



**The use of linear motor technology to increase  
capacity in conventional railway systems**

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## ABSTRACT

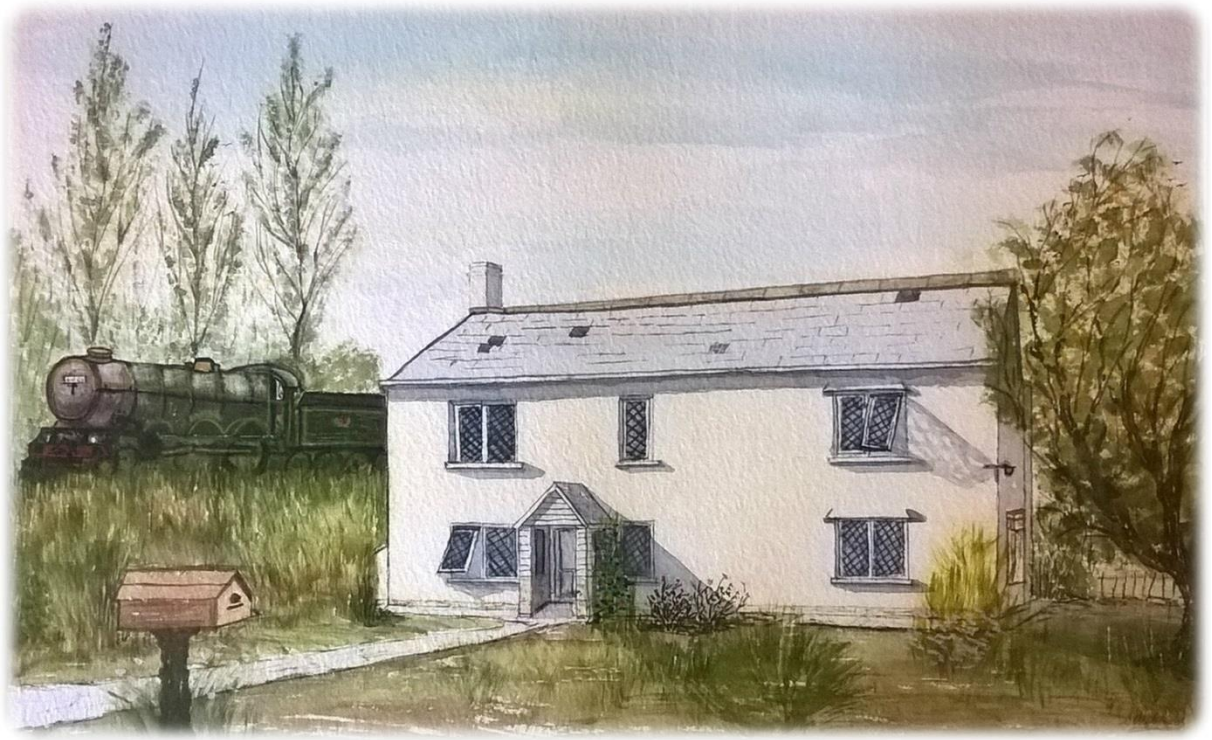
Wheel/rail adhesion is an important constraint on the design and operation of conventional railways. The research question considered for this thesis is whether linear motor technology can improve the performance of railway systems by reducing the dependence of tractive and braking effort on the available wheel/rail adhesion. The two principal contributions of the research are an analysis of the influence of several different linear motor technologies on the capacity of conventional railways, and the development of a new design concept for train braking (named LEMUR – Linear Electromagnetic Machine Using Rails).

Multi-train simulation of three different railway networks was used to investigate the capacity benefits and energy consumption of the LEMUR concept, along with four other existing or proposed implementations of linear induction motor technology with the running rail used as the secondary component of the motor. A model of each network was built using OpenTrack software, and Monte Carlo simulation with pseudorandom distributions of initial delays to train services was carried out to compare train movements under the influence of the delays typically encountered during day-to-day operation. An indication of the improvements in railway capacity possible with different linear motor technology options was then derived from these simulations.

The results of the experiments indicate that the LEMUR concept provided the greatest increase in capacity and the lowest energy consumption of the five linear motor technology options tested. Although the limitations of the study do introduce some uncertainty into the precise values of capacity and energy consumption obtained, the experimental methods were considered sufficiently robust for this conclusion to remain valid.

The most promising application in the study was suburban passenger services that are part of busy mixed-traffic networks. Here, the capacity benefits of the LEMUR concept appear to show sufficient promise to justify further development and application.





*Inspired by, and dedicated to, my parents.*



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## GLOSSARY

Abbreviation	Definition
ABB	ASEA Brown Boveri
AGV	Automotrice à Grande Vitesse
ASEA	Allmänna Svenska Elektriska Aktiebolaget
ATO	Automatic Train Operation
BREL	British Rail Engineering Limited
CIGGT	Canadian Institute of Guided Ground Transport
DB	Deutsche Bahn
DBTW	DB Regio Tyne and Wear
DEMU	Diesel-Electric Multiple Unit
DLB	DC Linear Booster
DMU	Diesel Multiple Unit
ECB	Eddy Current Brake
EMD	Electro-Motive Diesel
EMU	Electric Multiple Unit
ETCS	European Train Control System
GBRf	GB Railfreight
GEC	General Electric Company
GWR	Great Western Railway
HSST	High Speed Surface Transport
HST	High Speed Train
ICE	Intercity-Express
iRFP	Institut für Regional- und Fernverkehrsplanung
JR	Japan Railways Group
LEMUR	Linear Electromagnetic Machine Using Rails
LGV	Ligne à Grande Vitesse
LIM	Linear Induction Motor
LIMRV	Linear Induction Motor Research Vehicle
LRB	RTRI Linear Rail Brake
LSM	Linear Synchronous Motor
MTE	Matériel de Traction Électrique
NS	Nederlandse Spoorwegen
OTMR	On Train Monitoring Recorder
PRT	Personal Rapid Transit

RTRI	Railway Technical Research Institute
SP	Sprinter differential speed limit
SPAD	Signal Passed At Danger
TGV	Train à Grande Vitesse
TGV-NG	Train à Grande Vitesse - Nouvelle Génération
TGV-PSE	Train à Grande Vitesse - Paris Sud-Est
TRL	Transport Research Laboratory
TSI	Technical Specification for Interoperability
TSR	Temporary Speed Restriction
UIC	Union Internationale des Chemins de fer
VIRM	Verlengd InterRegio Materieel
VVVF	Variable-Voltage Variable-Frequency
WSP	Wheel Slip Protection
ZSL	Zero Slip Linear Induction Motor

<b>Symbol</b>	<b>Definition</b>
$a$	Acceleration
$F$	Force
$F_a, F_v$	Attractive force, vertical force
$F_B, F_{BE}$	Braking force, braking effort
$F_g$	Component of gravitational force tangential to ground
$F_L$	Longitudinal force
$F_r$	Resistance force
$F_{TE}$	Tractive effort
$g$	Acceleration due to gravity
$I$	Moment of inertia
$m$	Mass
$m_e$	Effective mass
$m_x$	Extra mass
$n$	Sample size
$R$	Normal reaction force
$v$	Velocity
$\lambda$	Rotating mass factor
$\mu$	Coefficient of adhesion
$\omega$	Angular velocity





# CHAPTER 1. INTRODUCTION

## 1.1. Background

### *1.1.1. The adhesion problem*

The modern railway emerged in Great Britain in February 1804, when a steam locomotive designed and built by Richard Trevithick hauled a train carrying passengers and iron along the Pen-y-darren tramway in South Wales. One of the principal features of the technology was smooth metal wheels and rails (Trevithick R. and Vivian, 1802; Trevithick F., 1872, pp. 138, 177-178). This allowed steam-powered locomotives to haul long trains of coupled vehicles, which in turn could transport large quantities of passengers and goods further, faster and more efficiently than ever before. As a result, railways were one of the most important factors that drove the Industrial Revolution and helped shape the modern world.

Although providing low resistance to motion, steel wheels running on steel rails also have an intrinsic weakness, as the adhesion (effectively the grip between wheel and rail) limits the traction and braking forces that can be transmitted at the wheel/rail interface. Despite Trevithick's successful demonstration, many contemporaries believed that wheel/rail adhesion was insufficient for locomotives to haul heavy trains (Hebert, 1836, pp. 387-392), and the first commercial application of steam locomotives at Middleton Colliery in 1812 used a rack-and-pinion arrangement to transmit traction and braking forces. A series of experiments conducted in 1813 at Wylam Colliery near Newcastle upon Tyne measured actual adhesion levels between a smooth wheel and rail (Hedley, 1836, quoted in Archer, 1882, pp. 12-13), and the locomotives developed at Wylam as a result of these experiments were instrumental in the subsequent successful adoption and expansion of 'conventional' adhesion-worked railways.

