which are defined as 10 s, together in this thesis. The safety margin for the moving block system is defined as 400 m (equals to 7.2 s with 200 mph). There is no signal-sighting time because of the provision of signalling information in the cab. However, it will be necessary to include a driver reaction time where trains are not operated automatically.

A brief description of the moving block system is shown in Figure 13.

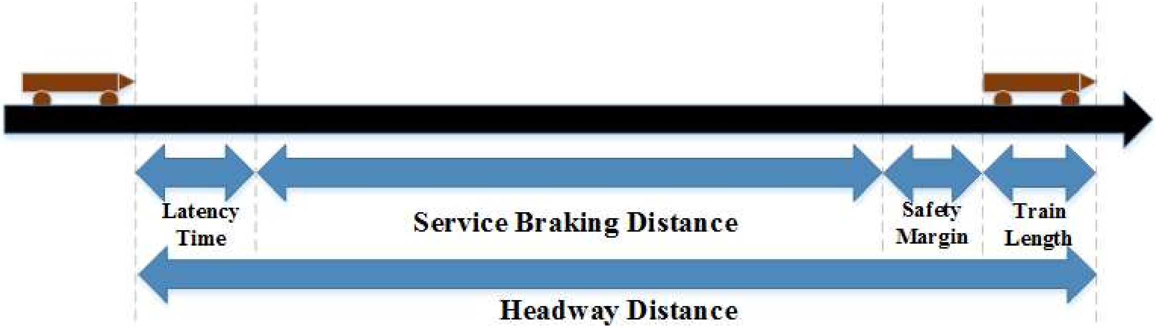

*Figure 13 – Moving Block Arrangement (Author, 2017)*

$$Headway\ Distance = LT + BD + SM + TL \cdots\cdots (17)$$

Therefore, with parameters previously stated, the headway distance is 4296 m and then headway time is 76.71 s.

Overall, the differences in the railway capacity for different types of signalling systems are compared in Table 2.

*Table 2 – The Impact of the Signalling System on Capacity (Author, 2017)*

| Signalling System | Headway Time [s] | Theoretical Capacity [tph] | Headway Effect | Capacity Effect |
|---|---|---|---|---|
| **Two aspect fixed block** | 145.7 | 24 | 0% | 0% |
| **Three aspect fixed block** | 130.7 | 27 | -10% | 13% |
| **Four aspect fixed block** | 102.7 | 35 | -30% | 46% |
| **Moving block** | 76.71 | 44 | -47% | 83% |

### 3.1.2 **Train Speed**

Based on the four aspect signalling system and its minimum technical headway formula, the effect of train speed on capacity is shown in Table 3. Naturally, the train speed is assumed to remain constant.

*Table 3 – The Effect of the Train Speed with 4 Aspect Signalling (Author, 2017)*

| Train speed (constant) | Headway Time [s] | Theoretical Capacity [tph] | Headway Effect | Capacity Effect |
|---|---|---|---|---|
| **125 mph (56 m/s)** | 102.7 | 35 | 0% | 0% |
| **100 mph (45 m/s)** | 88.8 | 40 | -14% | 17% |
| **175 mph (78 m/s)** | 132.7 | 27 | 30% | -25% |
| **250 mph (112 m/s)** | 181.4 | 19 | 79% | -44% |

To make the effect intuitive, as the relevant parameters have been specified, the relationships between speed and headway time and capacity are shown in Figure 14 and Figure 15 based on Eq. (18) (19).

$$Headway\ Time = 8 + \frac{3}{2} * v + \frac{600}{v}\ [s] \cdots\cdots (18)$$

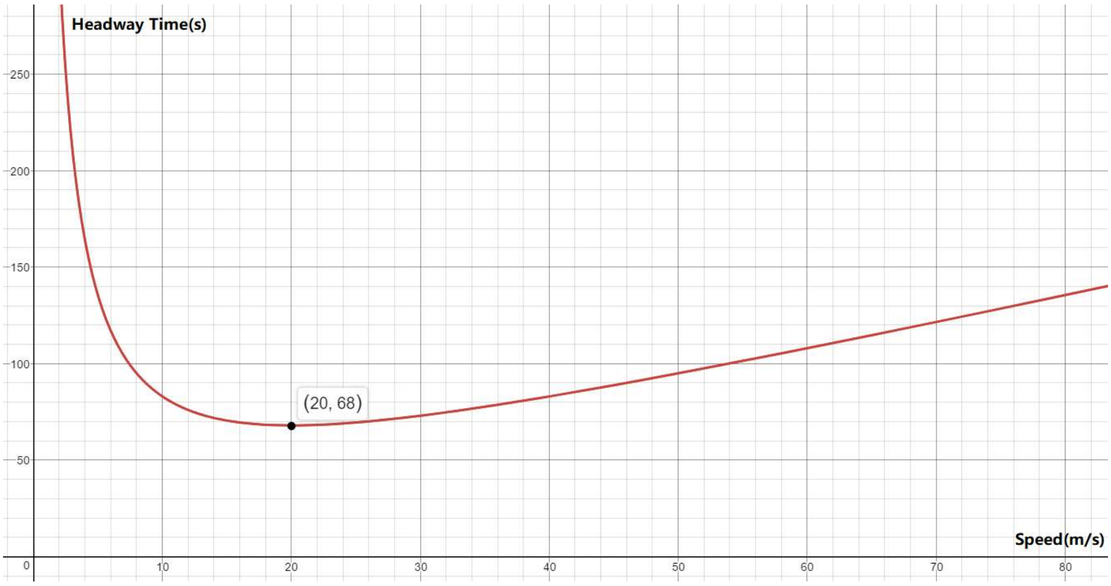

*Figure 14 – Relationship between Speed and Headway Time, 4 Aspect (Author, 2017)*

$$Capacity = \frac{3600}{\left(8 + \frac{3}{2} * v + \frac{600}{v}\right)} \; [tph] \cdots\cdots (19)$$

*Figure 15 – Relationship between Speed and Capacity, 4 Aspect (Author, 2017)*

When the train speed is 20 m/s, the line capacity reaches the maximum, 52 tph. When the speed is more than 20 m/s, there is a positive correlation between train speed and headway time while there is a negative correlation between train speed and capacity.

All other types of signalling systems have similar characteristics.

### 3.1.3 **Braking Rate**

Based on the four aspect signalling system and its minimum technical headway formula, the effect of the braking rate on capacity is shown in Table 4.

*Table 4 – The Effect of Deceleration Rate, 4 Aspect (Author, 2017)*

| Deceleration Rate [m/s²] | Headway Time [s] | Theoretical Capacity [tph] | Headway Effect | Capacity Effect |
|---|---|---|---|---|
| **0.5** | 102.7 | 35 | 0% | 0% |
| **0.4** | 123.7 | 29 | 20% | -17% |
| **0.6** | 88.7 | 40 | -14% | 14% |
| **0.7** | 78.7 | 45 | -23% | 29% |

To make the influence more apparent, as the relevant parameters have been specified, the relationships between braking rate and headway time & capacity are shown in Figure 16 and Figure 17 based on Eq. (20) (21).

$$Headway\ Time = \frac{42}{b} + 18.71\ [s] \cdots\cdots (20)$$

*Figure 16 – Relationship between Deceleration Rate and Headway Time (Author, 2017)*

$$Capacity = \frac{3600}{\frac{42}{b} + 18.71}\ [tph] \cdots\cdots (21)$$

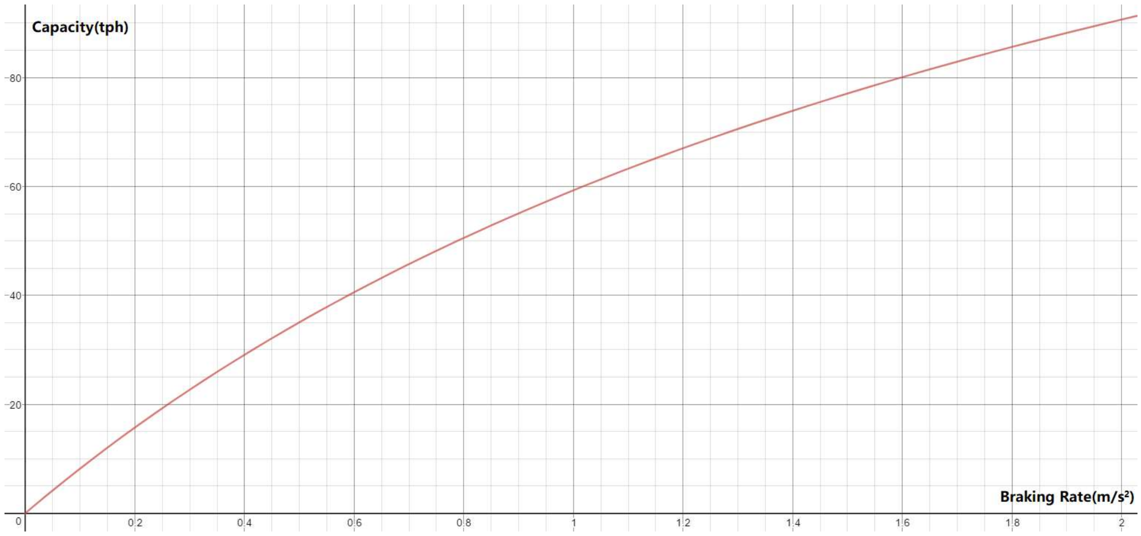

*Figure 17 – Relationship between Deceleration Rate and Capacity (Author, 2017)*

There is a negative correlation between deceleration rate and headway time while there is a positive correlation between deceleration rate and capacity.

All other types of signalling systems have similar characteristics.

### 3.1.4 **Train Length**

Based on the four aspect signalling system and its minimum technical headway formula, the effect of train length on capacity is shown in shown in Table 5.

*Table 5 – The Effect of Train Length (Author, 2017)*

| Fleet Size/Train Length [m] | Headway Time [s] | Theoretical Capacity [tph] | Headway Effect | Capacity Effect |
|---|---|---|---|---|
| **400** | 102.7 | 35 | 0% | 0% |
| **200** | 99.1 | 36 | -4% | 3% |
| **300** | 100.9 | 35 | -2% | 0% |
| **500** | 104.5 | 34 | 2% | -3% |

To make the influence more apparent, as the relevant parameters have been specified, the relationships between train length and headway time & capacity are shown in Figure 18 and Figure 19 based on Eq. (22) (23).

$$Headway\ Time = \frac{TL}{56} + 95.57\ [s] \cdots\cdots (22)$$

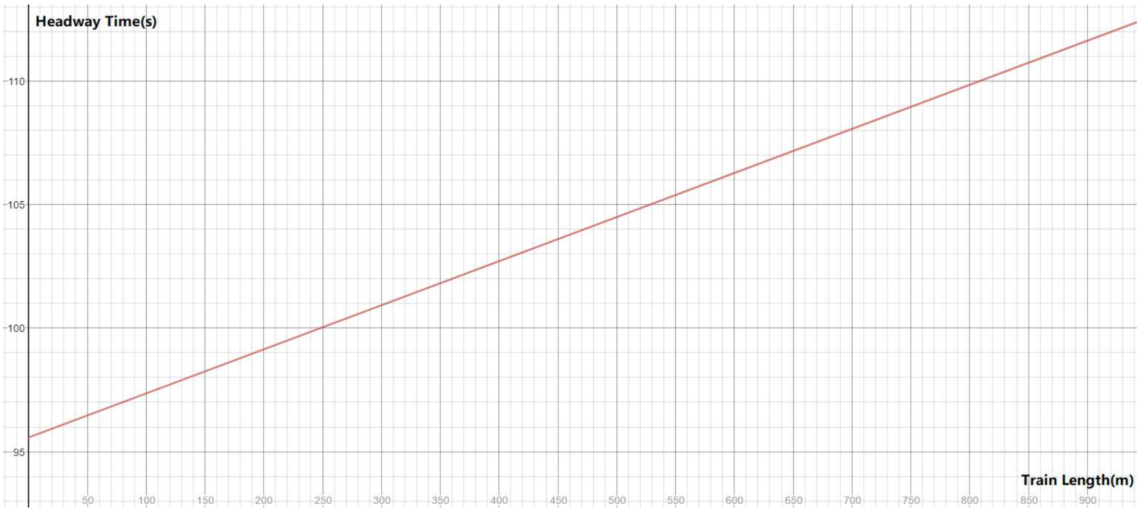

*Figure 18 – Relationship between Train Length and Headway Time (Author, 2017)*

$$Capacity = \frac{3600}{\frac{TL}{56} + 91.57} \ [tph] \cdots\cdots (23)$$

*Figure 19 – Relationship between Train Length and Capacity (Author, 2017)*

There is a positive correlation between train length and headway time while there is a negative correlation between train length and capacity.

All other types of signalling systems have similar characteristics.

## 3.2 Operational Strategy

A railway line is managed and operated by a railway undertaking. Considering human factors and demand, the operational strategy for railway lines varies. For example, a railway for commuting purposes should be operated at high frequency, while a high-speed service that links big cities might only stop at the termini.

### 3.2.1 **Trains Running at Different Speeds**[1]

To figure out the impact of trains running at different speeds, the train speed for each train is assumed to remain constant. If the first train is slower than the second train, as shown in Figure 20, the headway time between these two trains is obtained from Eq. (24).

$$Headyway\ Time = \frac{Route\ Length}{First\ Train\ Speed} - \frac{Route\ Length}{Second\ Train\ Speed} + Minimum\ Headway \quad (24)$$

The first two terms of the above formula represent the supplement time when trains run at different speeds. Using the four aspect signalling system and relevant data, as an example, the effect is shown in Table 6. Operating trains running at different speeds can be seen as extending the minimum technical headway. So, if there are more than two trains running at different speeds, extending the minimum technical headway of slow services accordingly can simulate the case simply. However, in a practical timetable, the pattern of running at different speeds must be considered to analyse the capacity.

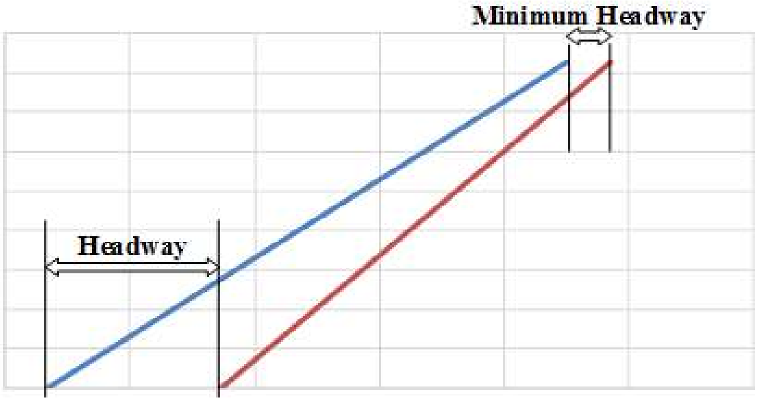

*Figure 20 – When the Second Train's Speed is higher than the First Train's (Author, 2017)*

*Table 6 – The Effect of Trains Running at Different Speeds (Author, 2017)*

| First Train speed [m/s] | Second Train speed [m/s] | Headway Time [s] | Theoretical Capacity [tph] | Headway Effect | Capacity Effect |
|---|---|---|---|---|---|
| **56** | **56** | 102.7 | 35 | 0% | 0% |
| **55** | **56** | 149.5 | 24 | 46% | -31% |
| **51** | **56** | 354.8 | 10 | 245% | -71% |
| **46** | **56** | 661.7 | 5 | 544% | -86% |
| **46** | **51** | 403.2 | 8 | 293% | -77% |

---

[1] The trains running at different speeds scenario mentioned in this thesis refers to the situation where the first train is slower than the second train. In addition, the second train will not pass over the first train.

The relationships for a 144 km long journey are shown in Figure 21 and Figure 22 based on Eq. (25) (26).

$$Headway\ Time = \frac{144000}{56 - speed\ difference} - \frac{144000}{56} + 102.7\ [s] \cdots\cdots (25)$$

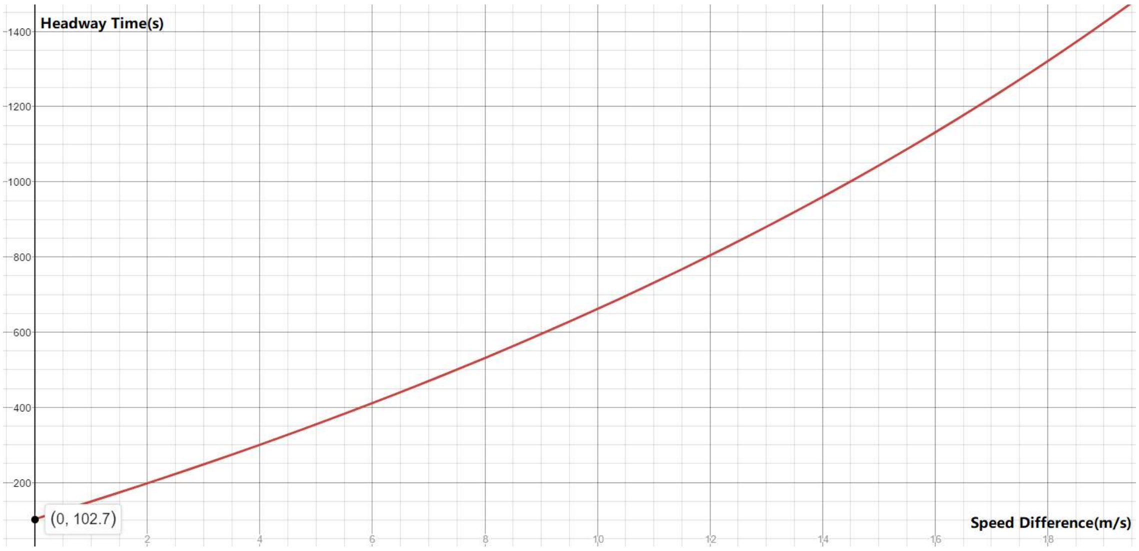

*Figure 21 – Relationship between Speed Difference and Headway Time (Author, 2017)*

$$Capacity = \frac{3600}{\frac{144000}{56 - sd} - \frac{144000}{56} + 99}\ [tph] \cdots\cdots (26)$$

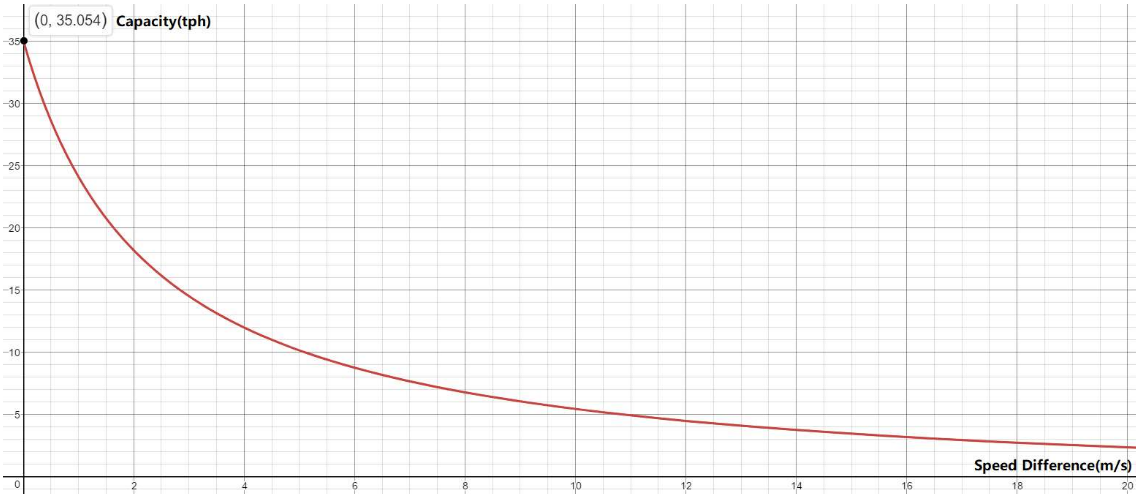

*Figure 22 – Relationship between Speed Difference and Capacity (Author, 2017)*

Overall, if the first train's speed is lower than the second train's, there is a positive correlation between the speed difference and headway time and there is a negative correlation between speed difference and capacity.