Nonetheless, the limits imposed by wheel/rail adhesion remained a constraint on the performance of railways. As trains became heavier and faster, and traffic levels increased, greater care had to be taken to ensure that trains in busy networks did not collide with each other. The distance required for a train with friction brakes to stop short of an obstruction (such as another train) fundamentally depends on the level of adhesion available to transmit the braking forces between wheel and rail. Decisions about safety in this respect are a trade-off between maximising the number of trains able to run in a given network, while making sure the risk of two trains colliding is low enough to be acceptable. Therefore, as well as limiting the speeds and haulage capabilities of individual trains, wheel/rail adhesion directly affects the quantities of passengers and goods that can be transported by the railway system.

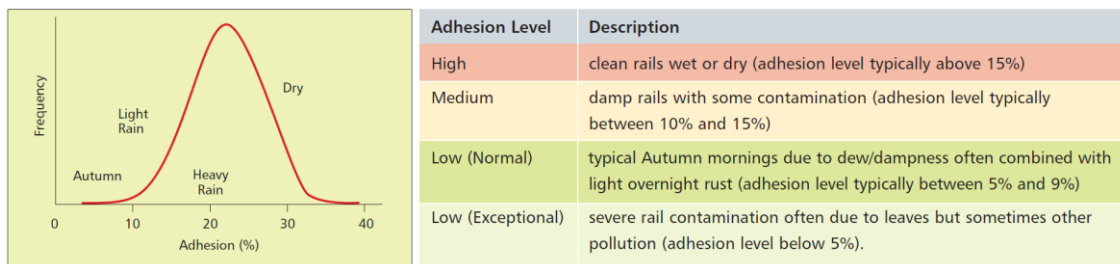
### 1.1.2. Typical adhesion levels and mitigation measures

Wheel/rail adhesion has been the subject of a number of theses in recent years, such as Vasić (2004), Arias-Cuevas (2010) and Zhu (2013), as well as railway industry publications, for example the guidance produced by the Adhesion Working Group in Great Britain (*Managing Low Adhesion*, 2004). This chapter therefore provides a brief overview of the importance of wheel/rail adhesion, and a more detailed review of current knowledge can be found in Appendix A.

The coefficient of adhesion  $\mu$  is strictly defined as the ratio of the longitudinal traction or braking force transmitted at the wheel/rail interface to the nominal vertical load:

$$F = \mu \cdot R \tag{1}$$

Figure 1 illustrates a typical distribution of adhesion levels in Great Britain, measured during extensive surveys by the British Rail Research Tribometer Train between the 1970s and 1990s.



**Figure 1: Distribution of adhesion levels on British Rail (*Managing Low Adhesion*, 2004)**

Given that adhesion is critical to the transmission of traction and braking forces between wheel and rail, the wide range of values observed represents a significant risk to railway operations. Therefore, many technologies and operational strategies have been developed over the years to attempt to mitigate the effects of low adhesion conditions.

Infrastructure-based measures include the removal of contamination from the rails using high-pressure water jets, and treatment of the rails with friction modifiers to improve the coefficient of friction at the wheel/rail interface. Longer-term strategies include management of lineside vegetation to minimise contamination of the tracks with leaves, and maintaining good quality track alignment. Wheel slip protection (WSP) for rolling stock typically consists of an automatic system that reduces tractive or braking effort when there is insufficient adhesion available. Some vehicles may also apply sand at the wheel/rail interface, or use magnetic track brakes that clamp onto the rail head to assist braking (these brakes can also

help remove contaminants). Further possibilities include scrubber blocks to clean contamination on wheel treads, and vehicle suspension designed to minimise the weight transfer between wheelsets and the lateral steering forces at the wheel/rail interface.

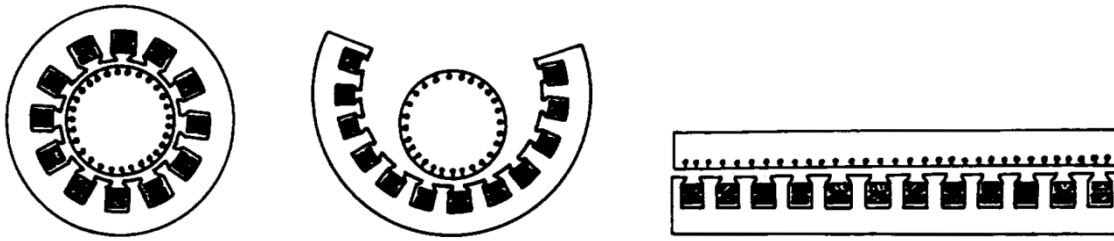
All of the mitigations outlined above aim to make best use of the maximum adhesion level available, but the influencing factors detailed in Appendix A suggest that the amount of control over the coefficient of friction at the wheel/rail interface is still rather limited, and it therefore remains an important constraint on railway operations. If the transmission of traction and braking forces can be decoupled from the available adhesion, there may be the potential for significant improvements in the performance of railway systems. This is the underlying motivation for the investigations supporting this thesis. The aim is to make best use of the railway's advantages of low resistance to motion of steel wheels running on steel rails, while reducing or removing the limits on tractive and braking effort imposed by adhesion.

Cable-hauled and rack-and-pinion railways both transmit forces without relying on adhesion, but remain a niche transport mode for relatively short railway lines that climb very steep gradients, as speeds are low and the resistance to motion (and hence the wear on components) is higher than conventional railways. There were also some experiments with atmospheric railways in the nineteenth century, with vehicles running partly or entirely inside a sealed pipe and changes in air pressure either side of the vehicle providing traction/braking forces, but these were not particularly successful. Aircraft propellers and jet engines were tried in the twentieth century, but were found to be rather impractical.

Another alternative that emerged in the twentieth century is linear motors. Although application to conventional railways has been limited, they are currently the dominant form of propulsion for unconventional guided transport systems such as magnetic levitation. A detailed history of the development of linear motor technology was written by Laithwaite (1986), and a summary of subsequent implementation in transport applications can be found in a paper by Hellinger and Mnich (2009).

### ***1.1.3. What is a linear motor?***

A linear motor can be thought of as a conventional rotary electrical machine 'split open and unrolled'. DC, synchronous AC and asynchronous (induction) AC rotary machines all have linear equivalents. A fundamental difference of linear motors to their rotary counterparts is the finite length of the motor field and armature, referred to throughout this thesis as the primary and secondary components respectively.



**Figure 2:** The imaginary process of splitting and unrolling a rotary machine (Laithwaite, 1975)

As drawn in Figure 2, the lengths of the primary and secondary components are similar and the travel is therefore limited; this arrangement is generally termed a linear actuator. For linear motors, either the primary or the secondary must be lengthened to cover the entire travel distance. Motors may be classified as long or short primary on this basis, and either component may be continuous or intermittent. A second distinction to be made is whether the primary is fixed and secondary moves, or vice-versa. The motor illustrated in Figure 2 is a single-sided design, and it is possible to add a second primary component on the opposite side of the secondary to form a double-sided motor. Other topologies have also been constructed, for example tubular motors where the primary and secondary are rolled up into a tube, distinct from a rotary machine with a hollow secondary as the motion is linear along the tube's axis rather than rotational around it.

The finite length of the components in a linear motor results in transient electromagnetic effects at each end of the shorter component as it moves relative to the longer component, which do not appear in a rotary machine as both components are closed loops and therefore effectively infinitely long. These 'longitudinal end effects' reduce the maximum force and efficiency achievable by a linear motor in comparison to a similarly sized rotary machine. Depending on the design and operating environment, the air gap between the primary and secondary in a linear motor may be somewhat larger than the equivalent rotary machine, which also results in a reduction in performance.

#### ***1.1.4. Thesis rationale***

The subject of this thesis is therefore the application of linear motor technology to conventional railways. The aim is to investigate whether the disadvantages of linear motors outlined above are outweighed by the potential for improvements in railway system performance, achieved by reducing the dependence of individual train performance on wheel/rail adhesion.

## **1.2. Aims and Objectives**

### ***1.2.1. Research question***

The research question for this thesis can therefore be stated explicitly as follows:

Can the application of linear motor technology improve the overall performance of a railway system by reducing the dependence of traction and braking forces on wheel/rail adhesion?

### ***1.2.2. Thesis scope and structure***

Chapter 2 contains a detailed literature review into previous research and applications of linear motor technology to railways. A principal finding of this review is that using a linear induction motor with the running rail as the secondary to improve the capacity of railway networks shows promise. Chapter 3 therefore considers the design of a study to measure the effect of this application of linear motor technology on railway capacity, and proposes three experiments. Chapter 4 details the first of these experiments, investigating train movements in existing railway networks. The purpose is twofold: to establish how wheel/rail adhesion limits current railway system performance, and to inform the development and application of linear motor technology to overcome these limits. The second experiment is detailed in Chapter 5, which describes the modelling and simulation of three different case studies to investigate the influences of changes to the design and operation of the railway system. The third experiment in Chapter 6 applies a number of new (developed as part of this thesis) and existing linear motor technologies and concepts to rolling stock in the three case studies, and measures the resulting effects on capacity. Chapter 7 then brings together the results of the literature review and the three experiments to draw some conclusions about potential applications of linear motor technology and the benefits to railway system performance.