If the speed difference is constant, 5 m/s for example as the case below, the relationships between the speed of the second train and headway & capacity are shown in Figure 23 and Figure 24 based on Eq. (27) (28), again for a journey of 144 km.

$$Headway\ Time = \frac{144000}{speed - 5} - \frac{144000}{speed} + 102.7\ [s] \cdots\cdots (27)$$

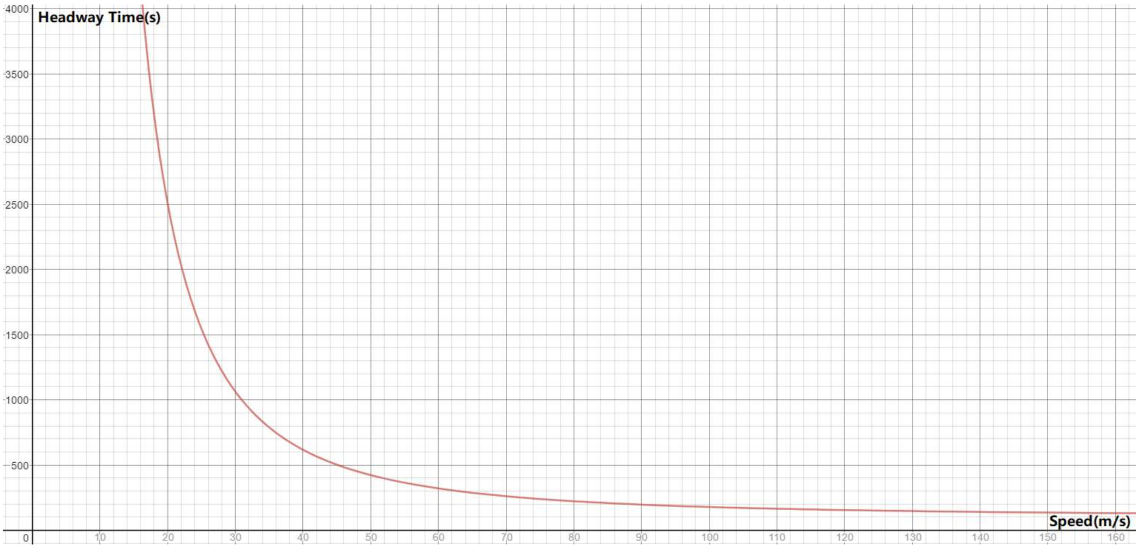

*Figure 23 – Relationship between Speed and Headway Time for Δv = 5 m/s (Author, 2017)*

$$Headway\ Time = \frac{3600}{\frac{144000}{speed - 5} - \frac{144000}{speed} + 102.7}\ [tph] \cdots\cdots (28)$$

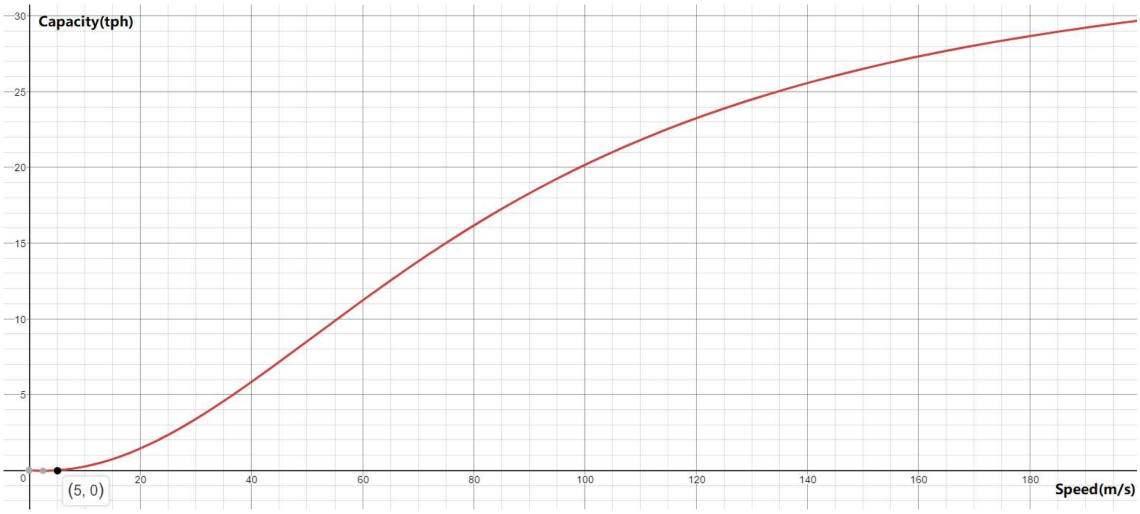

*Figure 24 – Relationship between Speed and Capacity for Δv = 5 m/s (Author, 2017)*

If the speed difference is constant, there is a negative correlation between speed and headway time and there is a positive correlation between speed and capacity. However, if the capacity effect of train speed in 3.1.2 is considered simultaneously, the result will be different, which will be discussed in detail in 3.3 and 3.4.

All other types of signalling systems have similar characteristics.

### 3.2.2 **Stopping Patterns**

Usually, a train service does not stop at all stations during the journey so as to ensure a competitive journey time. Therefore, it is essential to arrange the stopping patterns for a set of train services organically and wisely. It should be noted that stopping patterns are normally empirically managed by regulators according to traffic demand, policy and other requirements. In this section, the effect of stopping patterns on capacity is analysed and how to manage and organise stopping patterns scientifically in a timetable will be discussed in Chapter 4.

To find the influence of stopping patterns, the train speed should be assumed to remain constant. In the beginning, we also assume that trains can accelerate to maximum speed and stop instantly.

On the chosen route, there are four railway stations (including a terminus station), namely, London Euston, Watford Junction, Milton Keynes Central and Rugby. The dwell time for all stations is assumed to be two minutes. There are eight different types of stopping pattern for our case (single direction), which are shown in Table 7.

*Table 7 – Stopping Patterns on Part of the WCML (Author, 2017)*

| **Train Type** | **Watford Junction** | **Milton Keynes Central** | **Rugby** |
|---|---|---|---|
| **A** | STOP | STOP | STOP |
| **B** | STOP | STOP | PASS |
| **C** | STOP | PASS | PASS |
| **D** | STOP | PASS | STOP |
| **E** | PASS | STOP | STOP |
| **F** | PASS | STOP | PASS |
| **G** | PASS | PASS | PASS |
| **H** | PASS | PASS | STOP |

All stopping patterns have been simulated and analysed independently to assess the effect on headway time and capacity. The minimum technical headway has been set to 102.7 s, which is based on the four aspect signalling system shown in 3.1.1.

For example, if the first train type is A and the second train type is also A, the second train cannot be permitted into the platform until the first train has departed from the platform, with a minimum technical headway time (102.7 s). A simple time-distance graph is shown in

Figure 25. Here, the headway time has been increased to 222.7 s, and by doing so, the second train no longer needs to wait for platform re-occupation along the journey.

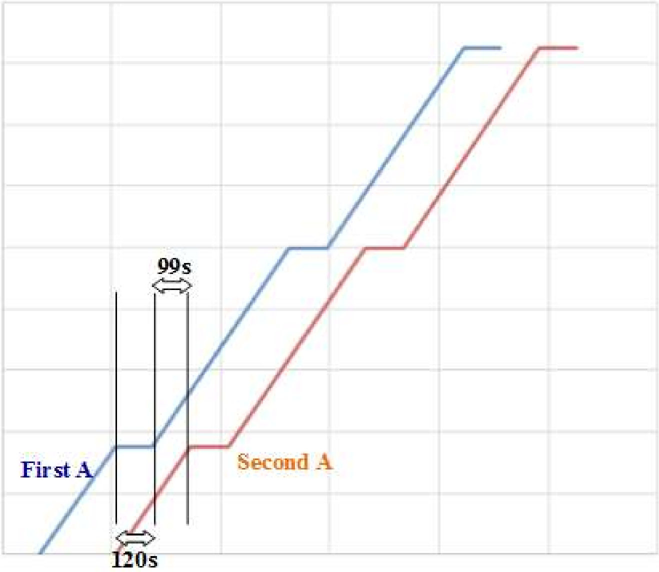

*Figure 25 – A-A Stopping Pattern (Author, 2017)*

The results for all possible scenarios are shown in Table 8, where (SPS) stands for Stop at Watford, Pass at Milton Keynes and Stop at Rugby, for example.

*Table 8 –Headway Time for Different Stopping Patterns (Author, 2017)*

| Second<br>First | A(SSS) | B(SSP) | C(SPP) | D(SPS) | E(PSS) | F(PSP) | G(PPP) | H(PPS) |
|---|---|---|---|---|---|---|---|---|
| **A(SSS)** | 222.7 | 222.7 | 342.7 | 342.7 | 342.7 | 342.7 | 462.7 | 462.7 |
| **B(SSP)** | 222.7 | 222.7 | 222.7 | 222.7 | 342.7 | 342.7 | 342.7 | 342.7 |
| **C(SPP)** | 222.7 | 222.7 | 222.7 | 222.7 | 222.7 | 222.7 | 222.7 | 222.7 |
| **D(SPS)** | 222.7 | 222.7 | 222.7 | 222.7 | 222.7 | 222.7 | 342.7 | 342.7 |
| **E(PSS)** | 102.7 | 102.7 | 222.7 | 222.7 | 222.7 | 222.7 | 342.7 | 342.7 |
| **F(PSP)** | 102.7 | 102.7 | 102.7 | 102.7 | 222.7 | 222.7 | 222.7 | 222.7 |
| **G(PPP)** | 102.7 | 102.7 | 102.7 | 102.7 | 102.7 | 102.7 | 102.7 | 102.7 |
| **H(PPS)** | 102.7 | 102.7 | 102.7 | 102.7 | 102.7 | 102.7 | 222.7 | 222.7 |

The number of stops is an essential indicator of a train service because more stops will bring more revenue, but will increase journey time. If two successive services pass all stations, the number of stops is zero. Considering all cases above, the number of intermediate stops ranges from zero to six, for a pair of trains. The data for headway time and capacity for a different number of stops are compared and shown in Table 9.

*Table 9 – The Influence of Stopping Patterns (Author, 2017)*

| **Number of stops** | 0 | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| **Minimum headway [s]** | 102.7 | 102.7 | 102.7 | 102.7 | 102.7 | 102.7 | 222.7 |
| **Maximum headway [s]** | 102.7 | 222.7 | 342.7 | 462.7 | 462.7 | 342.7 | 222.7 |
| **Average headway [s]** | 102.7 | 162.7 | 198.7 | 222.7 | 238.7 | 242.7 | 222.7 |
| **Headway Effect** | 0% | 58% | 93% | 117% | 132% | 136% | 117% |
| **Theoretical Capacity [tph]** | 35 | 22 | 18 | 16 | 15 | 14 | 16 |
| **Capacity Effect** | 0% | -37% | -49% | -54% | -57% | -60% | -54% |

Usually, it is impossible to achieve the best theoretical capacity, for practical reasons. To compare the impact of the stopping patterns, the concept of ‘average headway time’ is introduced here. If each train stops at only one station, which is very common in the real world (Swlines Ltd, 2017), the capacity will reduce by 49% compared to the non-stop scenario. The optimality analysis for the stopping patterns will be discussed in 3.3.2.

### 3.2.3 **Algorithm for Stopping Patterns**

If there are more than three stations on a railway line, it is difficult to simulate and analyse all scenarios. To obtain the headway time between two trains with specific stopping patterns logically, specific rules and algorithms are proposed.

Assuming that all stations are in the same condition[2] and that all trains can reach their maximum speed and stop instantly, the headway time can be formulated as shown in Eq. (29). As suggested before, the minimum technical headway and dwell time are defined by infrastructure, rolling stock, and industry custom. So, $n$ is the only variable affecting headway time between two successive trains with particular stopping patterns ($n$ can be obtained based on the following contents).

$$Headway\ Time = Minimum\ Technical\ Headway\ Time + n * Dwell\ Time \cdots\cdots (29)$$

Overall, the proposed method begins with the stopping pattern of the second train. Each stopping pattern of the second train has a checking formula. The headway time between two trains can then be calculated using the fomula.

The simulation shows that, whether or not the second train stops at the final station, the headway time between two trains will not change. For example, let us assume that there are three stations. When the first train stops at all stations (SSS), while the second train

---

[2] All stations are only served by one railway line. They feature two unidirectional platforms and they are all independent and well organised.

stops at the first and second stations (SSX) only (where X stands for undefined stop status, that is, it could be S (stop) or P (pass)), *n=1*. Other similar situations for the three-station case can be seen in Table 8. In summary, the final station's stop status for the second train is not relevant to the headway time between two trains.

For the two-station case, the checking table is shown below:

*Table 10 – Checking Table for the Two-Station Case (Author, 2017)*

| **Second** | **First train checking formula** |
|---|---|
| SX | SX |
| PX | SX+XC(CS≥1) (CS stands for Counting the number of S) |

There are two types of second train. When the first train satisfies each term in the corresponding checking formula in Table 10, *n=n+1*. For example, if the second train is SS, while the first train is SP, *n=1* because the stopping pattern of the first train meets the term SX.

If the second train is PX, the stopping pattern of the first train should check each term in the checking formula independently. For example, when the second train is PP and the first train is SS, *n=2*, because the stopping pattern of the first train meets both two terms (SX and XC(CS≥1)) in the checking table. For the three and four station cases, the checking tables are shown below.

*Table 11 – Checking Table for the Three-Station Case (Author, 2017)*

| **Second** | **First train checking formula** |
|---|---|
| SSX | SXX |
| SPX | SXX+XCC(CS≥2) |
| PSX | SXX+XSX |
| PPX | SXX+XCC(CS≥1+CS≥2) |

*Table 12 – Checking Table for the Four-Station Case (Author, 2017)*

| **Second** | **First train checking formula** |
|---|---|
| SSSX | SXXX |
| SSPX | SXXX+XCCC(CS≥3) |
| SPSX | SXXX+XSSX |
| SPPX | SXXX+XCCC(CS≥2+CS≥3) |

| | |
|---|---|
| PSSX | SXXX+XSXX |
| PSPX | SXXX+XSXX+XXCC(CS≥2) |
| PPSX | SXXX+XSXX+XXSX |
| PPPX | SXXX+XCCC(CS≥1+CS≥2+CS≥3) |

There are a few basic principles for extending the checking table to any number of stations.

1. When we want to add S in front of the type of the second train:
    a) If the first letter of the term in the checking formula is S, X should be added after the first S.
    For example, if we want to add S in front of SSX for the second train type, the checking formula of SSSX is SXXX (S+X+XX).
    b) If the first letter of the term in checking formula is X, S should be added after the first X.
    For example, if we want to add S in front of PSX for the second train, the checking formula of SPSX is SXXX+XSSX (S+X+XX; X+S+SX).
    c) If there is any C in the term of the checking formula, C should be added to the end of the formula and the number related to SC should be all plus 1.
    For example, if we want to add S in front of PPX for the second train, the checking formula for SPPX is SXXX+XCCC (SC≥2+SC≥3) (S+X+XX; XCC+C)
2. When we want to add P in front of the type of the second train:
    a) If the first letter of the term in the checking formula is S, X should be added after the first S; X should be added in front of the checking formula. That means there are two terms generated.
    For example, if we want to add P in front of SSX for the second train, the checking formula of PSSX is SXXX+XSXX (S+X+XX; X+SXX).
    b) If the first letter of the term in the checking formula is X, X should be added in front of the checking formula.
    For example, if we want to add P in front of PSX for the second train, the checking formula of PPSX is SXXX+XSXX+XXSX (S+X+XX; X+SXX; X+XSX).
    c) If there is any C in the term of the checking formula, X should be added in front of the checking formula and the number related to SC remains.
    For example, if we want to add P in front of SPX for the second train, the checking formula of PSPX is SXXX+XSXX+XXCC (SC≥2) (S+X+XX; X+SXX; X+XCC).
3. If the second train is $P_1P_2...P_nX$, the checking formula is:
    $SX_1X_2...X_n+XC_1C_2...C_n$ (SC≥1+SC≥2+…+SC≥n).