### ***1.2.3. Contribution***

The principal contribution of this thesis is to propose a concept design for a railway braking system based on linear induction motors, developed for application to existing railway networks and requiring little or no significant change to the infrastructure. The research includes an assessment of the effect of a number of different linear motor technologies and concepts (both new and existing) on the capacity of the wider railway system.

## CHAPTER 2. LINEAR MOTORS

### 2.1. Transport Applications

#### 2.1.1. History

The use of linear electric motors for railways was proposed over a hundred years ago, for conventional vehicles with steel wheels running on steel rails, with equipment mounted to the vehicle and additional structures fixed to the track to complete the motors. The idea of using electromagnetic forces instead of wheels for lateral guidance and vertical support (in addition to longitudinal traction and braking forces) was also explored from the start of the twentieth century. This form of transport is generally termed magnetic levitation or ‘maglev’.

The first practical implementations of linear motors to railways were test vehicles running on conventional tracks, using a linear induction motor (LIM) with a short primary on the vehicle and an aluminium plate fixed to the track as the secondary. In this arrangement, the secondary is usually termed a reaction rail, and a variety of single- and double-sided configurations have been tried with different reaction rail geometries and materials.

Figure 3 illustrates an example: the Linear Induction Motor Research Vehicle (LIMRV) built by the Garrett Corporation in the USA. This was powered by a double-sided LIM with a short primary on the vehicle and a vertical aluminium reaction rail between the running rails, and an additional jet engine to accelerate the vehicle up to the test speeds required on the limited length of track available. This held the world speed record between 1974 and 1989 for a vehicle with conventional steel wheels running on steel rails, reaching 255.7 mph during testing (Chi and D'Sena, 1975).



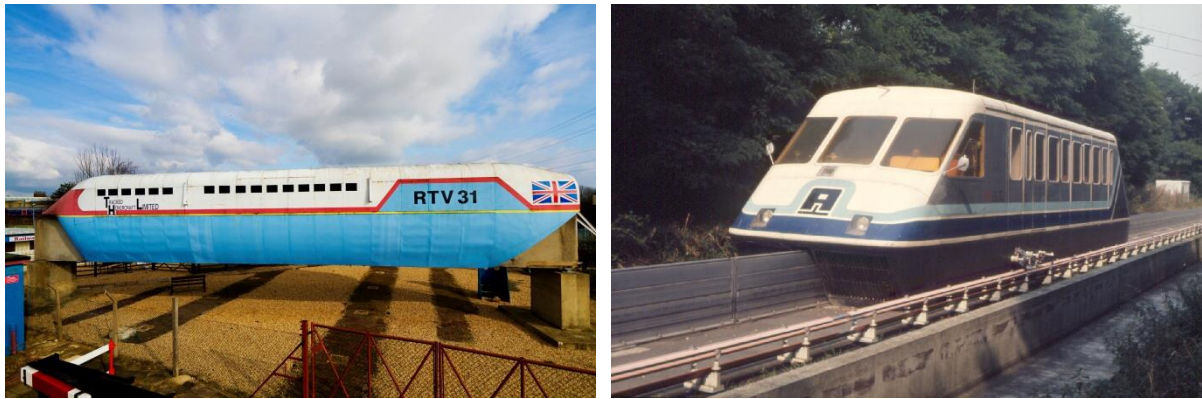
**Figure 3:** Garrett LIMRV<sup>1</sup>

Much of the research into the application of linear motors to transport was carried out in the 1960s and 1970s, concurrent with the development of hovercraft, and several experimental

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<sup>1</sup> Image sources are listed in the References section of this document.

systems were built using linear motors for propulsion and air cushions instead of wheels for support and guidance. Figure 4 illustrates test vehicles from both Great Britain and France from this period: RTV31 used a single sided LIM with an aluminium-capped iron reaction rail (Bailey, 1993), and the Bertin Aérotrain S44 used a double-sided LIM with a profiled aluminium reaction rail (Wiat, 1975; Patin, 1989).



**Figure 4:** Air cushion systems: Tracked Hovercraft Limited RTV31 and Bertin Aérotrain S44

Air cushions were effectively superseded by maglev systems, and the first commercial application was an airport shuttle at Birmingham in the 1980s (Pollard, 1984); it is however no longer in service. The vehicles had electromagnetic suspension using DC electromagnets, and a LIM with an aluminium-capped iron reaction rail for traction and braking. A few similar systems using linear motors have followed (and many more have been proposed), some of which also use maglev technology; these are generally categorised as Personal Rapid Transit (PRT) or cargo handling systems however as the vehicle capacities are small compared to conventional railway vehicles.

A significant amount of maglev research and development work was carried out in Germany, and their Transrapid system entered commercial service in Shanghai in 2004, linking the airport to the city centre. The Transrapid vehicles also use an electromagnetic levitation system, but with a long primary linear synchronous motor (LSM) for traction and braking (Transrapid, 2004; Tum *et al.*, 2007). In Japan, the HSST Linimo urban maglev started commercial service in 2005, using electromagnetic levitation and a short primary LIM (Yasuda *et al.*, 2004). Japan has also carried out extensive development of a very high speed maglev system with electrodynamic suspension using superconducting magnets, and a long primary LSM for traction and braking (Sawada *et al.*, 2000). The test track is currently being extended to form the first section of the Chūō Shinkansen line between Tokyo, Nagoya and Osaka. South Korea have also developed maglev technology, using electromagnetic suspension and a short primary LIM (Shin *et al.*, 2011), and a line at Incheon Airport opened

to passengers in February 2016. Figure 5 illustrates (clockwise from top left) the Japanese high speed superconducting maglev test track, the Linimo urban maglev, the Incheon Airport line, and the Transrapid in Shanghai.



**Figure 5:** Magnetically levitated systems

Maglev has remained a niche transport mode however, as the high cost of the track and incompatibility with the hundreds of thousands of kilometres of existing railway lines is a restriction on widespread adoption (Vuchic and Casello, 2002). Conventional railways have remained the dominant form of guided surface transport.

### ***2.1.2. Application to conventional railways***

The test programmes in the 1960s triggered a number of studies examining the potential for applying linear motor technology to conventional railways (Armstrong, 1967; Autruffe, 1968; Machefert-Tassin, 1971). However, the principal conclusion drawn from these studies is that the costs associated with additional equipment mounted to the track meant that there was no justification for the general replacement of conventional locomotives with trains powered by linear motors. Nevertheless, some specific cases were identified where limitations imposed by wheel/rail adhesion meant that the use of linear motors may be worthwhile: very high speeds, climbing steep gradients, assisting heavy locomotive-hauled freight trains (during acceleration, and on gradients), and increasing capacity by shortening headways between trains.



Subsequent development work for the TGV and Shinkansen trains has demonstrated that factors other than adhesion are more critical in limiting the maximum practical commercial operating speed of very high speed railways (Sone, 1994). A number of proposals have been made for application of linear motor technology to freight trains, including long and short primaries for both LIMs and LSMs, but at present the costs of fitting equipment to the infrastructure has remained a decisive factor in preventing adoption (Kalman and Hafele, 1969; Werle, 2003; Gurol, 2009; Hellinger and Mnich, 2009). A successful application of linear motor technology has been urban rail systems, following research and development work in both Canada and Japan.

Several cities across the world now have lines that use short primary LIMs with an aluminium-capped solid iron reaction rail mounted between the running rails for traction and braking. The iron may be laminated or the aluminium replaced with copper to improve energy efficiency where high forces are frequently transmitted, such as at stations. Figure 6 illustrates some example vehicles running on the Yokohama subway (left) and the Vancouver SkyTrain network (right); the reaction rail can be seen between the running rails in both photographs.



**Figure 6:** Yokohama subway and Vancouver SkyTrain

The most important technical factors that justified the adoption of linear motor technology in these urban rail systems were the ability to climb steep gradients, maintain performance in all weather conditions and allow short headways between trains (Isobe *et al.*, 1999; Vollenwyder, 2002). These allow a more frequent and reliable service to be provided, along track alignments that would be impractical with conventional traction equipment (Alm, 2010). The capital costs of bridges and tunnels for new routes in urban areas can potentially be lower as a result, which may offset the additional costs of the reaction rail. In addition, the elimination of rotary motors and associated transmission components can reduce maintenance costs, noise and resistance to motion. The wheels are no longer transmitting traction and braking forces and friction braking is minimised, and component wear is reduced as a result, with a

corresponding further reduction in vehicle maintenance costs. The lower energy efficiency of a LIM compared to an equivalent rotary machine remains a significant disadvantage, but Vollenwyder (*ibid.*, pp. 5-6) highlighted that energy consumption should be assessed in the context of overall railway system performance:

A vehicle with LIM propulsion must be compared with a vehicle of different technology providing the same passenger throughput and service availability. For example a rail vehicle with rotary drive may need more [powered] axles to achieve the same service level and availability under adverse adhesion conditions; its higher weight results in higher energy consumption. A rubber-tired [*sic*] system has a higher rolling resistance and may need guideway heating under wet or snow conditions, increasing the energy consumption. Comparison for the SkyTrain in Vancouver shows that the LIM technology is competitive in regards to energy cost on the basis of service provided.