For example, if the second train is PPPPX, its checking formula is SXXXX+XCCCC (SC≥1+SC≥2+SC≥3+SC≥4).

4. Each term in the previous formula must be evolved independently based on the current checking table.
5. All checking tables are based on the two-station checking table and have evolved step by step.

In conclusion, the evolution principles are shown in Table 13. If the number of stations is fixed, the corresponding checking table can be confirmed.

*Table 13 – Checking Table Evolution Principles (Author, 2017)*

| Change of Second Train | Previous Term | Evolution Term |
|---|---|---|
| S+ | S+R(Remainder) | S+X+R |
| | X+R | X+S+R |
| | XC(SC≥n) | XCC(SC≥n+1) |
| P+ | S+R | S+X+R; X+S+R |
| | X+R | X+X+R |
| | XC(SC≥n) | XXC(SC≥n) |
| $P_1P_2...P_nX$ | $SX_1X_2..._{}X_n+XC_1C_2...C_n$(SC≥1+SC≥2+…+SC≥n) | |

Although neglected until now, from a practical point of view, the braking and acceleration behaviours must be considered when the train arrives and departs from a station. The influence of these behaviours can be categorised into two types:

Type i is shown in Figure 26. In Type i, the braking and acceleration behaviours do not affect the interval time between two trains. The headway time only depends on the minimum technical headway and the dwell time as shown in Eq. (30). With previous stated parameters, the headway time is 222.7 s

$$Headway\ Time = \ Minimum\ Headway + Dwell\ Time \cdots\cdots (30)$$

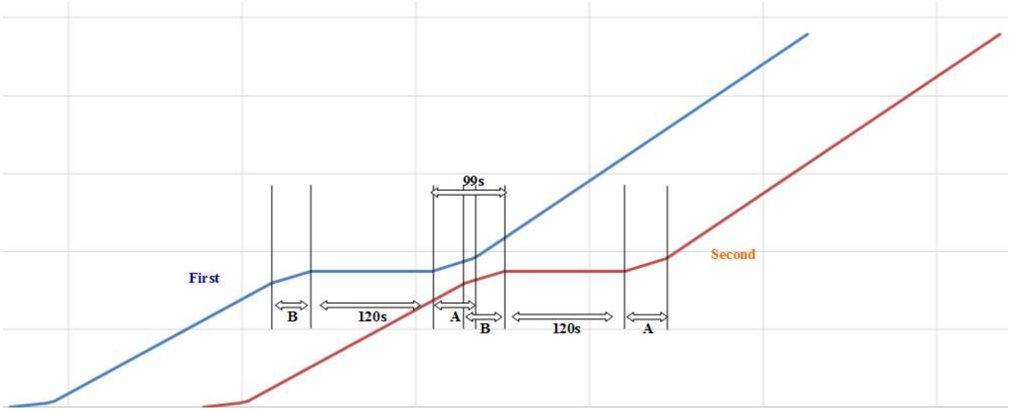

*Figure 26 – Type i (Author, 2017)*

Type ii is shown in Figure 27. In Type ii, the time loss due to the braking and acceleration behaviours must be considered. Assuming that the train is operated with constant acceleration and braking conditions, the time loss in Type ii is calculated by Eq. (31) (where *a* is the acceleration rate and *b* is the braking rate).

$$Time\ Loss\ (Time\ Supplement) = \frac{v}{2*a} + \frac{v}{2*b}\ [s] \cdots\cdots (31)$$

For example, where the braking rate is 0.7 m/s$^2$ and the acceleration rate is 0.7 m/s$^2$, the headway between the two trains is 302.7 s which is calculated by Eq. (32).

$$Headway\ Time = \ Minimum\ Headway + Dwell\ Time + Time\ Supplement \cdots\cdots (32)$$

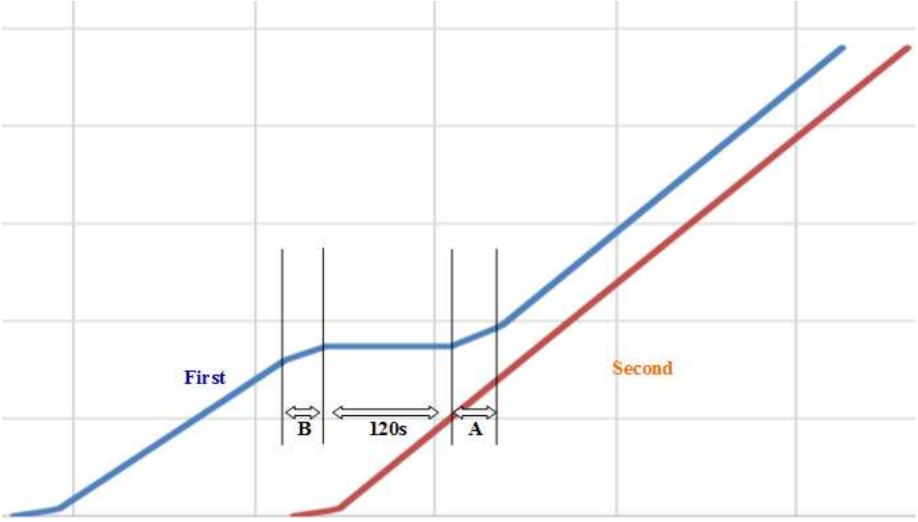

*Figure 27 – Type ii (Author, 2017)*

To identify the stopping type of two trains at a station when considering the braking and acceleration behaviours, a method based on the stopping pattern algorithm is proposed so that the headway time between two trains can be calculated as Eq. (33) subjected to Eq. (34). It can be summarised in eight steps, effectively a pseudo-code:

1. Compare the two trains' stopping patterns at each station. If the second train's is P and the first train's is S, this station should be marked as a potentially affected station.
2. Inspect the first marked station.
3. Count the number of S before the marked station (excluded) for each train. (If there is no station before the marked station, the number of S is zero.)
4. If the number of S for the second train is no more than that of the first train, this marked station is defined as Type ii. Otherwise, the mark should be removed.
5. Inspect next marked station until the last one has been reached.
6. Back to steps 3 and 4.
7. After inspecting all marked stations, the number of Type ii stations is defined as *m.*
8. The headway time between the two trains is (value *n* is determined by the above checking table):

$$Headway = Minimum\ Headway + n * Dwell\ Time + m * Time\ Loss(s) \cdots\cdots (33)$$

$$n \geq m \cdots\cdots (34)$$

For example, if the first train is PSSS and the second train is SPSP, the checking formula for SPSX is SXXX+XSSX, so *n=1*. According to the method, the second station and the fourth station are marked. For the second station, the number of S for the second train is 1, while that of the first train is 0, so the mark should be repealed. For the fourth station, the number of S for the second train and the first train are both 2, so only the fourth station is defined as Type ii, so *m=1*. Overall, the headway time between these two trains is calculated by Eq. (35).

$$Headway\ Time = 102.7 + 1 * 120 + 1 * 80 = 302.7(s) \cdots\cdots (35)$$

## 3.3 Optimality Analysis

An optimality analysis is trying to find the best inputs for a function through mathematical methods based on limitations and requirements. In the railway domain, one of the requirements for a railway line is to maximise its railway capacity. From the railway designer's point of view, railway capacity refers to the line capacity, usually expressed by TPH. A passenger is more likely to care about sufficient seats or spaces being available from the local station. Therefore, passenger capacity is introduced, expressed by passengers per hour per direction (pphpd) that is related to seats/spaces provided (passenger density).

Overall, considering all factors discussed in 3.1 and 3.2, the headway time and capacity indicators are calculated by the Eq. (36) (37) (38) (39).

$$Headway\ Time = Speed\ Difference\ Loss + Minimum\ Tchnical\ Headway + n * Dwell\ Time + m * Time\ Supplement \cdots\cdots (36)$$

$$Headway\ Time = \frac{RL}{v - sd} - \frac{RL}{v} + 8 + \frac{0.75 * v}{b} + \frac{t + 200}{v} + n * DT + m * \left(\frac{v}{2 * a} + \frac{v}{2 * b}\right) [s] \cdots\cdots (37)$$

$$Maximum\ Capacity = \left\lfloor \frac{60}{Minimum\ Headway\ Time} \right\rfloor [tph] \cdots\cdots (38)$$

$$Passenger\ Capacity = Line\ Capaity * t * Passenger\ Density\ [pphpd] \cdots\cdots (39)$$

To proceed to the optimality analysis, the related parameters / variables must be listed and defined. They are: running speed (*v*); speed difference (*sd or* Δ*v*); braking rate (*b*); train length (*t*); stopping pattern / the total number of stops (*st*); acceleration rate (*a*); dwell time (*dw*); passenger density in carriages (*d*); and route length (*RL*). These parameters can be classified into two sets, the first set is defined and determined at the design stage and the other one is defined at the operation stage.

During the design stage, the technical standard of the infrastructure has to be planned 3-10 years or more ahead of time (International Union of Railways, 2013), including the signalling system, route length, and the locations of stations. For rolling stock, the parameters are also confirmed before construction, including braking rate, acceleration rate, train length, and passenger density in the train. Dwell time is in accordance with local custom and practice. The parameters determined at the design stage cannot be optimally analysed in this subchapter because they are limited by the physical or social domain and hardly change during operation (excluding changing train length through coupling and uncoupling).

Once the design and construction stages have been completed, the running speed, speed difference and stopping pattern are three variables that are determined in the operation stage. It is clear that any difference in speed between trains has a significant impact on capacity and, usually, it neither brings any benefit nor is there an optimal value. Therefore, railway operators should avoid the speed difference situation as far as possible. Other analysable parameters are discussed in the following subsections.

### 3.3.1 **Running Speed Optimality**

For two trains, if they are both passing all stations before the terminus (st=0), the headway is calculated by Eq. (40).

$$Headway\ Time = \frac{RL}{v-sd} - \frac{RL}{v} + 8 + \frac{0.75*v}{b} + \frac{t+200}{v}(s=0) \cdots\cdots (40)$$

If the two trains are running at the same speed (sd=0), Eq. (40) changes to Eq. (41).

$$Headway\ Time = 8 + \frac{0.75*v}{b} + \frac{t+200}{v}(s=0, sd=0) \cdots\cdots (41)$$

The derivative of Eq. (41) is Eq. (42).

$$\frac{d(HT)}{d(v)} = \frac{0.75}{b} - \frac{t+200}{v^2} \cdots\cdots (42)$$

When

$$v(opt) = \left(\frac{b*(t\ +\ 200)}{0.75}\right)^{\frac{1}{2}}\ [m/s] \cdots\cdots (43)$$

From Eq. (43), it is clear that braking rate and train length both have positive correlations to *v(opt).* The maximum capacity can be obtained from Eq. (45) when Eq. (43).

$$Headway\ Time\ Min = 8 + \left(\frac{3*(t+200)}{b}\right)^{\frac{1}{2}}\ [s] \cdots\cdots (44)$$

$$Capacity\ Max = \frac{3600}{8+\left(\frac{3*(t+200)}{b}\right)^{\frac{1}{2}}}(tph) = \frac{3600*d*t}{8+\left(\frac{3*(t+200)}{b}\right)^{\frac{1}{2}}}\ [pphpd] \cdots\cdots (45)$$

When

$$v > \left(\frac{b(t\ +\ 200)}{0.75}\right)^{\frac{1}{2}}\ [m/s] \cdots\cdots (46)$$

According to Eq. (46), there is a negative correlation between speed and capacity. This is shown in Figure 14.

In consideration of the speed difference, the headway time can be obtained from Eq. (47).

$$Headway\ Time = \frac{RL}{v-sd} - \frac{RL}{v} + 8 + \frac{0.7*5v}{b} + \frac{t+200}{v} \cdots\cdots (47)$$

The derivative of Eq. (47) is Eq. (48).

$$\frac{d(HT)}{d(v)} = \frac{RL}{v^2} - \frac{t+200}{v^2} + \frac{0.75}{b} - \frac{RL}{(sd-v)^2} \cdots\cdots (48)$$

Similarly, when *v*> *v(opt)*, there is a negative correlation between speed and capacity.

Moreover, MATLAB simulation shows that all parameters *(RL, t, b, s)* have positive correlations with the optimal speed under which the train can achieve maximum capacity.

### 3.3.2 **Stopping Pattern Optimality**

To maximise the utilisation rate of railway lines and infrastructure, the stopping pattern must be analysed and optimised, since it has a significant impact on capacity. The influence of the stopping pattern contains two parts: the dwell time supplement, and the time supplement to stopping behaviours, which is shown in Eq. (49).

$$Headway\ Time\ influenced\ by\ stopping\ pattern$$
$$= n * DT + m * (\frac{v}{2*a} + \frac{v}{2*b})\ [s] \cdots\cdots (49)$$

In the above formula, *n* and *m* are decided by the logical algorithm introduced in 3.2.2. However, these two variables are non-linear, and cannot be quantitatively analysed like 3.3.1 and 3.3.3.

Therefore, the average headway time based on the total number of stops is introduced. For example, if there are three stations on a railway line (excluding the terminus station), the total number of stops of the two trains ranges from 0 to 6. The average headway times for different numbers of stops are shown in Table 14.

*Table 14 – Average Headway for 3-Station Case (Author, 2017)*

| **Number of Stops** | **Average Headway** |
|---|---|
| **0** | Minimum technical headway |
| **1** | Minimum technical headway + 1/2*dwell time + 1/2*time supplement |
| **2** | Minimum technical headway + 4/5*dwell time + 3/5*time supplement |
| **3** | Minimum technical headway + dwell time + 7/10*time supplement |
| **4** | Minimum technical headway + 17/15*dwell time + 3/5*time supplement |
| **5** | Minimum technical headway + 7/6*dwell time + 1/2*time supplement |
| **6** | Minimum technical headway + dwell time |
| **0verall Average** | Minimum technical headway + 15/16*dwell time + 19/32*time supplement |

Table 14 shows that 3, 4, or 5 stops might cause the greatest average headway times among all cases. The values of the dwell time and the time supplement decide how many stops will cause the greatest average headway. When the dwell time is less than the 0.75-fold time supplement, four stops cause the greatest headway; when the dwell time is more than a 0.75-fold time supplement and less than a 3-fold time supplement; five stops cause the greatest headway, when the dwell time is more than the 3-fold time supplement, six stops cause the highest headway, even though this scenario is uncommon and impracticable.

The author of this thesis uses a sampled technical specifications of Britain's Class390/0 trains running on West Coast Mainline (running speed (56 m/s); braking and acceleration rate (0.7 m/s$^2$); train length (288m); dwell time (100 s) with 4 aspect colour light signalling system) to find a specific result. The result for the average headway for the three intermediate stations case is shown in Figure 28. In general, the number of stops compromises the line capacity. However, 5 and 6 stops case show the opposite results, since in those two situations, stopping patterns of two successive trains are relatively similar. On the other hand, increased stop times could bring greater passenger capacity for stations. However, from a practical point of view, considering a 1-hour timetable, passenger demands, human factors, and real situations, stopping pattern management becomes more complicated, which will be discussed in detail in Chapter 4.

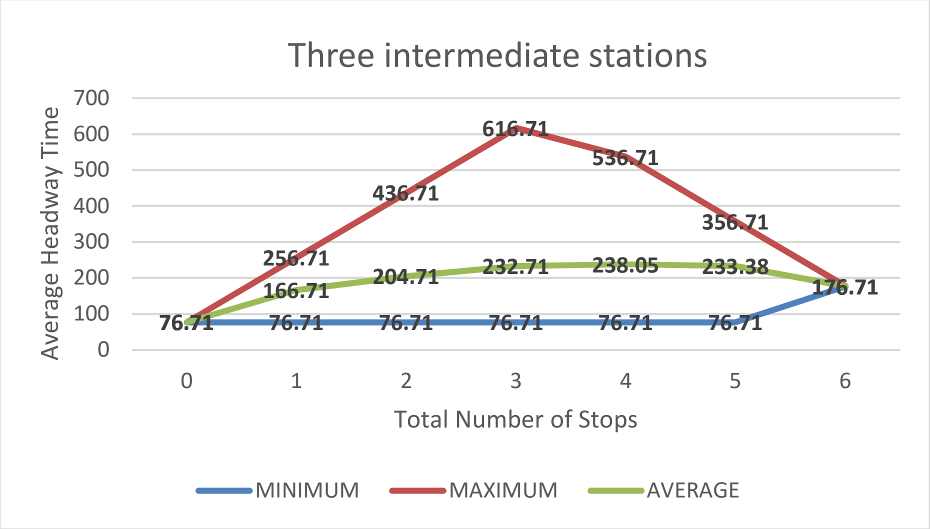

Figure 28 – Headway Comparison for 3 Stations with Different Stopping Patterns (Author, 2017)

### 3.3.3 **Train Length Optimality**

Even though train length is defined at the design stage, it can be changed by physical coupling or uncoupling. Regarding the line capacity model, train length has a dual impact on the result, as shown in Eq. (50) that is obtained from Eq. (38) (39) (40).

$$Passenger\ Capacity = \frac{3600 * d * t}{\frac{RL}{v - sd} - \frac{RL}{v} + 8 + \frac{0.75 * v}{b} + \frac{t + 200}{v}} [pphpd] \cdots\cdots (50)$$

$$t > 0 \cdots\cdots (51)$$

When Eq. (51). The derivative of Eq. (50) is Eq. (52).

$$\frac{d(Passenger\ Capacity)}{d(t)} > 0 \cdots\cdots (52)$$

Consequently, an optimal point for train length and line capacity does not exist, and there is a positive correlation between them.

## 3.4 Sensitivity Analysis

To quantify the effect of each parameter on railway capacity and to find the most influential one, advanced analysis methods should be applied. The approach of sensitivity analysis, as a principle, was introduced in 2.4.3. The analysis is performed using the Global Sensitivity Analysis Toolbox (GSAT) in MATLAB. The variables will be sampled by Sobol sequences with the number of samples set at 10000. Sobol sequences are a type of quasi-random low-discrepancy sequences and this method covers the input space more evenly so that the result of sensitivity analysis will be more stable and robust.

First, regardless of the influence of the operational strategy, the function of headway time is Eq. (53).

$$Headway\ Time = 8 + \frac{0.75 * v}{b} + \frac{t + 200}{v} \cdots\cdots (53)$$

The variables that will be analysed in the above function are Speed (v), braking rate (b) and train length (t). The input space is shown below, the two-fold relationship between minimum and maximum values aims to deliver a Parallel Coordinates Plot analysis later.

*Table 15 – Input Space for Sensitivity Analysis for the Headway Time (Author, 2017)*

| **Input Space** | **Minimum Value** | **Maximum Value** |
|---|---|---|
| **Speed [m/s]** | 40 | 80 |
| **Braking rate [m/s$^2$]** | 0.5 | 1.0 |
| **Train length [m]** | 300 | 600 |

*Table 16 – Results of Sensitivity Analysis for the Headway Time (Author, 2017)*

| | **First order index** | **Total index** |
|---|---|---|
| **Speed [v]** | 0.3647 | 0.3873 |
| **Braking rate [b]** | 0.6040 | 0.6263 |
| **Train length [t]** | 0.0081 | 0.0089 |

The results can also be shown in scatter graphs, as below. In Figure 29, for example, the range of headway time varies with the change of speed. When the speed goes up, the headway time increases and the range of it expands. Comparing the three figures below, the train length is not a significant factor, and therefore, it could be fixed if a more in-depth analysis were required.

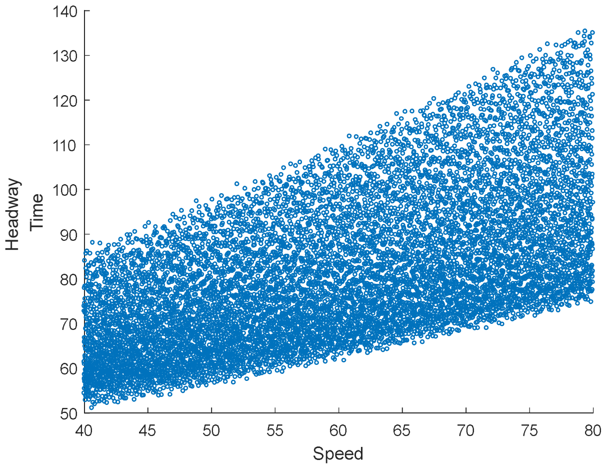

*Figure 29 – First Order Sensitivity to the Speed (Author, 2017)*

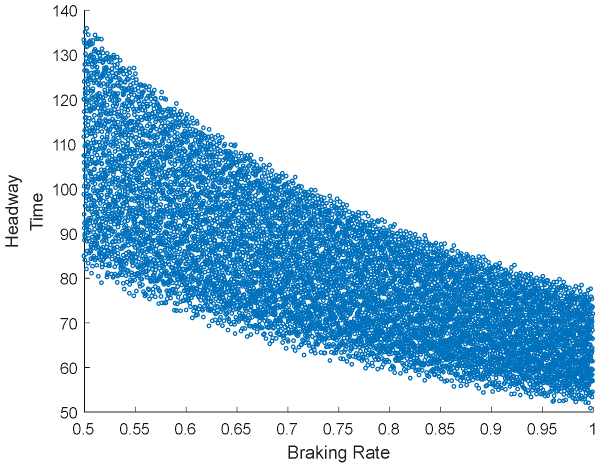

*Figure 30 – First Order Sensitivity to the Braking Rate (Author, 2017)*

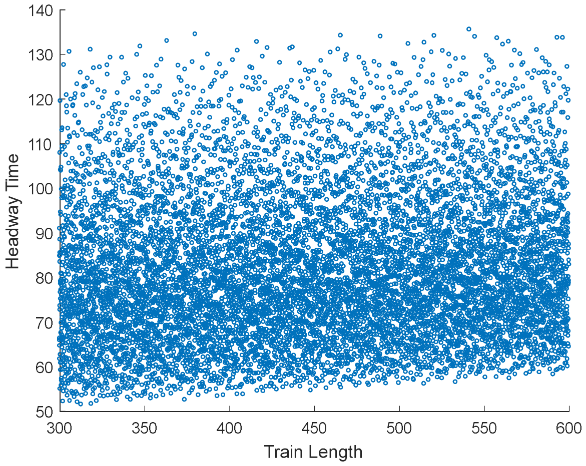

*Figure 31 – First Order Sensitivity to the Train Length (Author, 2017)*

Mathematical work might confuse a railway operator, so how does the railway company manage the assets to achieve the goal headway? A parallel coordinates plot can make the sensitivity analysis intelligible and practical. With given ranges of parameters and a given requirement, the parallel coordinates plot the possible combinations of parameters, and then the limitation of satisfying the requirement could be analysed. For example, assume that the requirement for the technical headway time is to be less than 60 seconds. With he given input space in Table 15, the result in Figure 32 shows that speed and braking rate must be restricted within two ranges, while train length is a relatively irrelevant parameter.

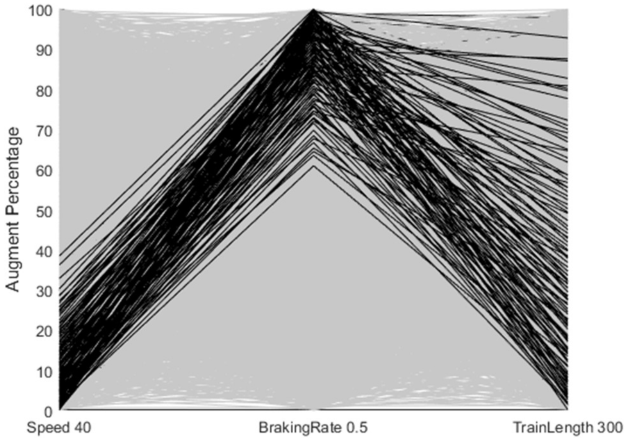

*Figure 32 – Parallel Coordinates Plot (Author, 2017)*

Beyond the parameters already discussed above, operational factors and other issues relevant to railway capacity can be integrated into the model. Now we will consider speed (*v*), braking rate (*b*), acceleration rate (*a*), train length (*t*), running at different speeds (*sd*), total number of stops (*s*), dwell time (*dw*) and passenger density in carriages (*d*) together to analyse the sensitivity of the passenger capacity against each of these factors in turn.

$$Passenger\ Capacity = \frac{3600 * d}{\frac{136000}{v - sd} - \frac{136000}{v} + 8 + \frac{0.75 * v}{b} + \frac{t + 200}{v}}\ (s = 0)\ \cdots\cdots (54)$$

For those train services with a number of stops greater than 0, we will choose the average extra headway data to assess the stopping pattern impact on passenger capacity. An example is shown in Eq. (55). Other cases can be modelled according to Table 14.

$$Passenger\ Capacity = \frac{3600 * d * t}{\frac{136000}{v - sd} - \frac{136000}{v} + 8 + \frac{0.75 * v}{b} + \frac{t + 200}{v} + 0.5 * dw + 0.5 * (\frac{v}{2 * a} + \frac{v}{2 * b})}\ (s = 1)\ \cdots\cdots (55)$$

The passenger density and dwell time are fixed here as 2.5 passengers per metre of train length and 120 seconds respectively. The input space is shown below.

*Table 17 – Input Space for Sensitivity Analysis for the Passenger Capacity (Author, 2017)*

| **Input Space** | **Minimum Value** | **Maximum Value** |
|---|---|---|
| **Speed [m/s]** | 40 | 80 |
| **Speed Difference [m/s]** | 0 | 5 |
| **Braking Rate [m/s$^2$]** | 0.5 | 1 |
| **Train Length [m]** | 400 | 800 |
| **Number of Stops** | 0 | 6 |
| **Acceleration Rate [m/s$^2$]** | 0.5 | 1 |
| **Dwell [s]** | 120 | |
| **Passenger Density [per meter)** | 2.5 | |

*Table 18 – Results of Sensitivity Analysis for the Passenger Capacity (Author, 2017)*

| | **First Order Index** | **Total Index** |
|---|---|---|
| **Speed (m/s)** | 0.0227 | 0.0590 |
| **Speed Difference (m/s)** | 0.2547 | 0.4096 |
| **Braking Rate (m/s$^2$)** | 0.0150 | 0.0312 |
| **Train Length (m)** | 0.1427 | 0.1691 |
| **Number of Stops** | 0.3725 | 0.5259 |
| **Acceleration Rate (m/s$^2$)** | 0.0029 | 0.0002 |

The results can also be shown in scatter graphs.

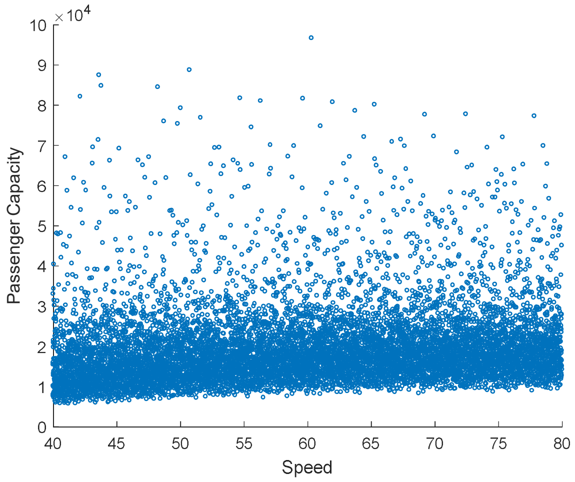

*Figure 33 – First Order Sensitivity to Speed (Author, 2017)*

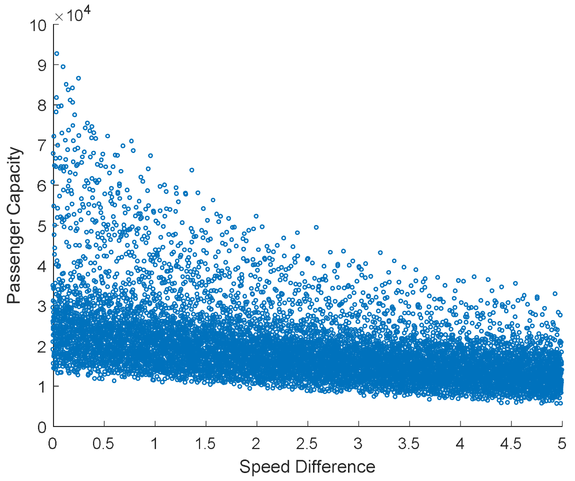

*Figure 34 – First Order Sensitivity to Speed Difference (Author, 2017)*

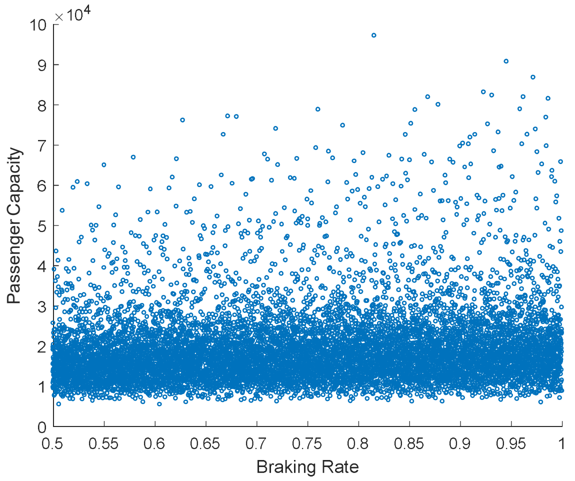

*Figure 35 – First Order Sensitivity to Braking Rate (Author, 2017)*

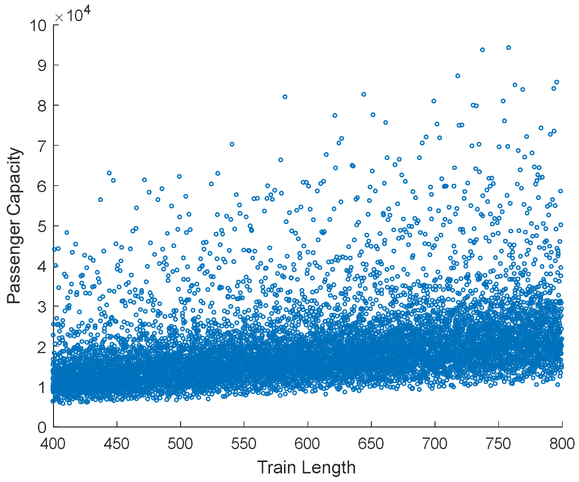

*Figure 36 – First Order Sensitivity to Train Length (Author, 2017)*

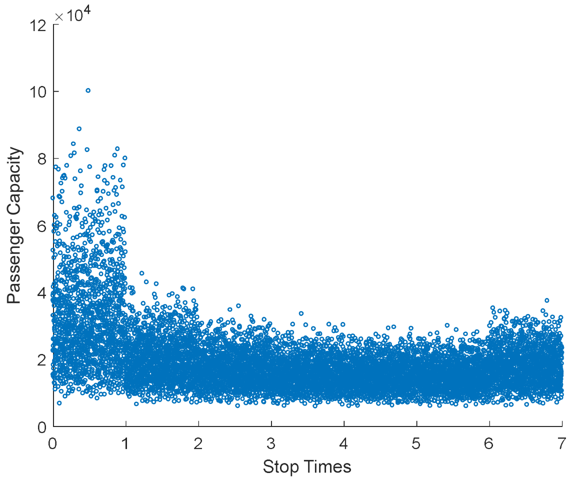

*Figure 37 – First Order Sensitivity to the Number of Stops (Author, 2017)*

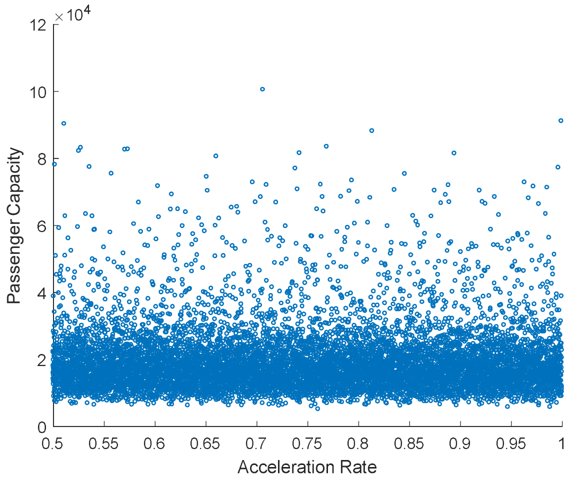

*Figure 38 – First Order Sensitivity to Acceleration Rate (Author, 2017)*

The results show that the number of stops, speed differences, and train length have a significant influence on passenger capacity. A similar Parallel Coordinates Plot can also be drawn to help engineers understand the results. Among those influencing factors, the stop times and speed differences are both related to the operational strategy which is easy to manage in the operations stage of the railway project lifecycle. The train length is also a changeable factor in daily operation by coupling and uncoupling segments of trains, where this is technically feasible.

In conclusion, the operational strategy has a considerable effect on passenger capacity, in addition to the technical factors. Therefore, the railway industry should apply appropriate strategies according to local situations, which are reflected directly in the timetable. The timetable issue is addressed in the next chapter.

# 4 Timetabling

To plan a new timetable or optimise an existing one, three aspects should be considered.

1. Demand and market: demand-oriented services should meet public and social requirements.
2. Infrastructure and rolling stock: physical and technical limitations (such as track, station, signalling system, train technical data).
3. Human factors: practical issues for both customers and operators.

A good timetable will take demand patterns into account, so as to offer the right service at a time that suits a large proportion of the potential passengers (or freight shippers in the case of transport of goods).

## 4.1 Passenger Demand Assessment

### 4.1.1 **Demand Estimation – Gravity Model**

Gravity models are used in the social sciences to predict and describe certain behaviours that mimic gravitational interaction, as described in Isaac Newton's law of gravity (Connor et al., 2015).

In the transportation and railway domains, a gravity model is used to estimate the traffic flow between cities or areas. We assume that a place is treated as a black hole with very high gravitation and attraction because of its job opportunities or places of interest or attracting views. The people near this place will be attracted by the black hole for their needs, such as competitive jobs, and leisure and entertainment possibilities. The attractive force between the places and the attracted people is inversely proportional to the square of the distance.

For industrial purposes, the gravity model has several sophisticated parameters and its application should be combined with many other investigations. For academic purposes, the method and formula can be simplified in Eq. (56).

$$Attraction\ Force = \frac{A * P}{D^2} * C \cdots\cdots (56)$$

Where,

A: the attraction of Place X;

P: the population of Place Y;

D: the distance between X and Y;

C: a calibration factor, a constant.

In our research, the employment opportunities in London can be seen as an object with huge mass which attracts people living in Watford, Milton Keynes and Rugby. So, Eq. (56) is transformed to Eq. (57) where the Passenger Demand equals to the Attraction Force and the Number of Jobs equals to the Attraction of place in the Gravity Model.

$$Passenger\ Demand = \frac{Number\ of\ Jobs\ in\ London * Population\ of\ the\ Town}{Railway\ Distance\ between\ London\ and\ the\ Town^2} * C \cdots\cdots (57)$$

Relevant data about the gravity model for the WCML case are summarised in from Table 20 to 23, which are described below. It should be noted that the calibration factor C in our model has been offset in calculations.

*Table 19 – Descriptions of Table 20, 21, 22, 23 (Author, 2018)*

| **Table** | **Description** |
|---|---|
| Table 20 | The estimated populations of London, Watford, Milton Keynes, Rugby in 2016 |
| Table 21 | The distance from London to these stations on WCML |
| Table 22 | The number of jobs in these cities |
| Table 23 | Based on the gravity model introduced above, the estimated demand between these stations |

Note that:

1. The passenger demand estimated in this section refers to the demand from the towns to London during the morning peak time or the demand from London to the towns during the evening peak time.
2. Since the purpose of the estimation of passenger demand is to find the best stopping pattern strategy for train services starting from London, we are only concerned with the down line service. In other words, the estimated passenger demand in this chapter is the demand from London to the towns during the evening peak time.
3. Taking into account the different distances between London and these towns and also the locations of the railway stations, the definitions of what constitutes London are different for each town. We can assume that, for Watford, London refers to the half district of Inner London (southeast) as people prefer London Overground service if their job place is located in the northwest of London; for Milton Keynes, London refers to Inner London; for Rugby, London refers to Greater London. A schematic diagram is shown in Figure 39.