Working of conventional rolling stock over lines equipped with an aluminium reaction rail is possible, and LIM-powered vehicles could potentially be hauled over conventional lines. However, many signalling systems include equipment mounted between the running rails, so interworking with conventional railways is not necessarily possible.

### ***2.1.3. Linear induction motor using running rails as the secondary component***

Given that conventional running rails are made of steel, it may be possible to obtain some of the benefits of adhesion-independent traction and braking forces without the costs associated with a separate reaction rail by using the running rails as the secondary component of a linear induction motor instead of a separate reaction rail. The objective would be to allow operation of vehicles with linear motor technology on existing railway networks, alongside existing rolling stock, with few modifications required to the infrastructure.

Investigating the feasibility of this idea, and quantifying its potential to improve the performance of railway systems, forms the basis of answering the research question detailed in Chapter 1. Other designs of linear motor, such as LSMs or long primary LIMs, would require extensive infrastructure changes and are therefore not within the scope of this thesis.

Section 2.2 contains a literature review focused on existing research into LIMs using the running rails as their secondary. The purpose is to investigate both the potential performance and the issues that must be overcome for widespread adoption, which together will ultimately determine the feasibility of the proposal. State-owned railway companies were involved in much of the research into linear motors, and the section is therefore nominally divided by country. The findings of the literature are then discussed further in Section 2.3.

## **2.2. Literature Review**

### **2.2.1. Great Britain**

Early reference was made to using the running rails as the secondary of a LIM by Japolsky (1931, quoted in Laithwaite, 1986, p. 41), but it was suggested that the idea would not be successful, as ‘commercial application was handicapped by the necessity of having a considerable air-gap for practical purposes, hence too great a reluctance in the magnetic circuit’. Armstrong (1967, p. 146) also dismissed the idea of using the running rails as a LIM secondary, stating that ‘the surface of the existing running rails is inadequate, in both total available area and conductivity, for the production of useful traction forces’. This conclusion was echoed by Laithwaite and Barwell (1970, p. 1255) who were likewise ‘of the opinion that an efficient and economical traction system cannot be designed using conventional running rails as reaction elements’.

The high magnetic permeability of a secondary made of solid steel increases the skin effect that concentrates flux on the surface of a steel plate, and the resulting small area of the flux path increases the overall resistance for the currents induced in the secondary. Saturation of the steel to allow greater penetration of the flux and an increase in this area reduces the effective permeability enough that the total gap reluctance is no better than aluminium, and the lower conductivity of steel compared to aluminium means the resistance of the secondary to the induced currents remains higher. There is also a significantly larger attractive magnetic force between the primary and a solid steel secondary than for other secondary materials (Laithwaite and Barwell, 1966).

Nonetheless, Penman *et al.* (1981) and Vadher (1982) provided some examples of applications where the advantages of using a solid steel secondary were sufficient to outweigh these disadvantages, such as steel-framed cranes. These papers included both theoretical motor performance calculations and validation tests. British Rail Research also carried out a series of tests with a maglev vehicle that concluded that a steel plate, rather than aluminium-capped iron, was a feasible option for the secondary component of a single-sided LIM (Bevan, 1977). In 1976, Gyro Mining Transport built a prototype diesel-electric mine train using a single-sided LIM with a solid steel reaction rail mounted between the running rails, replacing the rack-and-pinion or cable-hauled traction drive typically used for mine trains. The rail contamination within a coal mine environment means that the adhesion at the wheel/rail interface was sometimes unable to support sufficient traction forces to climb the steep gradients involved. Aluminium for the reaction rail was not permitted inside mines, due to the risk of sparks and potential gas explosion from any impacts with rusty steel.



**Figure 7:** Gyro Mining Transport Linear Motor Train prototype

The performance of the prototype linear motor train in tests was as predicted by calculations; the potential issues noted were a noticeable rise in temperature in the rail after several minutes of low speed or stationary operation and the large attractive force between the vehicle and track (Armstrong, 1977). However, no further examples were built and the prototype was converted to diesel-hydraulic drive in 1981 for testing rubber-tyred wheels, and subsequently dismantled in 1988 (Darville, 1988).

### **2.2.2. France**

Research into the possibilities of using the running rails as the secondary of a LIM was carried out in France by MTE (Matériel de Traction Électrique, part of Jeumont-Schneider and Creusot-Loire) from the mid-1960s, using a rotary test rig and small scale models, which showed that the idea was feasible (Société MTE, 1966; Wiart, 1970; Machefert-Tassin, 1971).

Further experiments with a full size locomotive produced a motor with a starting tractive effort of 3 kN per metre of individual primary length (90 s rating), a continuous tractive effort of up to 1.5 kN/m at 88% of maximum speed and a maximum brake effort of 6 kN/m (60 s rating). The superior performance in braking led to further investigations into the use of a LIM for braking only, termed '*frein linéaire à courants de Foucault*' or eddy current braking. When used in this way, the primary can be supplied by either AC or DC, whereas traction requires a variable-voltage variable-frequency (VVVF) AC supply, which was significantly more expensive to provide on board vehicles in the 1970s compared to DC. Using a primary with a design optimised for braking, an effort of 7 kN/m was achieved with a DC supply.

The development of eddy current brakes (ECBs) to provide an adhesion-independent brake was detailed in a further paper (Machefert-Tassin and Wiart, 1973). A series of tests were carried out on the French railway network in 1970-1971 using vehicle X2051 (a converted diesel railcar) with two different designs of brake, mounted between the wheelsets of a two-axle bogie. The primary measured 1930 mm long, 130 mm wide and 150 mm high, with seven poles and two half-poles, and an air gap between the primary and the rail of 7 mm.

At speeds below around 50 km/h, the vertical attractive force became large enough to require a reduction in the current in the primary to prevent excessive loads on the track. The vertical forces during the test were small enough not to cause lifting of point blades or broken rails however, and there were no problems caused when metallic debris was scattered on the ballast. There were also no problems reported with the eddy currents in the rail interfering with the track circuits on the routes where test took place, although some interference was noted with other electronic trackside components. Inducing eddy currents in the rail does however raise its temperature, and this was identified as a possible problem if many trains were operated over the same section of track in quick succession.

ECBs were also fitted to the Z7001 experimental vehicle (Zébulon), to carry out further testing as part of the TGV development programme (Portefaix *et al.*, 1975). Ultimately however, ECBs were not used for the production TGV-PSE rolling stock, as the heating of the rail proved unacceptable (Bouley, 1977). They were re-examined as part of the studies for the TGV-NG for use above 220 km/h, to allow service speeds of up to 360 km/h within existing signalling headways, which could not be guaranteed without adhesion-independent brakes (Raison, 1998). 8.5-15 kN per bogie of braking effort was to be provided for service braking and up to 20 kN in an emergency. The theoretical performance was verified in a series of on-track tests, which showed no problems with bogie dynamic stability or compatibility with track circuits, although there was some interference with hot axle-box detectors.

However, the TGV-NG was never built, and the Alstom AGV was chosen for development instead. Provision was made for ECBs in the AGV prototype train, but they were ultimately rejected due to the significant increase in unsprung mass that would result and the complexity of proving compatibility with the infrastructure (Lacôte and Hughes, 2007). Nevertheless, fitment of ECBs to future French high speed trains remains an option under consideration (Schykowski, 2008). The European Commission-funded ECUC project<sup>2</sup>, completed in 2015, investigated these compatibility issues in more detail to help support greater adoption of ECBs within Europe.

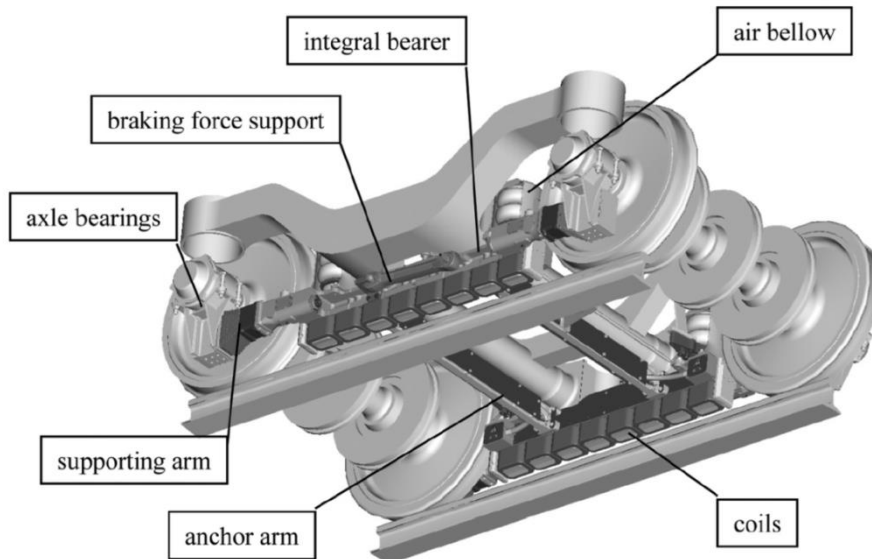
### **2.2.3. Germany**

In Germany, ECBs are now in commercial service on the ICE 3 trains to augment the regenerative and friction brakes (Gräber *et al.*, 2003; Berger, 2010). The reduction in component wear results in lower life-cycle costs for the train compared to the use of friction brakes alone.