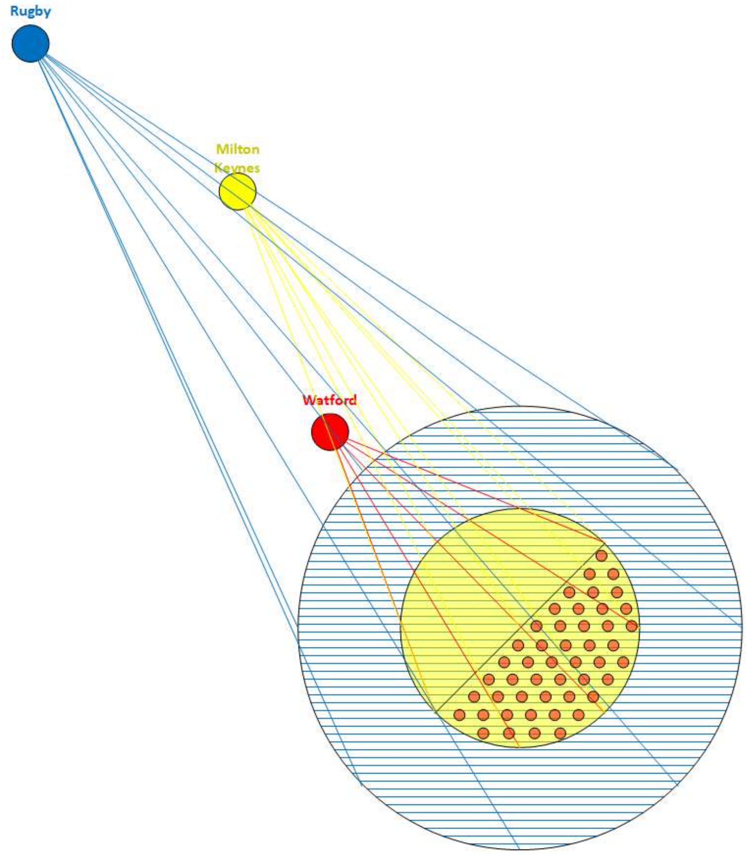

*Figure 39 – London's Urban Influences by WCML (Author, 2017)*

*Table 20 – The Estimated Population (Office for National Statistics, 2017)*

| **City or Area** | **Population (2016)** |
|---|---|
| Inner London | 3,439,110 |
| Greater London | 8,787,892 |
| Watford | 96,773 |
| Milton Keynes | 264,479 |
| Rugby | 103,815 |

*Table 21 – The Railway Distance on WCML (fast) (NetworkRail, 2017b)*

| **Distance (m)** | **Watford Junction** | **Milton Keynes Central** | **Rugby** |
|---|---|---|---|
| London Euston | 28,050 | 80,161 | 132,770 |

*Table 22 – The Number of Jobs in Towns and Cities (Nomis, 2015)*

| City or Area | Number of Jobs |
|---|---|
| Inner London | 3,558,000 |
| Greater London | 5,776,000 |
| Watford | 91,000 |
| Milton Keynes | 183,000 |
| Rugby | 51,000 |

*Table 23 – The Estimated Travel Demand – Normalised (Author, 2017)*

| Demand | Watford | Milton Keynes | Rugby |
|---|---|---|---|
| London | 218.81 | 146.44 | 34.02 |
| Normalised | 6.4 | 4.3 | 1 |

Generally, the estimated ideal demand for Watford, Milton Keynes, and Rugby, to London can be seen as 6.4:4.3:1. However, to estimate the real demand, the results should be calibrated by taking into account generalised cost, road availability, changes in Gross Domestic Product (GDP) and so forth.

### 4.1.2 **Station Usage**

Station usage is an intuitive indicator of passenger demand. The station usage data for all of Britain's railway stations can be found in government documents. Entry & exit data indicate the passenger flow through the ticket barriers in the station, while the interchange data indicate the passengers that only change service at that station. When stopping patterns are focused on in the analysis, all of them should be considered as station usage, because the connectivity between stations is one important output of timetabling.

*Table 24 – Station Usage Data in 2015-2016 (ORR, 2016)*

| Station | 15-16 Entries & Exits | 15-16 Interchanges | 15-16 Total Usage |
|---|---|---|---|
| Milton Keynes Central | 6,835,570 | 462,272 | 7,297,842 |
| Rugby | 2,281,588 | 93,031 | 2,374,619 |
| Watford Junction | 8,189,586 | 567,733 | 8,757,319 |

The ratio of station usage between Watford Junction, Milton Keynes Central and Rugby is 3.7:3:1. Considering the urban attraction effect, most station usage in Watford Junction is related to London, while the station usage in Rugby is distributed between London, Birmingham, and even Manchester.

In conclusion, real station usage generally conforms to passenger demand. We can calculate that the relative passenger demand for Watford, Milton Keynes, and Rugby is 6.4:4.3:1. Unfortunately, however, the precise data for daily traffic flow cannot be found or calculated, and thus, we cannot quantify train service demand per hour. So, we assume that the current provided traffic capacity for Rugby meets traffic demand.

### 4.1.3 **Passenger Crowding**

Passenger crowding data can reflect the relationship between traffic demand and actual usage. The crowding data for major cities and central London stations can also be found in national statistics. In the report for 2016 (National Statistics, 2017), Euston station has a 0.7% growth in PiXC (the overall percentage of passengers that exceed train capacity) which is used in measuring crowding levels. On the other hand, the passenger standing percentage has increased by around 2.4% compared to 2015. Compared to other stations in London, Euston is a moderately crowded station but has a growing trend.

However, the passenger crowding data for small towns and stations are not provided in the national report. The real demand and capacity assessments could be done by other methodologies (e.g., questionnaire, interview) to improve the accuracy of the timetable improvement project.

Even though this thesis is focused on the WCML down fast line, the capacity assessment should consider both fast line services and all other possible route services because of the integrality of passenger flows.

Furthermore, from a long term perspective, a 6% growth of passenger flow (NetworkRail, 2017a) should be considered to meet potential demand.

## 4.2 The Efficiency of Stopping Patterns

In Britain, the timetable of a significant part of the mainline railway is typically designed on a one-hour pattern timetable (NetworkRail, 2018a). Trains follow the peak time or off-peak time timetable in each hour. It is easier for the railway operator to manage traffic flows in this manner.

If unnecessary speed changes are not permitted along the journey[3], each train service is separated by the minimum headway distance on a given path. Furthermore, if all trains use

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[3] Speed is only changed by line speed limitation; stopping behaviour (including braking and acceleration) only takes place at stations that offer passenger service.

unified rolling stock with a unified operational strategy, the stopping pattern is the only factor affecting railway traffic.

To analyse and balance the relationship between stopping pattern and station capacity, the concept of the Efficiency of Stopping Pattern (EoS) for a station is introduced in this thesis. The unit of EoS is minutes per train (mpt). This indicator reflects the average waiting time for passengers at a station. For example, on the Euston-Rugby line, if the EoS for Watford Junction is 20 mpt, then there are three tph stopping at Watford Junction per direction.

Different stopping patterns for the services in one hour will result in different EoS values and line capacity. Some of the potential stopping pattern sequences for the Euston-Rugby route are listed and compared in Table 25.

*Table 25 – Examples of Stopping Pattern Sequence (Author, 2017)*

| **Stopping Pattern Sequence** | **EoS1 for WJ** | **EoS2 for MK** | **EoS3for RB** | **Line Capacity (Average Headway Time)** | **Characteristics** |
|---|---|---|---|---|---|
| 111-111-111-111 | 5 | 5 | 5 | 5 | Best solution for metro |
| 000-111-000-111 | 15 | 15 | 15 | 7.5 | Low stop efficiency and low line capacity |
| 000-001-010-100 | 15 | 15 | 15 | 3.75 | Low stop efficiency but high line capacity |
| 011-110-101 | 7.5 | 7.5 | 7.5 | 5 | Moderate stop efficiency and line capacity |
| 100-101-110 | 5.3 | 16 | 16 | 5.3 | High EoS1 |

In the first column, ‘1’ stands for ‘stop at a station’ while ‘0’ stands for ‘pass’. The service ‘111’ means stop at all three stations. The sequence 111-111-111 is a set of stopping patterns that a set of successive train services follow. The line capacity in the fifth column shows the average minutes per train leaving from London Euston. The related technical indicators were defined in Chapter 3 and, based on those, the operational minimum headway time is 3 minutes; the dwell time is 2 minutes and the time supplement for stop behaviours is 1 minute.

It should be noted that, in this chapter, the relationship between stopping pattern and service journey time will not be discussed, even though the journey time is a non-negligible indicator for urban railway transit. Briefly, in this case, every stop will result in around 5 minutes of additional journey time.

Naturally, since any stopping behaviour will result in time consumption compared to non-stop services, the average headway time is always more than the minimum headway time. In addition, the EoS is no less than the average headway time.

## 4.3 Timetable Improvement

In the present research, there are three steps to undertaking a timetable improvement project.

1. Combine current resources and information (such as the current timetable, estimated passenger demand, the station usage situation) to define the project requirements;
2. List and find fitted stopping pattern sequences in the WCML case[4];
3. Consider real situations and conditions and make the timetable pattern ergonomic.

### 4.3.1 **Timetable Analysis**

Through the following process, a 1-hour timetable can be analysed in the form of EoS table for all stations. Table 26 is an example of a fast line 1-hour timetable and its EoS indicators are in Table 28. Furthermore, considering all train services between Euston and Rugby, the EoS table is Table 31.

*Table 26 – 2017/8/22 WCML Fast Line Timetable from London Euston (Swlines Ltd, 2017)*

| Time | Destination | WJ | MK | RB | Operator |
|---|---|---|---|---|---|
| 1800 | Manchester Piccadilly | 0 | 0 | 0 | VT |
| 1803 | Wolverhampton | 0 | 0 | 1 | VT |
| 1807 | Liverpool Lime Street | 0 | 0 | 0 | VT |
| 1810 | Holyhead | 0 | 1 | 0 | VT |
| 1813 | Birmingham New Street | 0 | - | - | LM |
| 1816 | Birmingham New Street | 0 | - | - | LM |
| 1820 | Manchester Piccadilly | 0 | 1 | 0 | VT |
| 1823 | Birmingham New Street | 1 | 0 | 0 | VT |
| 1830 | Glasgow Central | 0 | 0 | 0 | VT |
| 1833 | Liverpool Lime Street | 0 | 0 | 1 | VT |
| 1840 | Manchester Piccadilly | 0 | 0 | 0 | VT |
| 1843 | Crewe (via Birmingham) | 0 | 1 | 0 | VT |
| 1849 | Crewe | 0 | 1 | - | LM |

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[4] Since there are four tracks on WCML, running at different speeds does not have to be considered when we are only looking at the Fast Line.

| | | | | | |
|---|---|---|---|---|---|
| 1852 | Birmingham New Street | 0 | - | - | LM |

Notes:

1. 0 means nonstop while 1 means stop at that station;
2. LM = London Midland (now North West Railway), VT = Virgin Trains West Coast;
3. London Midland services might move onto the slow line along the journey. Those services do not occupy the fast line after changing to the slow line. The stop condition is recorded as '–'.
4. The 1813 train runs on the fast line near Milton Keynes Central, but it slows down before Milton Keynes Central (not intending to stop). So, it can be seen as a service moving onto the slow line before the station.
5. However, when counting the fast line services stopping at each station, the London Midland services that run on the slow line at Milton Keynes could be treated as a fast service, since their journey time is less than 10 minutes slower than that of Virgin Trains. On the other hand, those stopping at Rugby cannot be seen as fast services, since the slow line between Milton Keynes and Rugby will go through Northampton, which is further than the fast line.

According to the WCML Route Utilisation Strategy (NetworkRail, 2011), the minimum operational headway is 3 minutes; the minimum dwell time is 2 minutes; the minimum time loss (time supplement) that is defined in 3.2.3, is 1 minutes. Based on these minimum allowance time, the timetable can be compressed as shown in Table 27 (again, it is treated as a well-maintained metro-style line without any junctions or speed limitations). In the table, 50 minutes of the hour have been occupied, which means the real timetable has reached 83% of maximum capacity. In the present research, all timetable improvement processes are based on the compressed timetable.

*Table 27 – The Compressed Timetable of the services of Table 26 (Author, 2017)*

| Time | Destination | WJ | MK | RB | Operator |
|---|---|---|---|---|---|
| 1800 | Manchester Piccadilly | 0 | 0 | 0 | VT |
| 1803 | Wolverhampton | 0 | 0 | 1 | VT |
| 1806 | Liverpool Lime Street | 0 | 0 | 0 | VT |
| 1809 | Holyhead | 0 | 1 | 0 | VT |
| 1812 | Birmingham New Street | 0 | - | - | LM |
| 1815 | Birmingham New Street | 0 | - | - | LM |
| 1818 | Manchester Piccadilly | 0 | 1 | 0 | VT |

| | | | | | |
|---|---|---|---|---|---|
| 1821 | Birmingham New Street | 1 | 0 | 0 | VT |
| 1827 | Glasgow Central | 0 | 0 | 0 | VT |
| 1830 | Liverpool Lime Street | 0 | 0 | 1 | VT |
| 1836 | Manchester Piccadilly | 0 | 0 | 0 | VT |
| 1839 | Crewe (via Birmingham) | 0 | 1 | 0 | VT |
| 1844 | Crewe | 0 | 1 | - | LM |
| 1847 | Birmingham New Street | 0 | - | - | LM |

Table 28 shows the fast services’ EoS for each station. However, because of the limited seats and higher ticket prices, some people prefer slower trains for their commuting needs. Therefore, all rail services between these towns and London should be considered.

*Table 28 – Efficiency of Fast Service Stopping Pattern for Each Station (Author, 2017)*

| **Indicators** | **WJ** | **MK** | **RB** |
|---|---|---|---|
| Fast services stop | 1 | 7 | 2 |
| EoS | 60 | 8.57 | 30 |

*Table 29 – Slow Line Timetable (Swlines Ltd, 2017)*

| **Time** | **Destination** | **WJ** | **MK** | **RB** |
|---|---|---|---|---|
| 1805 | Northampton | 1 | 1 | |
| 1812 | Tring | 1 | | |
| 1813 | Birmingham New Street | - | 1 | 1 |
| 1816 | Birmingham New Street | - | 1 | 1 |
| 1821 | Milton Keynes Central | 1 | 1 | |
| 1830 | Northampton | 1 | 1 | |
| 1834 | Bletchley | 1 | | |
| 1841 | Tring | 1 | | |
| 1849 | Crewe | - | - | 1 |
| 1852 | Birmingham New Street | - | 1 | 1 |
| 1854 | Milton Keynes Central | 1 | 1 | |

*Table 30 – London Overground Timetable (TfL, 2017)*

| **Time** | **Destination** | **WJ** | **MK** | **RB** |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| 1817 | Watford Junction | 1 | | |
| 1837 | Watford Junction | 1 | | |
| 1857 | Watford Junction | 1 | | |

All rail transits have been considered and the total EoS for each station is shown in Table 31.

*Table 31 – Efficiency of All Service Stopping Patterns for Each Station (Author, 2017)*

| Indicators | WJ | MK | RB |
|---|---|---|---|
| All services stop | 11 | 11 | 6 |
| EoS | 5.45 | 5.45 | 10 |

### 4.3.2 **Requirements**

There are two different main methods for designing or improving a timetable. They are the stopping pattern efficiency-oriented method and the line capacity-oriented method. The choice of methods depends on the requirements of the railway service.

The requirements in our case are as follows:

1. The WCML is one of the most important and busiest railway routes in the UK;
2. It has already reached 83% of maximum capacity. It is unrealistic to expect to be allowed to compromise line capacity significantly;
3. It is a mixed-traffic line, with intercity rail, regional rail, commuter rail and freight services. Fast services and slow services have different requirements;
4. The timetable should meet ergonomic criteria such as maximum waiting time.

Therefore, considering the requirements above, the line capacity-oriented method should be applied. The requirements are listed in order of importance:

1. The line capacity should be no lower than the original one (14 tph or 4.29 min/train);
2. The capacity utilisation should be no more than the suggested value (85%) to ensure self-recovery ability;
3. For all intermediate stations, the number of stopping services (both fast services and slow services) should be no fewer than the original;
4. The improved stopping pattern should meet the demand requirements as closely as possible;
5. The improved timetable should follow the original as closely as possible under the premise given before.

### 4.3.3 **Solutions**

Since a daily railway operation in Great Britain is typically based on the arrangement of a 1-hour timetable, the 1-hour timetable should be able to form a cycle. Moreover, to improve the logic and manageability of timetables, the one-hour timetable is comprised of a set of cyclic sequences where a sequence is comprised of a set of services with different stopping patterns. Therefore, the question of the design of a timetable is transferred to how to design efficient and suitable sequences that satisfy requirements. A schematic diagram is shown in Figure 40.

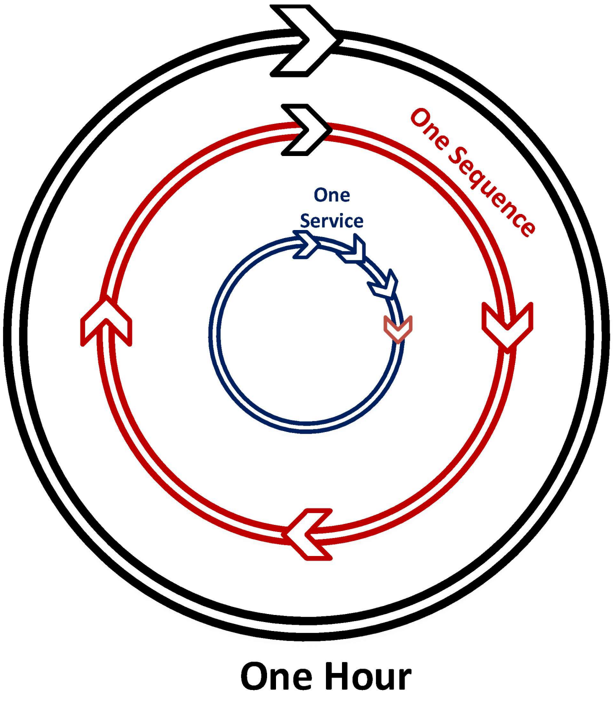

*Figure 40 – A Schematic Diagram for a One Hour Timetable (Author, 2017)*

As the priority is to ensure the line capacity, we will discuss and analyse the sequence using the line capacity-oriented method.