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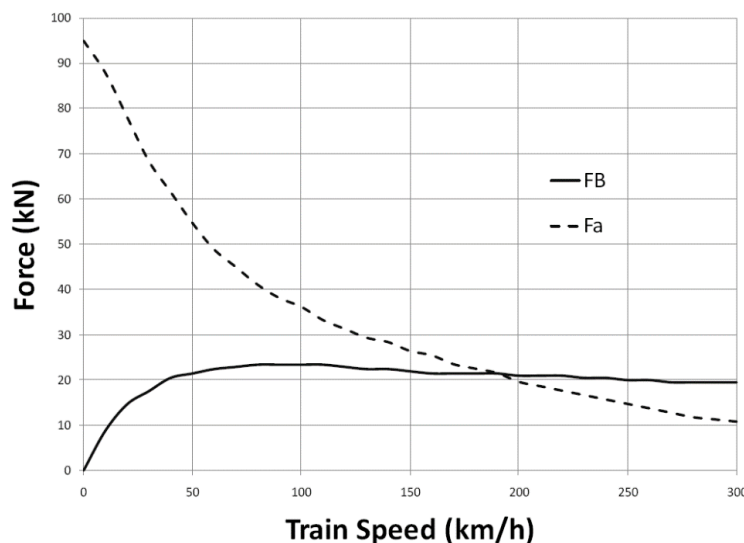
<sup>2</sup> <http://www.ecuc-project.eu/>

The ICE 3 ECB is illustrated in Figure 8, and consists of eight magnetic coils (with a total length of 1540 mm) mounted in the space between the wheelsets of the bogie, with an air gap of  $6.5 \pm 0.5$  mm between the magnets and rail. Both bogies on each of the four trailer coaches in an eight-coach ICE 3 train are fitted. The additional weight on the bogie is 860 kg.



**Figure 8:** ICE 3 ECB design (Gräber *et al.*, 2003)

The longitudinal braking and vertical attractive forces produced by one bogie under emergency braking are shown in Figure 9. The maximum power input required to energise the brake is 86 kW per bogie, and this is usually fed by regenerated energy from the traction motors. In normal service braking, each bogie provides up to 19 kN of braking force, although this is ramped down to zero between 100 km/h and 50 km/h to prevent the attractive vertical force exceeding the permissible axle load.



**Figure 9:** ECB braking (FB) and attractive (Fa) forces (Berger, 2010)

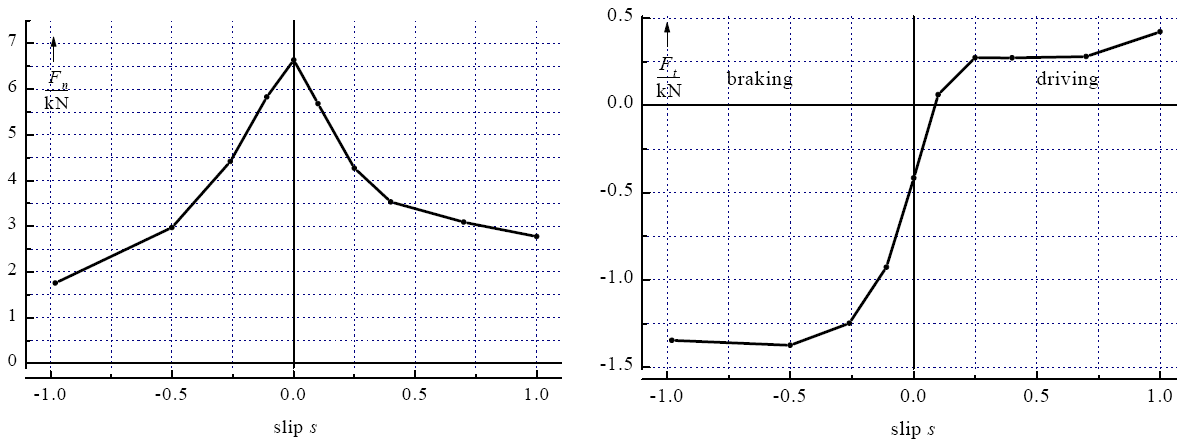
Repeated brake applications in the same location will cause a significant rise in the temperature of the rails over a period of several hours. If the ECB is to be used purely as an emergency brake, the only requirement for the infrastructure is that there is no interference with the signalling equipment, as emergency brake applications are rare enough that several consecutive applications in the same location are considered sufficiently unlikely. Where the ECB is also to be used as part of service braking, the track structure must also be able to resist the thermal stresses that result from the rises in rail temperature. Modifications to axle counters and other lineside equipment were also required to prevent interference with the signalling system when ECBs were introduced.

Regulatory provision has been made for ECBs in the infrastructure, rolling stock and operation sections of the High Speed TSI (Schykowski, 2008), and they are now permitted on the LGV Est in France. Plu *et al.* (2013) described the work required to allow the ICE 3 trains on cross-border services to use ECBs on this line. This included a detailed analysis of the problems of temperature rise in the rails, as the line has conventional ballasted track (unlike the slab track used on high speed lines in Germany, which provides greater resistance to rail buckling forces). A single train making a service brake application includes up to 105 kN of force from the ECBs, which raises the rail temperature by around 2°C.

In addition to the work in Germany on ECBs, the use of a LIM with the running rails as the secondary component has been proposed. A patent filed by Siemens (1997) detailed the use of a LIM instead of an ECB, to reduce the heat input to the rail and reduce energy consumption. A second Siemens patent application (Konrad and Heidt, 2000) proposed a similar LIM arrangement, but operating at synchronous speed to provide attractive normal forces only, intended to reduce the risk of vehicle derailment or rollover when running at high speed or in a crosswind.

The use of a LIM with the running rail as the secondary was investigated in detail by Darmstadt University, in collaboration with DB (Binder *et al.*, 2000; Werle, 2003). The LIM would provide some traction and braking forces independent of wheel/rail adhesion, with the magnetic attraction increasing the vertical force on the wheelsets, hence allowing greater forces to be transmitted at the wheel/rail interface by the main traction/braking system for a given coefficient of friction. It was to be mounted within a bogie in a similar manner to the ICE 3 ECBs, also with an air gap of around 6.5 mm. The available space within the bogie constrained the size of the proposed motor to around 1400 mm in length, 135 mm in width and 250 mm in height. Within this envelope, a pole pitch of 160 mm and primary iron width of 96 mm was proposed.

The calculations and modelling predicted significantly larger attractive vertical forces than longitudinal traction or braking forces, and these are illustrated by Figure 10 for an air gap of 6.5 mm. The predicted maximum efficiency was 0.3 for traction and 0.6 for braking (both at low values of slip), and the power factor close to 0.1 across the majority of the range of slip values.



**Figure 10:** LIM booster vertical (left) and longitudinal (right) forces (Werle, 2003)

The conclusion from the calculations was that the use of a LIM with the running rails as the secondary is not viable as the main traction drive, due to the low efficiency. However, it shows potential when used intermittently as a booster to provide extra longitudinal and vertical forces, such as when low adhesion conditions are encountered.

The concept was then compared against a LIM with a separate iron-backed aluminium reaction rail, and a DC electromagnet acting on the running rails to provide a vertical force only. The case study considered German Class 152 locomotives, hauling freight trains on the steep gradient between Geislingen and Amstetten, with a reduction of tractive effort from 300 kN to 211 kN in wet weather conditions due to the reduction in wheel/rail adhesion. The LIM with a separate reaction rail performed best, with a 25% increase in tractive effort at 60 km/h, the DC electromagnet provided an 18% increase and the running rail LIM only 8%. However, the running rail LIM required a significantly larger power supply because of the low power factor (900 kVA, compared to 250 kVA for the aluminium reaction rail LIM and 8 kW for the DC electromagnet). When the potential increase in freight capacity and the investment and maintenance costs were compared for the booster concepts and an extra banking locomotive, it was concluded that DC electromagnets are a better solution than either of the LIM designs. In addition, separate banking locomotives also performed better than either LIM option in this case. A patent was filed by Knorr-Bremse for a further development of this DC booster concept (Kröger *et al.*, 2003), which combined the booster with an ECB for braking.