Assume that there are *x* services (*x* is the length of a sequence) in the sequence and the duration of the sequence is *t* minutes.

The line capacity should be subjected to Eq. (58).

$$x * Floor\left(\frac{60}{t}\right) \leq Line\ Capacity \leq x * \frac{60}{t}\ \ [tph] \cdots\cdots (58)$$

By definition, the term Floor $(\frac{60}{t})$ is an integer value, then Eq. (58) turns to Eq. (59).

$$line\ capacity = x * \frac{60}{\mathrm{t}}\ [tph] \cdots\cdots (59)$$

In each sequence, every service absorbs at least a minimum headway time as shown in Eq. (60), and therefore, line capacity can be obtained from Eq. (61).

$$t = x * minimum\ headway\ time\ (HT) + extra\ time\ caused\ by\ stopping\ pattern\ sequence\ (ET) \cdots\cdots (60)$$

$$line\ capacity = x * \frac{60}{x * HT + ET}\ [tph] \cdots\cdots (61)$$

*x* has a positive effect on *t*, while *ET* has an adverse effect on *t*.

*Table 32 – Examples of Stopping Pattern Sequences (Author, 2017)*

| **Stopping Pattern sequence** | **EoS1** | **EoS2** | **EoS3** | **AHT** | **x** | **Extra Time (ET)** |
|---|---|---|---|---|---|---|
| 000-000 | 0 | 0 | 0 | 3 | 1 | 0 |
| 111-111 | 5 | 5 | 5 | 5 | 1 | Dwell time |
| 000-111-000-111 | 15 | 15 | 15 | 7.5 | 2 | 3*dwell time + 3*time supplement |
| 000-001-010-100 | 15 | 15 | 15 | 3.75 | 4 | dwell time + time supplement |
| 011-110-101 | 7.5 | 7.5 | 7.5 | 5 | 3 | 2*dwell time + 2*time supplement |
| 100-101-110 | 5.3 | 16 | 16 | 5.3 | 3 | 3*dwell time + time supplement |
| 001-010-100 | 12 | 12 | 12 | 4 | 3 | dwell time + time supplement |

However, even though we can improve the line capacity until we reach the theoretical limit, we must consider the performance of the EoS simultaneously. Therefore, there is a trade-off between EoS and line capacity. As shown in Figure 41, we aim to find a solution on or near the optimality line. However, in the WCML case, the adjustment space is limited because of the requirements and restrictions of line capacity, which is shown in Figure 42. Since the stopping pattern indicators are not analogue values, we require a fuzzy approach to the optimality target to be defined and solved.

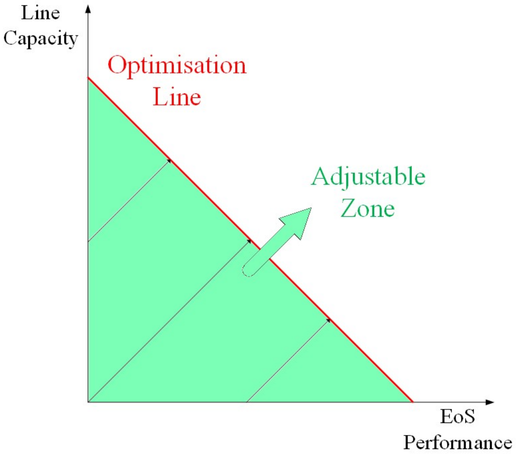

*Figure 41 – The Relationship between Line Capacity and EoS Performance (Author, 2017)*

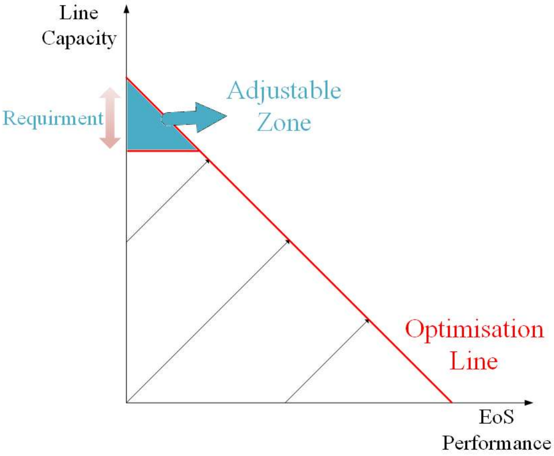

*Figure 42 – The Limited Zone in the WCML Case (Author, 2017)*

To leave more space for the EoS optimisation, the line capacity should be equal to or slightly higher than that of the original.

The average headway time is subjected to Eq. (62) (63).

$$\begin{aligned} &Average\ Headway\ Time\ (AHT) \\ &\quad = Minimum\ Technical\ Headway\ (H) + \frac{Extra\ Time\ (ET)}{x} \\ &\quad \leq 4.29 \cdots\cdots (62) \end{aligned}$$

$$x \geq \frac{ET}{1.29} \cdots\cdots (63)$$

Empirically, as long as the length of the sequence is not 1, the ET should be no less than the dwell time + time supplement, which is expressed by Eq. (64).

$$ET = a * dwell\ time + b * supplement\ time (a \geq b \geq 1) \cdots\cdots (64)$$

*x* is therefore subjected to Eq. (65) which is obtained from Eq. (63) (64).

$$x \geq 2.32, 3.87, 4.65 \ldots \cdots\cdots (65)$$

To make sure that the timetable has acceptable self-recovery ability according to UIC 406 guidance, the sequence should satisfy Eq. (66) ($\alpha$ is the unoccupied time in one hour or in a given period; *n* is the number of loops of the sequence).

$$x * H + ET = \frac{60 - \alpha}{n} \cdots\cdots (66)$$

In our WCML case, Eq. (66) turns to Eq. (67).

$$x * H + ET = \frac{50 - \alpha}{n} \cdots\cdots (67)$$

Empirically, for one sequence loop, the minimum ET is 3 minutes in the WCML context. Accordingly, to satisfy the essential demand[5] for EoS, the best solution for ET=3 is 001-010-100 (this is the line capacity-oriented method's fundamental solution, while the best solution for the EoS oriented method is 111-111-111, the metro style). Based on this sub-sequence, the sequence comparison table can be created and extended, as shown in Table 33. In the table, with the restriction of ET to each unit, the way to increase the length of sequence in each unit is to add a non-stop service later than the initial sub-sequence. Even though this means improves the average headway time but it compromises the EoS and possibly decreases the number of loops. Therefore, the effect on line capacity by increasing the length in a ET unit could only be discussed in a real case.

The table is not endless. When we design a sequence comparison for a real case, there are four principles which make the table contents limited and rigorous.

1. The ET should be subjected to Eq. (64).
2. The *x* is subjected to Eq. (65).
3. In each ET unit, the row should not be extended when 000 appears in the sequence column.
4. $\alpha$ is obtained from Eq. (67). It could be negative.

*Table 33 – Sequence Comparison Table (Author, 2017)*

| ET | Criteria | *x* | AHT | Sequence (probable) | EoS1 | Eos2 | Eos3 | α | *n* | *x*n(LC)* |
|---|---|---|---|---|---|---|---|---|---|---|
| 3 | x≥2.32 | 3 | 4 | 001-010-100 | 12 | 12 | 12 | 2 | 4 | 12 |
| | | 4 | 3.75 | 001-010-100-000 | 15 | 15 | 15 | 5 | 3 | 12 |
| | | 5 | 3.6 | 001-010-100-000-000 | 18 | 18 | 18 | 14,-4 | 2,3 | 10,15 |
| 5 | x≥3.87 | 4 | 4.25 | 001-010-100-100 | 8.5 | 17 | 17 | 16,-1 | 2,3 | 8,12 |

---

[5] The basic demand aims for at least one service stopping at a station in an hour.

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 5 | 4 | 001-010-100-100-000 | 10 | 20 | 20 | 10,-10 | 2,3 | 10,15 |
| | | 6 | 3.83 | 001-010-100-100-000-000 | 11.5 | 23 | 23 | 4 | 2 | 12 |
| | | 7 | 3.71 | 001-010-100-100-000-000-000 | 13 | 26 | 26 | 24,-2 | 1,2 | 7,14 |
| 6 | x≥4.65 | 5 | 4.2 | 001-010-100-010-100 | 10.5 | 10.5 | 21 | 8 | 2 | 10 |
| | | 6 | 4 | 001-010-100-001-010-100 | 12 | 12 | 12 | 2 | 2 | 12 |
| | | 7 | 3.86 | 001-010-100-001-010-100-000 | 13.5 | 13.5 | 13.5 | 23,-4 | 1,2 | 7,14 |
| | | 8 | 3.75 | 001-010-100-001-010-100-000-000 | 15 | 15 | 15 | 20,-10 | 1,2 | 8,16 |
| 7 | x≥5.43 | 6 | 4.12 | 001-010-010-100-100-000 | 12.5 | 12.5 | 25 | 0 | 2 | 12 |
| | | 7 | 4 | 001-010-010-100-100-000-000 | 14 | 14 | 28 | 22,-6 | 1,2 | 7,14 |
| 8 | x≥6.20 | 7 | 4.14 | 001-010-100-001-010-100-100 | 9.7 | 14.5 | 14.5 | 21,-8 | 1,2 | 7,14 |
| 9 | x≥6.98 | 7 | 4.29 | 010-100-001-010-100-010-100<br>001-010-010-100-100-100-000 | 10<br>10 | 10<br>15 | 30<br>30 | 20,-10 | 1,2 | 7,14 |

There are some negative values in the column α because, in our case, the original 50-minute occupancy in one hour still leaves 10 minutes of spare time for use. Therefore, the negative values are the extended time based on 50 minutes. It should be noted that the UIC 406 guidance should be respected.

If we cannot occupy extra time compared to the original timetable in one hour, on the premise of meeting the requirements and taking into account the London Midland service on the fast line, the 3-3 5-6 7-6 sequence could be chosen.

On the other hand, if the extra occupation is allowed, the 3-5 5-4 5-7 6-7 could be the solution, since it requires only a small amount of extra time and also offers high line capacity.

Among these sequences, the selection should respect the real situation. In the real case, all particular timetable and route requirements should be respected. The requirements are listed below:

1. The London Midland services occupy the time slots 12 to 18 and 45 to 51 in the hour;
2. For the Virgin Train service before the 12 London Midland service, as long as it does not stop at Watford Junction, the interval time between these two trains is 3 minutes (minimum technical headway). Otherwise, their interval time is 6 minutes

(minimum technical headway + dwell time + supplement time). That is because the London Midland service will change to the slow line before Milton Keynes.

3. For the Virgin Train service before the 45 London Midland service, when we calculate the interval time between them, the stopping pattern of 01- can be treated as 011. That is because the London Midland service will move onto the slow line before Rugby.
4. Trains travelling to Birmingham do not occupy the mainline tracks at Rugby station.

Therefore, if the London Midland services are fixed, x must be subjected to Eq. (68). Because of Eq. (69), *x* is subjected by Eq. (70).

$$x * H + ET \leq 12 \cdots\cdots (68)$$

$$H = 3 \ and \ ET \geq 3 \cdots\cdots (69)$$

$$x \leq 3 \cdots\cdots (70)$$

Only the sequence 001-010-100 can be fitted into the timetable. Moreover, as long as we fit seven services in the 18 and 44 time slot, the available total ET is 5 minutes, so the total number of stops is 4 (theoretically). However, if we extend the timetable by 1 minute, the total number of stops will increase to 6, which is acceptable even though the time occupancy rate reaches 85%. A potential improved timetable is shown in Table 34. Because the minimum time unit is 1 minute, there is no apparent difference between the evenly fixed and evenly expanded decompression methods which are described in 2.1.2. The decompressed timetable is shown in Table 35.

*Table 34 – Improved Timetable (Author, 2017)*

| Time | Destination | WJ | MK | RB | Operator |
|---|---|---|---|---|---|
| 1800 | Manchester Piccadilly | 0 | 0 | 1 | VT |
| 1803 | Wolverhampton | 0 | 1 | 1 | VT |
| 1806 | Liverpool Lime Street | 1 | 0 | 0 | VT |
| 1812 | Birmingham New Street | 0 | - | - | LM |
| 1815 | Birmingham New Street | 0 | - | - | LM |
| 1818 | Holyhead | 0 | 0 | 1 | VT |
| 1821 | Manchester Piccadilly | 0 | 1 | 0 | VT |
| 1824 | Birmingham New Street | 1 | 0 | 1 | VT |
| 1830 | Glasgow Central | 0 | 0 | 1 | VT |
| 1833 | Liverpool Lime Street | 0 | 1 | 0 | VT |
| 1836 | Manchester Piccadilly | 1 | 0 | 0 | VT |

| | | | | | |
|---|---|---|---|---|---|
| 1842 | Crewe (via Birmingham) | 0 | 0 | 1 | VT |
| 1845 | Crewe | 0 | 1 | - | LM |
| 1848 | Birmingham New Street | 0 | - | - | LM |

*Table 35 – The Decompressed Timetable (Author, 2017)*

| **Time** | **Destination** | **WJ** | **MK** | **RB** | **Operator** |
|---|---|---|---|---|---|
| 1800 | Manchester Piccadilly | 0 | 0 | 1 | VT |
| 1804 | Wolverhampton | 0 | 1 | 1 | VT |
| 1807 | Liverpool Lime Street | 1 | 0 | 0 | VT |
| 1814 | Birmingham New Street | 0 | - | - | LM |
| 1817 | Birmingham New Street | 0 | - | - | LM |
| 1821 | Holyhead | 0 | 0 | 1 | VT |
| 1824 | Manchester Piccadilly | 0 | 1 | 0 | VT |
| 1828 | Birmingham New Street | 1 | 0 | 1 | VT |
| 1835 | Glasgow Central | 0 | 0 | 1 | VT |
| 1838 | Liverpool Lime Street | 0 | 1 | 0 | VT |
| 1842 | Manchester Piccadilly | 1 | 0 | 0 | VT |
| 1849 | Crewe (via Birmingham) | 0 | 0 | 1 | VT |
| 1852 | Crewe | 0 | 1 | - | LM |
| 1856 | Birmingham New Street | 0 | - | - | LM |

*Table 36 – Improved Stopping Pattern Performance (Author, 2017)*

| **Indicators** | **WJ** | **MK** | **RB** |
|---|---|---|---|
| Fast services stop | 3 | 7 | 6 |
| EoS | 20 | 8.57 | 10 |
| Improvement | 300% | 100% | 200% |

The improved timetable respects all requirements and principles but brings 2 and 4 extra stops for Watford Junction and Rugby respectively. If the improved station capacity for Rugby is surplus, some of the stops at Rugby can be removed, which can reduce journey time and bring more recovery opportunity for delays.

Overall, the line capacity is unchanged, 14 tph; the time occupancy increases to 85%, which still meets the guidance proposed in UIC 406. It also provides some direct fast links between smaller towns and big cities, e.g., Watford to Manchester.

On the other hand, if the London Midland services could be removed from the fast line, this would bring more possibilities.

According to the analysis in 4.1, the shortage of station capacity at Watford Junction and Milton Keynes is the main issue that we want to solve through the timetable improvement project. So, on the premise of meeting the requirements and associated principles, we should improve the EoS1 and EoS2 as much as possible. However, because of the removal of the London Midland service, the line capacity utilisation is compromised due to the decrease in the track utilisation rate between Euston and Milton Keynes.

To keep the line capacity of 14 tph, there is no single potential sequence in Table 33. However, we can combine different sequences to achieve the objective.

The combined ET should be no more than 9 minutes to ensure that the time occupancy is no more than 85%, as per the guidance proposed in UIC 406. For a station, each extra (from the second) stop will add at least 2 minutes of extra time to the sequence. In addition, the extra time of a cyclic sequence is at least 3 minutes. From Eq. (73), given 9 minutes of available extra time, the maximum number of stops for a station in an hour is 4.

$$Added\ ET \geq 2 \cdots\cdots (71)$$

$$Basic\ ET = 3 \cdots\cdots (72)$$

$$Added\ ET * (number\ of\ stops - 1) + Basic\ ET \leq Available\ ET \cdots\cdots (73)$$

Therefore, the fitted sequence could be 001-010-100-100-100-100-000-000-000-000-000-000-000-000. Overall, we find EoS1=15, EoS2=60, EoS3=60, Time Occupancy=85%. It is not an applicable solution in the real world as the total number of stops is only 6, with poor ergonomics.

On the other hand, to improve the number of stops, the parameter of total number of stops per ET should be introduced. According to Table 33, it is easy to find that the sub-sequence 001-010-100 has the highest total number of stops per ET. From this point of view, 001-010-100 is substantially equal to 111-111-111.

Therefore, a possible sequence could be 001-010-100-000-000-001-010-100-000-000-001-010-100-000. EoS1=EoS2=EoS3=20, Time Occupancy=85%.

The two sequences above are two extreme solutions for the WCML and other options in between these are also applicable.

The maximum line capacity dramatically restricts the stopping pattern adjustment for the WCML, including improving EoS1 and EoS2. So, the maximum line capacity should be released from both operational and technical points of view. Operationally, introducing the London Midland services between Euston and Milton Keynes is a good approach, as the operators did, since it improves the track utilisation but it brings some uncertainty factors to daily operation. Technically, the most direct and effective solution is to reduce the minimum technical headway by updating the signalling system.

## 4.4 General Solutions

A general timetable solution based on the stopping patterns sequence for the line capacity-oriented method is introduced here. Based on the requirements and technical indicators, a probable one-hour timetable with optimal EoS performances can be planned.

*a: Available Extra Time;*

*r: Required Line Capacity;*

*m: Minimum Technical Headway Time;*

*d: Dwell Time;*

*t: Time Supplement;*

*I: Number of Intermediate Stations.*

$$a = 60 * 85\%(Recommended) - r * m \cdots\cdots (74)$$

$$a \geq r * (d + t) \cdots\cdots (75)$$

If Eq. (75) is true, the stopping patterns should be as below.