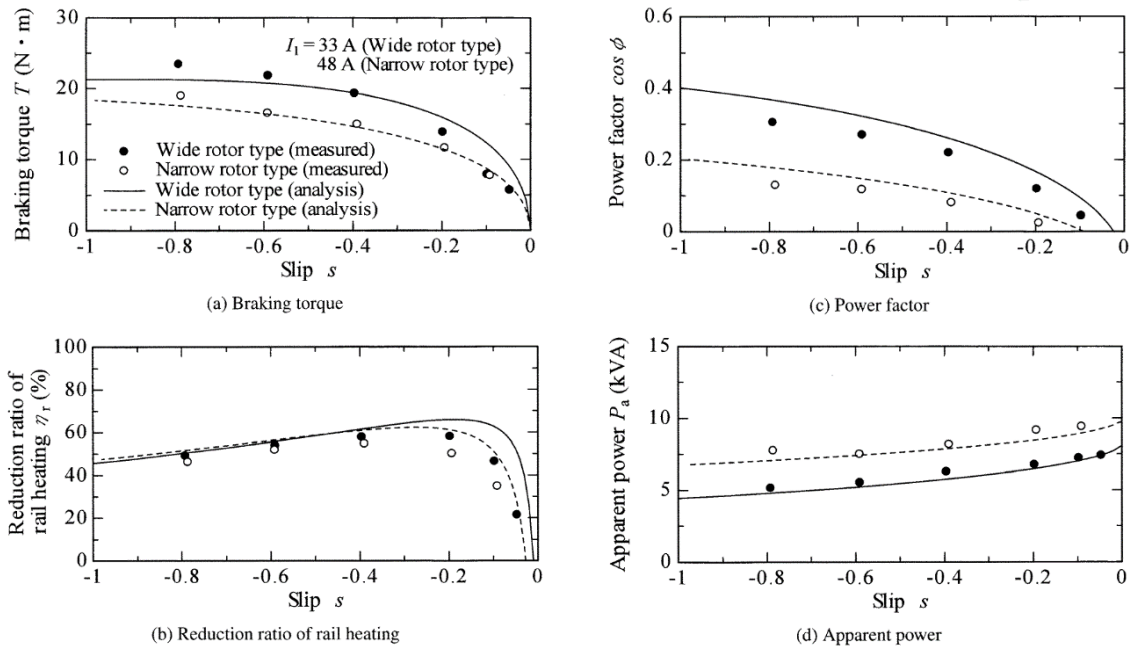
#### 2.2.4. Japan

Japan has also conducted research into linear eddy current brakes (Takahashi *et al.*, 1970). Tests were carried out on the Tōkaidō Shinkansen, but it was found that ECBs resulted in an unacceptable temperature rise in the rail, and they were not adopted for use in regular service (Kashiwagi *et al.*, 2009). Fujino (2008) nevertheless identified ‘high deceleration non-adhesive brakes using magnetic force’ as one of the enabling technologies for the next generation of JR East Shinkansen rolling stock, and the Japanese Railway Technical Research Institute (RTRI) has carried out extensive research into the use of bogie-mounted LIMs that use the running rail as their secondary component. The primary aim is to achieve the benefits of adhesion-independent braking, but reduce the heat input to the rails by comparison with ECBs.

This reduction in rail heating is achieved by operation of the LIM above its synchronous frequency as a generator, so that regenerative braking recovers some of the kinetic energy of the train to provide excitation of the LIM primary (Kashiwagi *et al.*, *op. cit.*). By comparison, all of this kinetic energy is dissipated as heat in the rails in the ECB case. There is also the potential for more energy to be recovered to reduce the rail heating effect further; this excess can be dissipated by a braking resistor, stored on-board or fed back to the railway power supply. With only a small amount of energy required for initial excitation compared to a DC-fed ECB (which requires all of the excitation to be provided externally), the brake can also operate independently from an external power source, and therefore still operate in an emergency if there is a power supply failure elsewhere. The principal difficulties to overcome are the high resistivity of steel rails and the associated skin effect, as well as the narrow width of the secondary compared to the primary pole pitch. These difficulties result in relatively small forces and a low power factor, which in turn requires an increase in the power supply equipment’s capacity.

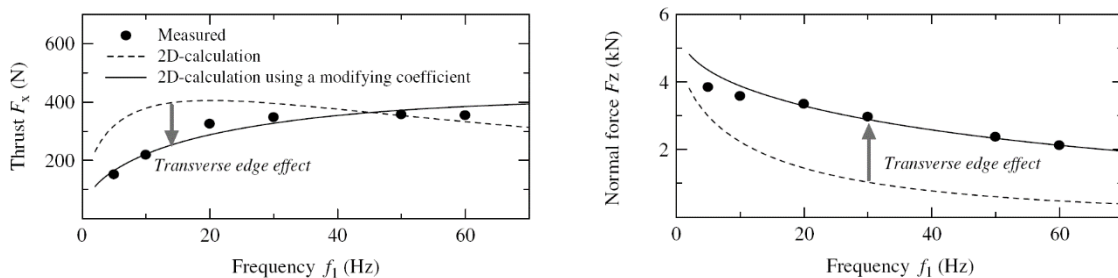
Experiments to investigate the influence of the narrow steel secondary were described by Sakamoto *et al.* (2012c), using a test rig to drive a conventional rotary induction motor. The squirrel cage rotor was replaced by two different solid steel rotors, one the full width of the squirrel cage (175 mm) and the other corresponding to the width of the rail profile (65 mm). Figure 11 compares (clockwise from top left) the braking torque, power factor, apparent power and the calculated reduction in rail heating if an equivalent LIM type rail brake is compared to a similarly rated ECB, extrapolated from measurements in the tests. The power factor was found to be low compared to a conventional rotary induction motor, due to the increased impedance of a narrow steel secondary compared to the primary impedance. The

rail heating ratio was not significantly affected by the rotor width however, and it was inferred that the eddy current losses on the side of the rail are therefore not large, and the main effect of the current in the sides of the rail is to increase the reactance of the secondary.



**Figure 11:** Characteristics of an induction motor with solid steel rotors (Sakamoto *et al.*, 2012c)

A second paper examined the transverse edge effects of a narrow secondary in more detail (Sakamoto *et al.*, 2012a), using a static test rig with a LIM primary mounted above a section of rail. This is essentially equivalent to a locked rotor test for rotary machines. The primary was 1.2 m long and 65 mm wide, with a pole pitch of 288 mm, and an air gap of 8 mm to the rail (also 65 mm wide). The relative permeability of the rail steel and its influence on the depth of the skin effect were also quantified, and a 2D calculation used to predict the forces with a modifying coefficient to account for transverse edge effects. These transverse edge effects were found to reduce the braking force in the low frequency region and increase the normal force, as illustrated in Figure 12 for an input current of 75 A. The relative magnitudes of the vertical and longitudinal forces can also be seen.



**Figure 12:** Transverse edge effects for steel rails (Sakamoto *et al.*, 2012a)

The third experiment in the series was an experimental verification of a LIM rail brake design derived from the results of the previous studies (Sakamoto *et al.*, 2012b), using a rotary test rig with a curved LIM primary mounted around a flywheel at an air gap of 6.5 mm. The flywheel had a profiled steel rail fixed around the circumference, and the rotary inertia of the system could be changed to model different vehicles. The core of the primary was 983 mm long, 95 mm wide and 150 mm high, with 36 slots, each 14 mm wide and 79.5 deep, giving a pitch of 25.5 mm. The ring-wound coils had a cross section of 2.6 x 12 mm, with 28 turns; overall there were four poles with a pole pitch of 229.5 mm.

The LIM primary was able to provide a constant brake force of 5 kN between 300 and 50 km/h, ramping up from zero to full brake force in around 1.4 s. At high values of slip, the force depends only on the current in the primary throughout this speed range, with the actual value of the frequency determining the power generated, which in turn sets the reduction in rail heating. The influence of longitudinal end effects is also small in the high slip region, due to the high resistivity of the steel and the long, narrow design of the primary. A constant frequency across the speed range provides an approximately constant force and power output, but apparent power increases significantly at lower speeds. Varying the frequency with the velocity to provide constant apparent power operation reduces the power generated at lower speeds. This means that there is a trade-off to be made in the design between the reduction in rail heating and the apparent power. Below 50 km/h, the force reduces significantly and the generated power becomes insufficient to maintain excitation of the primary.