*r(111)*

Otherwise,

$$n_1 = \left\lfloor \frac{a}{d+t} \right\rfloor$$

$$n_2 = \left\lfloor \frac{a}{d+t} \right\rfloor - 1$$

$$n_3 = \left\lfloor \frac{a}{d+t} \right\rfloor - 2$$

$$m = \left\lfloor \frac{a - (d+t) * n}{d} \right\rfloor$$

The stopping sequence should be as below.

*(n-p)(001-010-100)-(m-s)(100)-(r-I*n-m-q)(000)-p(001-010-100)-s(100)-q(000)*

# 5 Optimised Headway Distance Moving Block (OHDMB)

## 5.1 Introduction

Railway signalling systems are designed to act as a safety system that prevents collisions between trains and to maximise the utilisation of the rail network with traffic management systems. Nowadays, different signalling systems are widely used safely. However, to achieve higher capacity and reliability, these existing systems may have to be updated or replaced in the future. With the development and evolution of signalling systems, technologies from other engineering domains are increasingly being integrated into railway signalling systems to improve their reliability and efficiency.

As discussed in Section 2.3.3.2, Relative Distance Braking Mode Moving Block (RDBM-MB), dispenses with the provision of a full braking distance between trains following each other. To meet future capacity demand, the Optimised Headway Distance Moving Block or OHDMB signalling system is first proposed in this thesis. It combines ‘traditional’ moving block and aspects of relative distance braking and it applies advanced radio transmission methods, advanced positioning systems, Automatic Train Control (ATC), Automatic Train Protection (ATP) and Connected Driver Advisory System (CDAS). Introducing the concept of optimised headway distance braking provides an approach to trains’ ‘Closer Running’ from a technical perspective, by changing the headway calculation formula.

## 5.2 Operation Principles

The principle of the proposed novel signalling system is making the best use of relative distance braking on the premise that the following train can still stop behind the leading train within the safety margin. This approach to RDBM Moving Block will not require revised safety principles, whereas it needs the leading train to distinguish and communicate its stopping condition in a very short time.

Six scenarios are presented here to include up to three contiguous trains’ reactions when the first train experiences unexpected braking. The two braking applications and the variety of braking performances are also considered. The minimum technical headway distance of OHDMB can be obtained through simulating the following six basic scenarios with different trains interval distances and based on those, further situations can be deduced.

It should be noted that the communication time and system delays are dismissed here to limit the discussion of the principles.

1. A massive wall appears in front of Train B, resulting in it being stopped instantaneously. This first scenario is shown in Figure 43.

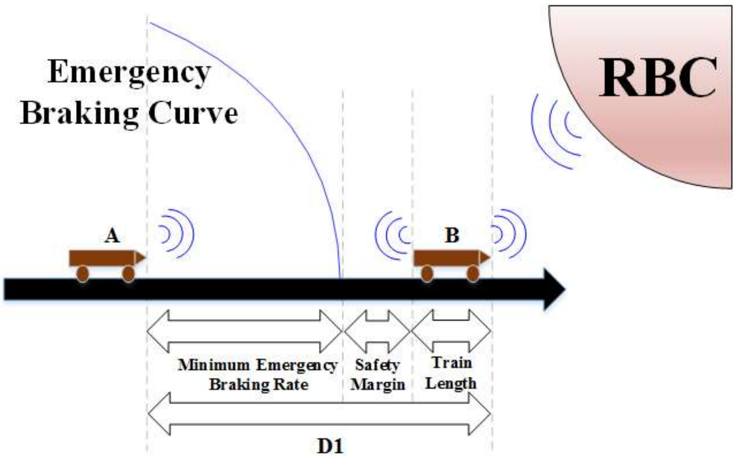

*Figure 43 – Scenario One (Author, 2017)*

When Train A receives information from the RBC or Train B that train B has lost control or stopped instantly, it will begin to apply emergency braking. Therefore, the minimum distance D1 between Train A and Train B is obtained from Eq. (76).

$$D1 = \frac{v^2}{2 * B_{Em}} + SM + TL \cdots\cdots (76)$$

where (also apply to Eq. (76) to (80))

$v$: Trains running speed;

$B_{Em}$: Minimum emergency braking rate;

$B_{EM}$: Maximum emergency braking rate;

$B_{Sm}$: Minimum service braking rate;

$B_{EM}$: Maximum emergency braking rate;

$SM$: Safety margin;

$TL$: Train Length.

2. Train B suffers a critical failure and applies emergency braking. The second scenario is shown in Figure 44.

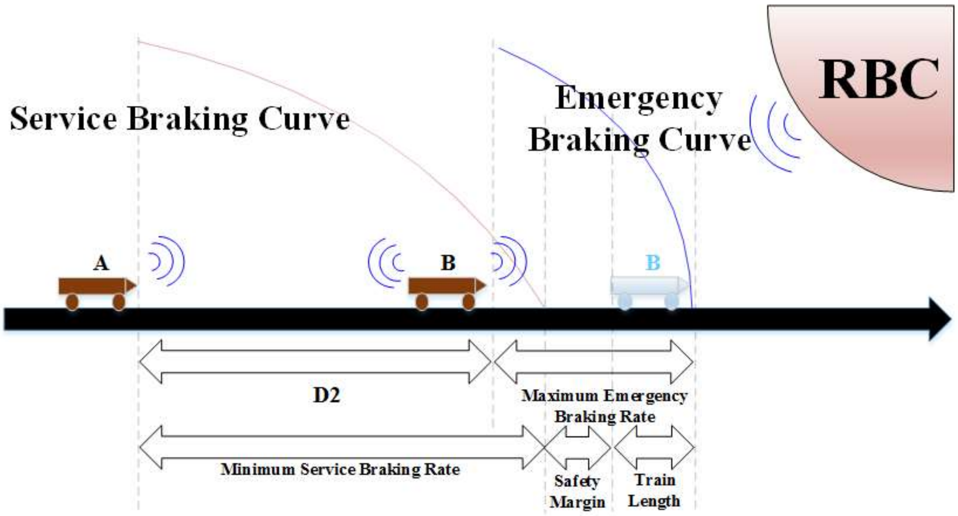

*Figure 44 – Scenario Two (Author, 2017)*

When Train A receives this information from the RBC or Train B, it will begin to apply service braking. Train A and Train B will slow down synchronously, and train A can stop behind Train B. Therefore, the minimum distance D2 between Train A and Train B is obtained from Eq. (77).

$$D2 = \frac{v^2}{2*B_{Sm}} + SM + TL - \frac{v^2}{2*B_{EM}} \cdots\cdots (77)$$

Based on the two preceding scenarios, the minimum headway distance D is obtained from Eq. (78).

$$D = \max(D1, D2) \cdots\cdots (78)$$

3. Train B suffers a non-critical failure and applies service braking. The third scenario is shown in Figure 45.

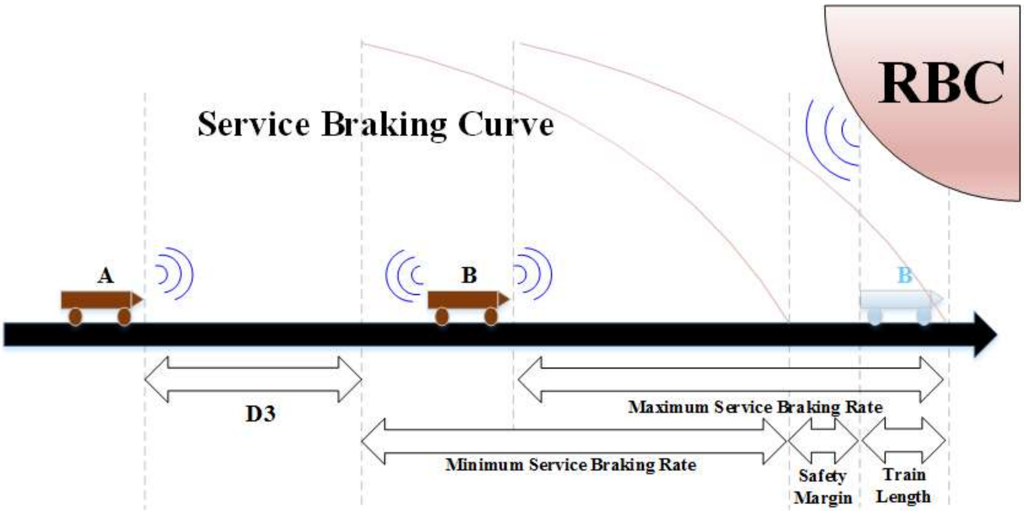

*Figure 45 – Scenario Three (Author, 2017)*

When Train A receives information from the RBC or Train B, it can keep moving for distance D3 and then applies the service brake. Train A must stop behind Train B.

$$D3 = \max(D1, D2) + \frac{v^2}{2^*\mathrm{B_{SM}}} - \left(\frac{v^2}{2^*\mathrm{B_{Sm}}} + SM + TL\right) \cdots\cdots (79)$$

$$D3 = \max\left(\frac{v^2}{2^*\mathrm{B_{Em}}}, \frac{v^2}{2^*\mathrm{B_{Sm}}} - \frac{v^2}{2^*\mathrm{B_{EM}}}\right) + \frac{v^2}{2^*\mathrm{B_{SM}}} - \frac{v^2}{2^*\mathrm{B_{Sm}}} \cdots\cdots (80)$$

4. A massive wall appears in front of Train C, stopping it instantaneously). The fourth scenario is shown in Figure 46.

When Train B receives the information from the RBC or Train C, it will begin to apply the emergency brake. When Train A receives information from the RBC or Train B that Train B has begun to apply the emergency brake, Train A will begin to apply the service brake. Train A and Train B will slow down synchronously. Train A must stop behind Train B and Train B must stop behind Train C.

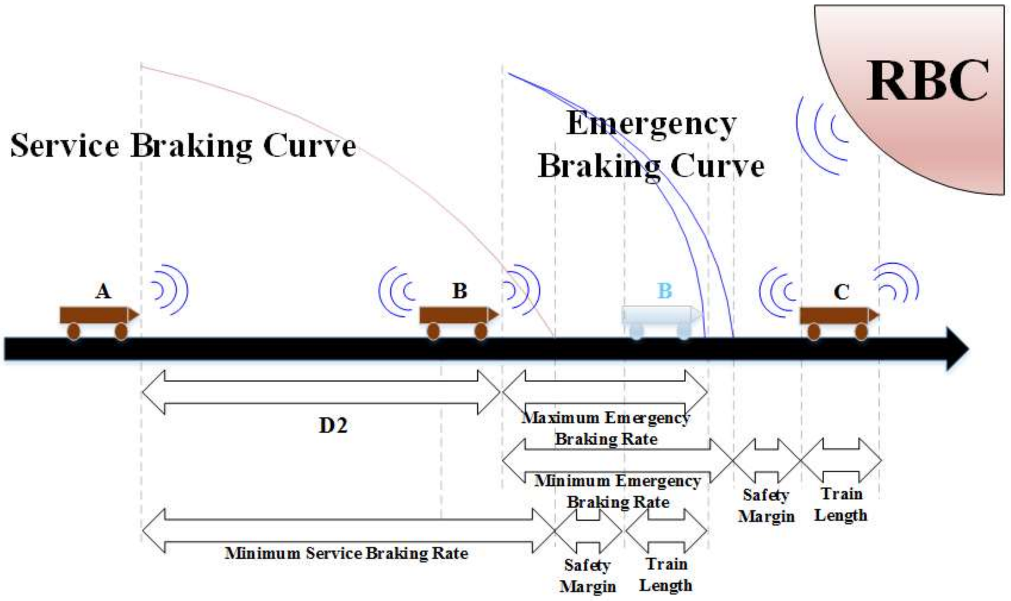

*Figure 46 – Scenario Four (Author, 2017)*

5. Train C suffers a critical problem and applies the emergency brake. The fifth scenario is shown in Figure 47.

When Train B receives information from the RBC or Train C, it will begin to apply the service brake. When Train A receives information from the RBC or Train B that Train B has begun to apply the emergency brake, it can keep moving for distance D3 and then apply the service brake. Train A must stop behind Train B and Train B must stop behind Train C.

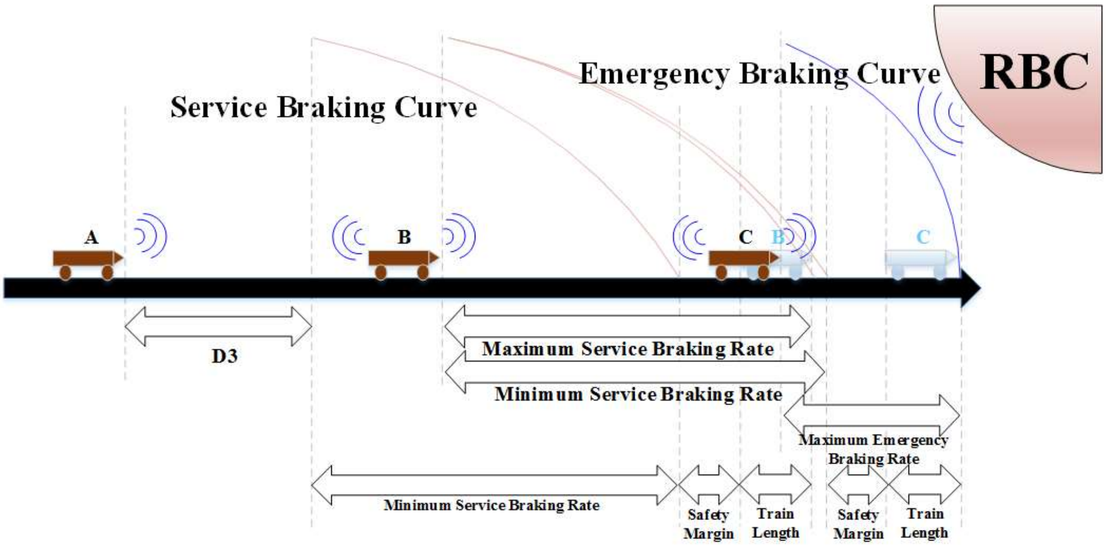

*Figure 47 – Scenario Five (Author, 2017)*

6. Train C suffers a non-critical problem and applies the service brake). The sixth scenario is shown in Figure 48.

When Train B receives the information from the RBC or Train C, it can keep moving for distance D2 and then apply the service brake. When Train A receives information from the RBC or Train B that Train B has begun to apply the service brake, Train A can keep moving for distance D2 and then apply the service brake. Train A must stop behind Train B and Train B must stop behind Train C as well.

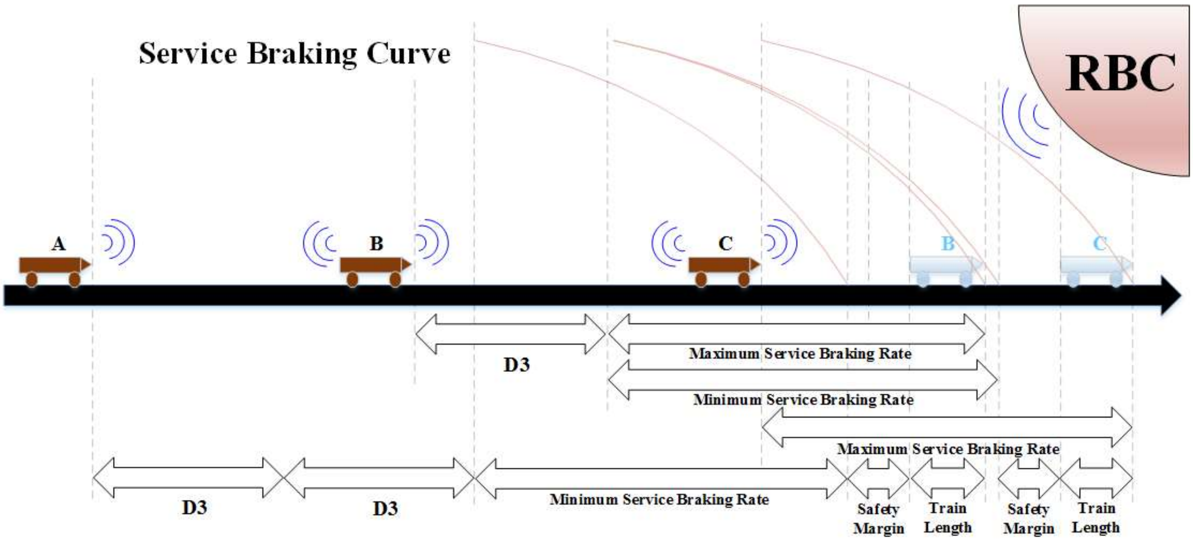

*Figure 48 – Scenario Six (Author, 2017)*

In conclusion, OHDMB is a feasible approach to 'closer running' compared to 'standard' relative braking distance moving block, because trains are always at least emergency braking apart. Using the values of the parameters provided in Chapter 3, as listed in Table 37, the theoretical line capacity for the RBDMB and the 'traditional' moving block system can be obtained from Eq. (17) and (78) respectively. The result shows that the proposed OHDMB system increases capacity by 59% from 44 to 70 tph, compared to the traditional moving block system.

*Table 37 – Technical Parameters*

| **Parameter** | **Value** | **Parameter** | **Value** |
|---|---|---|---|
| Overlap for Fixed Block | 200 (m) | Service Braking Rate | 0.5~0.6 (m/$s^2$) |
| Safety Margin for Moving Block | 200 (m) | Emergency Braking Rate | 0.7~1.0 (m/$s^2$) |
| Running Speed | 56 (m/s) | Train Length | 400 (m) |

## 5.3 Safety Risk Analysis

Safety is one of the core requirements for signalling systems and it is a through-life element, particularly for passenger traffic. A scientific risk assessment should be carried out to prevent potential hazards before a new signalling system enters the market. To realise the proposed new signalling system, we must allow that the headway distance between two successive trains is less than the full service braking distance, which goes against current regulations. According to the report of RSSB (Fenner, 2016), the change brings three new risks that should be considered and assessed, as proposed by RSSB:

1. *What is the risk of derailment of the lead (or intermediate) train?*

Currently, if the leading train derails, the following train can still stop before reaching the rear of the derailed train with immediate service braking. If a shorter headway distance is allowed, when the leading train derails or suffers unexpected failures, the following train must apply emergency braking rather than service braking to avoid collisions. Therefore, both the risk of derailment of the leading train and the risk of an emergency braking failure of the following train or the information transmission failure should be considered.