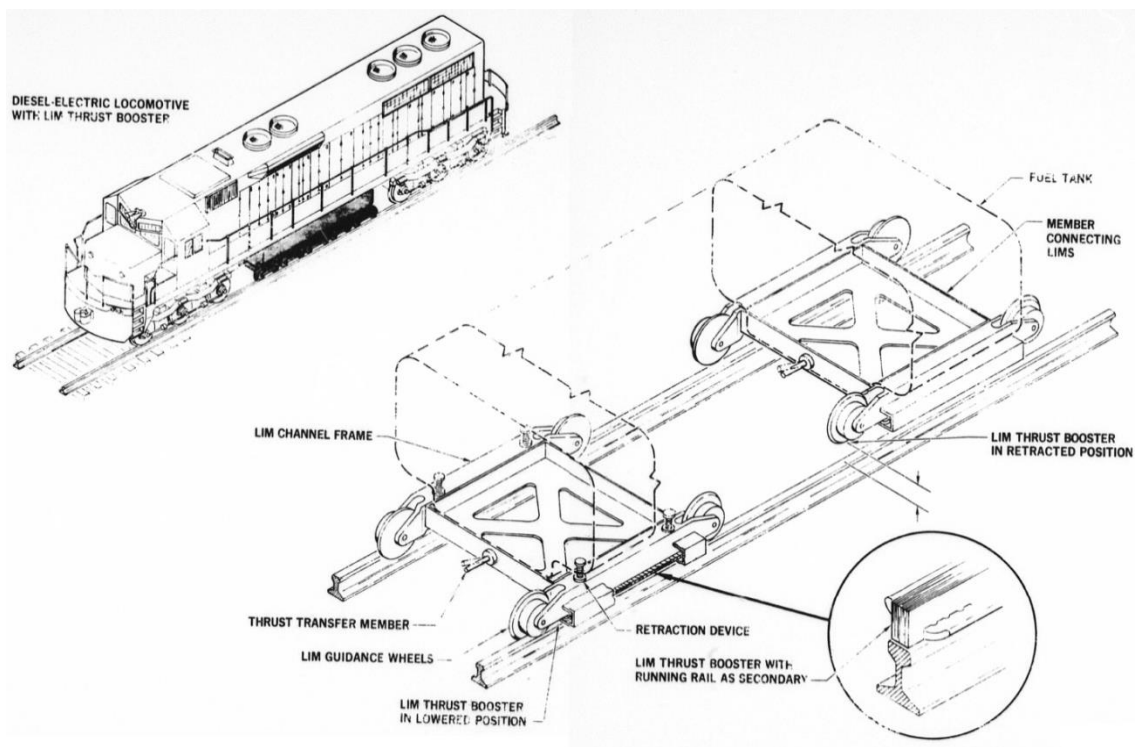
Following these tests, a prototype was constructed and tested (Sakamoto *et al.*, 2014), and is shown in Figure 13. The prototype tests confirmed that the LIM rail brake could provide a braking force of 10 kN for a single bogie, with an air gap of 6-7 mm. The additional weight on the bogie is around 600 kg for an armature length of 1.1 m. The potential effects on signalling and bogie dynamics were not reported however.



**Figure 13:** RTRI linear motor type rail brake (Sakamoto *et al.*, 2014)

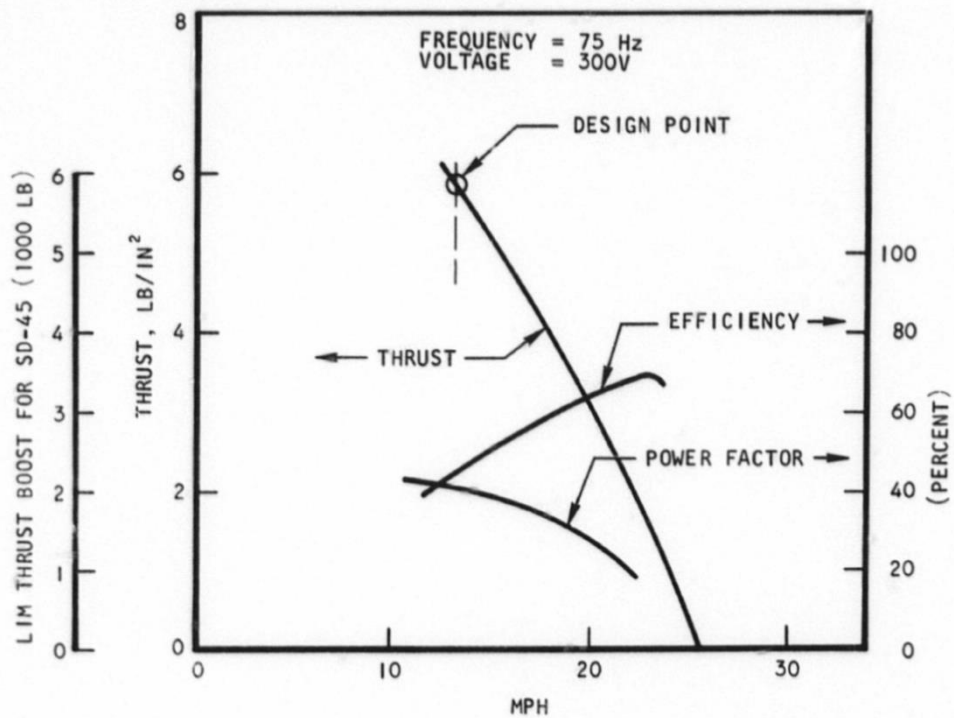
### 2.2.5. United States

A feasibility study by the Garrett Corporation (Kalman and Hafele, 1969) considered the use of LIMs to provide additional tractive effort for diesel-electric locomotives, using surplus engine power at low speeds where tractive effort is limited by adhesion rather than by power. The use of a separate reaction rail was dismissed because of the capital costs of additional infrastructure and the use of the running rails as the secondary proposed instead, despite the limited thrust due to the small rail surface area and degraded performance when using a solid steel secondary. The LIMs were to be mounted in a separate rigid frame beneath the locomotive, under the central fuel tank, as illustrated by Figure 14.



**Figure 14:** Garrett LIM thrust booster concept (Kalman and Hafele, 1969)

The use of a separate frame to carry the LIM allows a small air gap of 0.1 in. (2.5 mm), which would be less sensitive to lateral and vertical movements than designs mounted to the main bogies. The magnetic attraction would not result in excessive axle load, as there is very little vertical force on the wheels supporting the LIM frame compared to the main wheelsets. The LIM frame would be retracted clear of the rails at higher speed to avoid large dynamic forces and excessive wear that may result. The rail head width was given as approximately 2.7 in. (69 mm), and a primary width of 2 in. (51 mm) was used to allow for current return in the overhanging region of the rail head. A pole pitch of 3 in. (76 mm) was found to give the highest thrust and efficiency, and the overall performance of the motor is summarised in Figure 15.



**Figure 15:** Estimated performance of LIM thrust booster (Kalman and Hafele, *ibid.*)

The peak thrust at the design point was given as 6000lb (27 kN) for the SD-45 locomotive illustrated in Figure 14, equivalent to around 2.1 kN per metre of individual primary length. The maximum temperature rise in the rails was predicted to be around 10°F (5.6°C), which the report suggested is negligible. The report also claimed that the design did not interfere with the presently used switching and signalling systems, but this was not investigated in detail.

Kalman and Hafele (*ibid.*) also included an outline economic analysis, focusing on heavy freight trains hauled by several locomotives working in multiple, which are typical for the USA. Given that the motor was designed specifically for the adhesion-limited low speed region, it is not practical to run trains with fewer locomotives overall, as the train would not have sufficient power to reach higher speeds. However, an application in which the idea proved economically viable was to replace banking locomotives used to assist trains on steep gradients, as the additional costs of the LIM equipment more than offset the savings in the capital and operating costs of the extra banking locomotives. Although design and construction of a prototype for trials was recommended, no evidence has been found to suggest that this took place.

Caudill *et al.* (1982) considered the impact of different configurations of linear motor on vehicle and suspension dynamics, applicable for LSMs, LIMs with a separate reaction rail and

LIMs using the running rails as the secondary, as well as DC electromagnets acting on the running rails. The analysis demonstrated that improvements in vehicle stability, curving performance and safety against derailment can be achieved, in addition to improved traction and braking derived from a reduced dependence on adhesion.

Reference to the LIMs using the running rail as the secondary also appears in a later General Motors patent for diesel electric locomotives (Savage *et al.*, 1988), integrated with the sanding system to improve adhesion. The LIM primary was to be mounted between the wheelsets in the bogies of the locomotive (rather than in separate frames), to make use of surplus diesel engine power in low adhesion conditions to provide additional vertical and longitudinal force from the LIM. No evidence of trials or further application has been found.

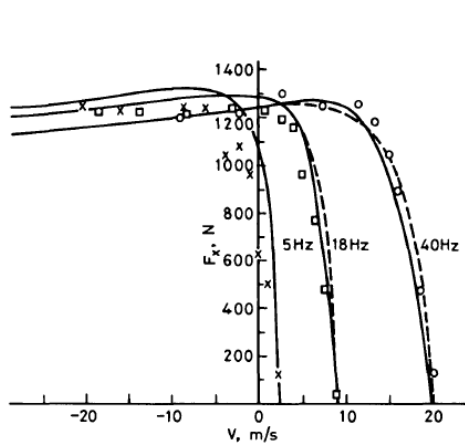
### **2.2.6. Brazil**

The use of a bogie-mounted LIM to provide additional longitudinal and vertical forces for locomotives was also proposed for the line between Curitiba and Paranaguá in Brazil, which connects high-altitude ore mines with a port, and consequently has heavy trains and steep gradients (dos Santos, 1980). No further literature has been found on this proposal however.

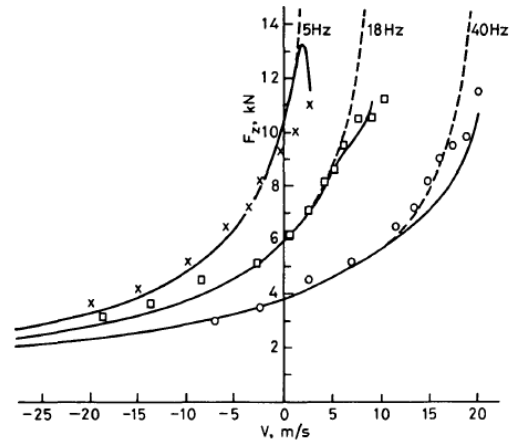
### **2.2.7. Canada**

Canada was heavily involved in maglev research and development, and the introduction of conventional trains with LIM traction drives were one result of this work, such as the Vancouver SkyTrain illustrated in Figure 6. An extensive test programme into the forces produced by a LIM with a solid steel secondary was carried out at the Canadian Institute of Guided Ground Transport (CIGGT) in the 1980s, detailed by Gieras *et al.* (1985). The test rig consisted of a 7.6m diameter flywheel, with the secondary attached around the rim and a stationary short primary mounted in a six-component force balance. It was used for a number of years to test different linear motor configurations, and further details of its design can be found in previous papers (Atherton and Eastham, 1975; Atherton *et al.*, 1977; Eastham and Katz, 1980).