2. *Is the new level of risk significantly more than the risk we already accept for collision with a derailed train on an adjacent line?*

Safety is a relative concept. Even though a comprehensive safety analysis will have been carried out before a system is made available for public use, systematic failures or random failures may sometimes occur to threaten personal and property safety. What a system engineer should do is to guarantee a lower level of risk than the risk that we already accept.

3. *What risk reduction strategies could be invoked, e.g., hazard brake, operations permitted only on plain line, elimination of level crossing, derailment detection?*

The level of safety risk can be expressed and assessed by the product of the probability and severity of the risk. Reduction strategies can be categorised into two classes: probability reduction strategies and consequence severity reduction strategies.

A general safety risk analysis workflow with relevant methods is shown below. Through this, the safety risk for new a signalling system can be analysed from systematic and logical perspectives to help the railway industry deliver better railway services.

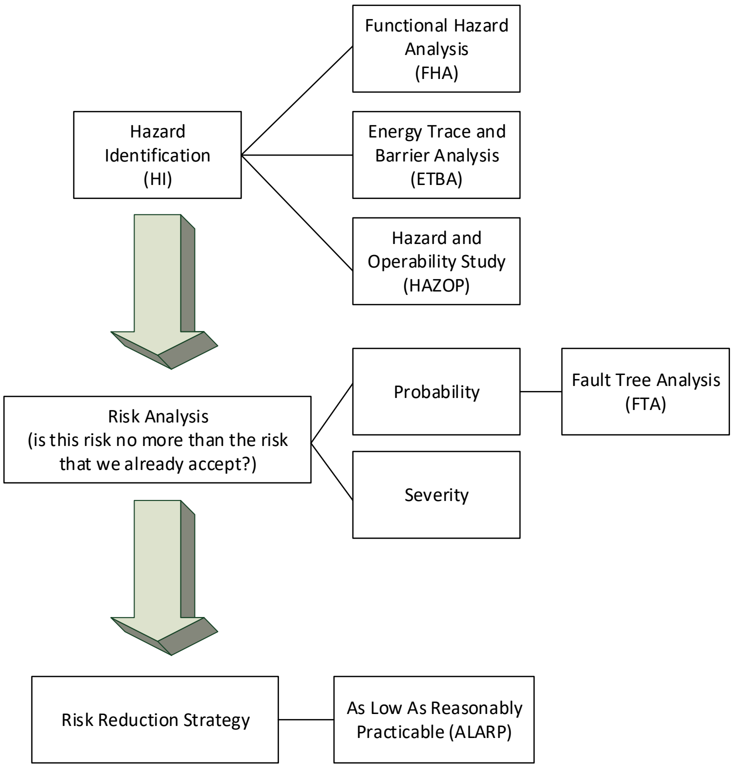

*Figure 49 – Safety Risk Analysis Workflow (Author, 2017)*

No safety analysis of this kind has been carried out for OHDB-MB so far. This is future work.

# 6 Conclusions

## 6.1 Findings

The writer of this thesis has conducted both quantitative and qualitative analyses of railway capacity. Clearly, technical headway and operational strategy both have a significant effect on capacity, even though they are planned and managed at different stages of the railway's life-circle. At the design stage, the results show that braking rate and train length have positive correlations with capacity and there is an optimal point for train running speed. The braking rate is the single most influential parameter in achieving minimum technical headway. In the operation stage, operating trains at the optimal point can achieve maximum capacity, given the existing infrastructure and rolling stock, but the technical factors are hard to change and become unimportant. Instead, operational strategy is the main factor preventing railway lines from reaching their highest utilisation. While running at different speeds is an organisational problem without any upside, the stopping pattern is a controllable and complicating factor with potential benefits. An algorithm for analysing stopping patterns has been constructed that can identify the headway changes caused by different stopping patterns.

Based on the results of the logical analysis of stopping patterns, the operation of the WCML was chosen as the case study. Considering estimated passenger demand, station usage, passenger crowding and practical situations, a specific timetable improvement project has been conducted to a significant level of detail. The results show that the project can bring 2 and 4 extra stops for Watford Junction and Rugby respectively, to meet local demand. However, it proves that the route between Euston and Rugby has nearly reached its maximum line capacity. In addition, introducing the London Midland services between Euston and Milton Keynes could improve the track utilisation, even though more uncertainty might be created.

Given the limited room for capacity improvement at the operation stage and the 6% annual growth in passenger flows, a technology-based approach should be taken into account to satisfy future demands. However, train speeds and braking rates are restricted by physics. To meet demand for railway capacity and reliability, new signalling systems should be studied and implemented. By employing advanced radio transmission methods and ATC systems, an Optimal Headway Distance Moving Block (OHDMB) system is proposed. Contrasting with other future signalling systems proposed by railway engineers, OHDMB is feasible and practicable without changing some of the fundamental safety principles. Based on the technical data of WCML, the theoretical capacity could be improved by nearly 60% compared to the traditional moving block signalling system.

## 6.2 Recommendations

Any research and planning for railways should go beyond existing requirements. At the designing and planning stage, physics and the technical parameters fundamentally limit the minimum theoretical headway. The stopping pattern is another crucial factor in line capacity and it is also designed for a long-term operation. Therefore, a survey of passenger demand between specific Origin-Destination pairs could help us to find the critical bottleneck in terms of passenger flow. Based on the demand, railway operators should take steps to plan stopping patterns wisely to achieve maximum benefits for both railway operators and the public. One should bear in mind that each railway line has its own requirements and limitations, so variability and diversity must be respected.

The proposed stopping pattern algorithm and timetabling method provide an approach to dynamic scheduling, which can be integrated into an Automatic Train Regulation (ATR) system. To handle unexpected delays and failures, a smart and scientific re-scheduling system can deliver enhanced reliability, customer experience and better revenue outcomes.

There are many simplifications throughout the case study, such as treating the WCML as a metro-style line. Thus, more specific work based on current research should be made to improve its practicality. For example, modelling the real WCML is helpful to investigate the real performance with the proposed timetabling method.

In the future, the signalling systems for mainline railways might be updated, but many issues restrict its development. Communication methods and positioning systems are two core technical obstacles to achieving dynamic headway control. Fortunately, there is no need for railway capacity beyond the capability of ETCS Level 3 right now. So, our research into modern signalling systems should stay at the conceptual stage and more inspirations could be introduced from the automobile, aerospace and other industries.

To summarise, recommendations are briefly listed below:

- A preliminary survey should be done comprehensively to help railway companies find crucial requirements and bottlenecks in railway services;
- Based on the stopping pattern algorithm and timetabling method proposed in this thesis, automatic scheduling should be studied and realised in the ATR system to achieve maximum benefits;
- A safety analysis of the proposed OHDMB should be conducted to assess whether the system can satisfy the normal requirements by the safety regulators of railways;

- To meet the future requirements in terms of railway capacity and reliability, the conceptual design of signalling systems should not be confined to the solutions available in the field of railways.

# 7 References

ABRIL, M., BARBER, F., INGOLOTTI, L., SALIDO, M. A., TORMOS, P. & LOVA, A. 2008. An assessment of railway capacity. *Transportation Research Part E: Logistics and Transportation Review,* 44**,** 774-806.

BALAS, M. M. 2000. The Imposed Distance Braking of the Railway Coaches. *VSDIA 2000 International Mini-Conference on Vehicle Dynamics.* Budapest.

BALAS, M. M., BALAS, V. E. & BARNA, C. The Constant Effort Imposed Distance Braking for Urban Railway Vehicles. EUROCON 2005 - The International Conference on "Computer as a Tool", 21-24 Nov. 2005 2005. 365-368.

BARGER, P., SCHON, W. & BOUALI, M. 2010. *A study of railway ERTMS safety with Colored Petri Nets,* Boca Raton, Crc Press-Taylor & Francis Group.

BARNEY, D., HALEY, D. & NIKANDROS, G. 2001. Calculating train braking distance. *Proceedings of the Sixth Australian workshop on Safety critical systems and software - Volume 3.* Brisbane, Australia: Australian Computer Society, Inc.

BUREIKA, G. & MIKALIŪNAS, Š. 2008. Research on the compatibility of the calculation methods of rolling ‐ stock brakes. *Transport,* 23**,** 351-355.

CALLE-SáNCHEZ, J., MOLINA-GARCíA, M., ALONSO, J. I. & FERNáNDEZ-DURáN, A. 2013. Long term evolution in high speed railway environments: Feasibility and challenges. *Bell Labs Technical Journal,* 18**,** 237-253.

CANNAVó, F. 2012. Sensitivity analysis for volcanic source modeling quality assessment and model selection. *Computers & Geosciences,* 44**,** 52-59.

CONNOR, P., HARRIS, N. G. & SCHMID, F. 2015. *Designing and Managing Urban Railways,* London, A&N Harris.

DAKIN, P. 2017. *Beyond ETCS Level 3 - An Analysis of the Risk, and Capacity Benefits of ETCS Level 4.* Msc, University of Birmingham.

DEPARTMENT FOR TRANSPORT 2015. Supplement to the October 2013 Strategic Case for HS2 Technical Annex: Demand and Capacity Pressures on the West Coast Main Line. *In:* TRANSPORT, D. F. (ed.). London.

EMERY, D. 2009. Reducing the headway on high-speed lines. *9th Swiss Transport Research Conference.* Ascona.

EUROPEAN UNION AGENCY FOR RAILWAYS. 2016. *Radio Communication* [Online]. Available: http://www.era.europa.eu/Core-Activities/ERTMS/Pages/Radio-Communication.aspx [Accessed 11 November 2016].

FENNER, D. 2016. UK Railway Safety and Standard Board Research into 'Closer Running'. *IRSE NEWS***,** 11-15.

FERRETTI, F., SALTELLI, A. & TARANTOLA, S. 2016. Trends in sensitivity analysis practice in the last decade. *Science of The Total Environment,* 568**,** 666-670.

GAO, S.-G., DONG, H.-R., NING, B., ROBERTS, C., CHEN, L. & SUN, X.-B. 2015. Cooperative adaptive bidirectional control of a train platoon for efficient utility and string stability. *Chinese Physics B,* 24**,** 090506.

GAO, S., DONG, H. & NING, B. Adaptive cooperation of multiple trains in moving block system using local neighboring information. 2016 35th Chinese Control Conference (CCC), 27-29 July 2016 2016. 10227-10231.

GüMüŞKAYA, H. 2009. *Railway Signalling* [Online]. Available: http://www.gumuskaya.com/Research/RailwaySignalling/RailwaySignalling-index.htm [Accessed 15 February 2017].

HARRIS, N. G. & GODWARD, E. W. 1991. *Planning Passenger Railways,* London, A & N Harris.

INTERNATIONAL UNION OF RAILWAYS 2013. UIC 406.

INTERNATIONAL UNION OF RAILWAYS. 2017. Italy: Trials begin for ERTMS Level 3 Regional System – a new way of developing railway operations beyond the digitalisation of signalling. *UIC eNews* [Online]. Available: https://uic.org/com/uic-e-news/573/article/italy-trials-begin-for-ertms-level-3-regional-system-in-italy-a-new-way-of?page=iframe_enews.

KOZAN, E. & BURDETT, R. 2005. A railway capacity determination model and rail access charging methodologies. *Transportation Planning and Technology,* 28**,** 27-45.

LAI, Y.-C. & WANG, S.-H. 2012. Development of Analytical Capacity Models for Conventional Railways with Advanced Signaling Systems. *Journal of Transportation Engineering,* 138**,** 961-974.

LANDEX, A. 2008. *Methods to Estimate Railway Capacity and Passenger Delays.* PhD, Danmarks Tekniske Universitet.

LIN, J. & DANG, J. 2012. Reliability Models of GSM-R Redundant Network on High-Speed Railway. *Applied Mechanics and Materials,* 198-199**,** 1783.

LINDNER, T. 2011. Applicability of the analytical UIC Code 406 compression method for evaluating line and station capacity. *Journal of Rail Transport Planning & Management,* 1**,** 49-57.

MAZZARELLO, M. & OTTAVIANI, E. 2007. A traffic management system for real-time traffic optimisation in railways. *Transportation Research Part B: Methodological,* 41**,** 246-274.

MUSSONE, L. & WOLFLER CALVO, R. 2013. An analytical approach to calculate the capacity of a railway system. *European Journal of Operational Research,* 228**,** 11-23.

NATIONAL STATISTICS 2017. Rauk Passenger numbers and crowding statistics: 2016 report. *In:* TRANSPORT, D. F. (ed.).

NETWORKRAIL 2011. West Coast Main Line Route Utilisation Strategy. London.

NETWORKRAIL 2016. Network Specification 2016: London North Western. *Delivering a better railway for a better Britain.* London: Network Rail Limited.

NETWORKRAIL. 2017a. *Passengers* [Online]. London. Available: https://www.networkrail.co.uk/communities/passengers/ [Accessed 26 October 2017].

NETWORKRAIL 2017b. Sectional Appendix.

NETWORKRAIL. 2018a. *Electronic national rail timetable* [Online]. Available: https://www.networkrail.co.uk/running-the-railway/timetabling/electronic-national-rail-timetable/ [Accessed 17 July 2018].

NETWORKRAIL 2018b. Long-term planning Report.

NGAI, A. 2010. *What is ERTMS/ETCS ?* [Online]. IRSE. Available: http://irse.org.hk/eNewsletter/issue06/Technical-Articles/ETCS/ETCS.htm [Accessed 17 February 2017].

NING, B. 1998. Absolute braking and relative distance braking - train operation control modes in moving block systems. *Transactions on the Built Environment,* 34.

NOMIS 2015. Jobs Density. *In:* STATISTICS, O. L. M. (ed.).

OFFICE FOR NATIONAL STATISTICS 2017. Population Estimates for UK, England and Wales, Scotland and Northern Ireland: mid-2016. *In:* STATISTICS, O. F. N. (ed.).

OMB 2003. Circular A4. Office for the Management and Budget of the White House.

ORR 2016. Estimates of Station Usage 2015-16. *In:* TRANSPORT, D. F. (ed.). Office of Rail and Road.

PAN, D. & ZHENG, Y. 2014. Dynamic Control of High-speed Train Following Operation. *PROMET - Traffic&Transportation,* 26**,** 291-297.

PUGI, L., MALVEZZI, M., PAPINI, S. & VETTORI, G. 2013. Design and preliminary validation of a tool for the simulation of train braking performance. *Journal of Modern Transportation,* 21**,** 247-257.

RAILENGINEER. 2013. *The future of GSM-R and its possible replacement* [Online]. Available: https://www.railengineer.uk/2013/04/18/the-future-of-gsm-r-and-its-possible-replacement/ [Accessed 5 January 2017].

RAILWAY GAZETTE. 2005. *http://www.railwaygazette.com/news/single-view/view/banverket-to-pilot-ertms-regional.html* [Online]. Available: http://www.railwaygazette.com/news/single-view/view/banverket-to-pilot-ertms-regional.html [Accessed 17 July 2018].

RSSB 2012. Railway Technical Strategy 2012. London.

RSSB 2014a. *Lineside Signals, Indicators and Layout of Signals,* London, RSSB.

RSSB 2014b. Review of the braking tables in RGS GK/RT0075 Lineside Signal Spacing and Speed Signage T999.

SALTELLI, A. 2002. Sensitivity Analysis for Importance Assessment. *Risk Analysis,* 22**,** 579-590.

SALTELLI, A. 2017. Sensitivity Analysis. Denmark: Technical University of Denmark.

SALTELLI, A., RATTO, M., ANDRES, T., CAMPOLONGO, F., CARIBONI, J., GATELLI, D., SAISANA, M. & TARANTOLA, S. 2007. *Introduction to Sensitivity Analysis, in Global Sensitivity Analysis. The Primer,,* John Wiley & Sons, Ltd, John Wiley & Sons, Ltd.

SCHMID, F. & HARRIS, N. 2016. Making Money with Railways. *Railway Operations and Railway Control Systems.* University of Birmingham.

STANLEY, P. & IRSE 2011. *ETCS for Engineers*, Eurailpress.

SWLINES LTD. 2017. *Realtime Trains* [Online]. Available: http://www.realtimetrains.co.uk/about [Accessed 22 August 2017].

TAKEUCHI, H., GOODMAN, C. J. & SONE, S. 2003. Moving block signalling dynamics: performance measures and re-starting queued electric trains. *IEE Proceedings - Electric Power Applications,* 150**,** 483-492.

TFL. 2017. *Watford Junction to Euston Timetable* [Online]. Transport for London. Available: http://content.tfl.gov.uk/watford-junction-euston-timetable-may-2017.pdf [Accessed 21 November 2017].

WANG, H. F., TANG, T., ROBERTS, C., GAO, C. H., CHEN, L. & SCHMID, F. 2014. A novel framework for supporting the design of moving block train control system schemes. *Proceedings of the Institution of Mechanical Engineers Part F-Journal of Rail and Rapid Transit,* 228**,** 784-793.

WOODLAND, D. 2017. Railway Capacity and its Management. Ricardo Rail.

XUN, D., XIN, C. & WENYI, J. The analysis of GSM-R redundant network and reliability models on high-speed railway. Electronics and Information Engineering (ICEIE), 2010 International Conference On, 1-3 Aug. 2010 2010. V2-154-V2-158.

ZHAO, Y. & IOANNOU, P. 2015. Positive Train Control With Dynamic Headway Based on an Active Communication System. *IEEE Transactions on Intelligent Transportation Systems,* 16**,** 3095-3103.

ZIMMERMANN, A. & HOMMEL, G. A train control system case study in model-based real time system design. Proceedings International Parallel and Distributed Processing Symposium, 22-26 April 2003 2003. 8 pp.

ZIMMERMANN, A. & HOMMEL, G. 2005. Towards modeling and evaluation of ETCS real-time communication and operation. *Journal of Systems and Software,* 77**,** 47-54.