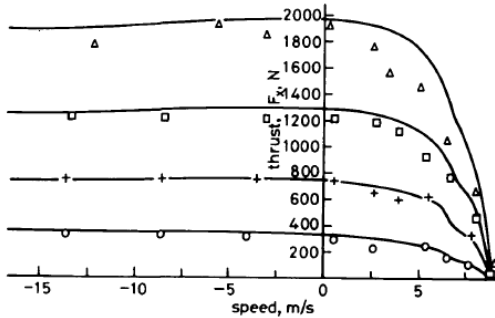
One particularly relevant observation from these papers is that for the primary geometry tested, end effects are not a dominant factor in the performance of the motor, especially for the case of a solid steel secondary. The particular configuration used was a 111 mm wide, 254 mm deep steel reaction rail, at a nominal air gap of 15 mm from the 1.73 m long, six-pole LIM primary. Test results for different supply currents, frequencies and air gaps are summarised in Figure 16.



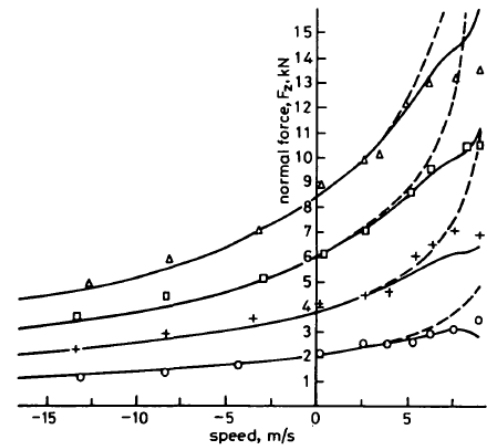
Thrust at 5 Hz, 18 Hz and 40 Hz as a function of speed, at  $I = 200$  A, airgap  $g = 15$  mm, and secondary width  $w = 0.111$  m  
 — calculations with end effects  
 - - - calculations without end effects  
 experimental points: x 5 Hz, □ 18 Hz, ○ 40 Hz



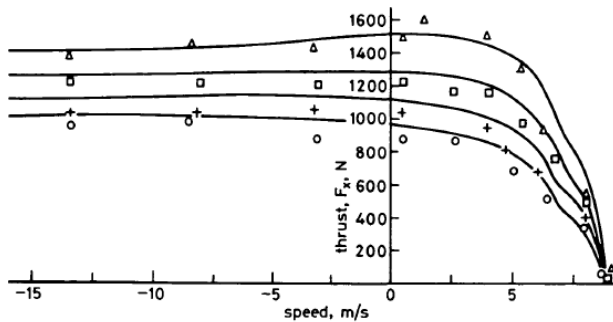
Normal force at 5 Hz, 18 Hz and 40 Hz as a function of speed, at  $I = 200$  A,  $g = 15$  mm, and  $w = 0.111$  m  
 — calculations with end effects  
 - - - calculations without end effects  
 experimental points: x 5 Hz, □ 18 Hz, ○ 40 Hz



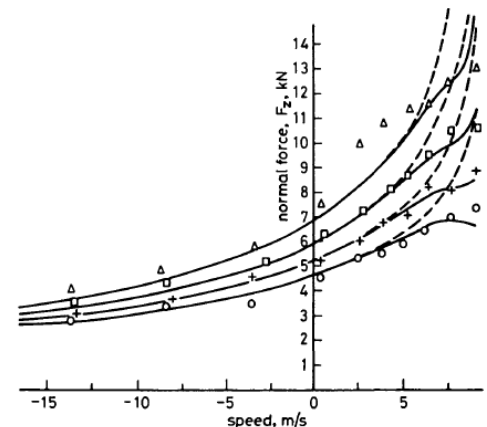
Thrust at  $I = 100$  A, 150 A, 200 A and 250 A as a function of speed at  $f = 18$  Hz,  $g = 15$  mm and  $w = 0.111$  m  
 — calculation ○ 100 A, + 150 A, □ 200 A, Δ 250 A



Normal force at  $I = 100$  A, 150 A, 200 A and 250 A as a function of speed at  $f = 18$  Hz,  $g = 15$  mm and  $w = 0.111$  m  
 — calculations with end effect;  
 - - - calculations without end effect;  
 ○ 100 A, + 150 A, □ 200 A, Δ 250 A



Thrust at various gaps as a function of speed at  $f = 18$  Hz,  $I = 200$  A and  $w = 0.111$  m  
 Δ 12.5 mm, □ 15.0 mm, + 17.5 mm, ○ 20.0 mm



Normal force at various gaps as a function of speed at  $f = 18$  Hz,  $I = 200$  A and  $w = 0.111$  m  
 — calculations with end effect, - - - calculations without end effect;  
 Δ 12.5 mm, □ 15.0 mm, + 17.5 mm, ○ 20.0 mm

Figure 16: CIGGT test results (Gieras *et al.*, 1985)

The geometry of this test rig is similar, but not an exact match, to conventional running rails. Nevertheless, the overall trends in the results are likely to be comparable.

## **2.3. Findings**

### **2.3.1. Concepts**

Linear motor technology has been successfully applied to conventional railways, using short-primary LIMs and an aluminium reaction rail mounted between the running rails. Although this has been shown to bring worthwhile benefits, the capital and maintenance costs associated with the reaction rail have limited adoption to a handful of urban rail systems across the world. The total track length of these lines is typically relatively low but the service density high, which helps to mitigate the costs of the reaction rail, but this arrangement is less applicable to wider railway networks.

To overcome this problem, it is proposed to investigate the use of the existing running rails as the secondary component of a LIM, instead of a separate reaction rail. Eliminating the costs of the reaction rail has the potential to allow more widespread adoption of linear motor technology in railway systems.

However, the findings from the literature suggest that the performance of such a concept is not likely to be competitive with conventional traction on a like-for-like basis. The lower conductivity of a solid steel secondary compared to aluminium or copper, combined with the skin effect and the transverse edge effect of narrow rails, results in significantly lower tractive effort, efficiency and power factor when compared to conventional rotary traction drives or other designs of linear motor. A solid steel secondary also results in large attractive forces between the rails and the LIM primary, which can be enough to exceed permissible axle loads.

Nonetheless, the concept does provide benefits. The attractive force can be harnessed to allow a conventional rotary traction system to achieve greater tractive and braking efforts for a given coefficient of adhesion between wheel and rail. Braking efforts can also be generated independently of the available wheel/rail adhesion, and (unlike tractive effort) can be comparable with those obtained from other braking systems. Consideration of energy efficiency is less applicable to braking than for traction. Furthermore, energy should be assessed in the context of the service provided by the railway system, rather than by the consumption of individual trains alone. An increase in energy consumption may be acceptable if adhesion-independent traction and braking allows an improved service to be provided.

Sections 2.3.2 and 2.3.3 therefore examine the potential influence of linear motor technology on the wider railway system, to support the design of experiments to investigate the research question from Chapter 1.



### ***2.3.2. Train performance***

The principal benefits of linear motor technology are ultimately derived from increases in tractive and braking effort. These increases could be used to achieve acceleration and deceleration levels above that of conventional rolling stock, reducing journey times. Alternatively, if the target journey time remains the same, there is an opportunity to provide a greater recovery time margin against delays. This extra margin can be exploited to reduce energy consumption when the train in question is running on time.

However, Armstrong (1967) suggested that passenger comfort (rather than adhesion) may already limit the maximum acceptable longitudinal acceleration for conventional trains with all axles powered. This was confirmed in research by Powell and Palacín (2015), which also highlighted that passengers are less tolerant of high accelerations on long distance intercity or regional services compared to commuters in urban rail systems. These conclusions suggest that it may not be possible to increase the maximum acceleration levels of existing trains further, and the use of linear motors is therefore limited in this respect. High-performance freight trains may represent an exception, but the acceleration levels of the majority of existing freight trains are typically well below those of passenger multiple unit trains. Accelerations in the high speed maglev systems outlined in Section 2.1.1 can be significantly higher than current passenger trains, but passengers are typically all seated in a similar manner to an aircraft during take-off and landing. This arrangement could not realistically be applied across existing conventional railway networks, as passengers are frequently standing or walking around within trains during acceleration and braking.

Although most trains have brakes acting on all axles, the proportion of powered axles is usually rather lower, as trains typically consist of one or more locomotives hauling unpowered trailing vehicles or multiple units with a mix of powered and unpowered axles. The use of linear motor technology to increase tractive effort for a given proportion of powered axles was explored in previous research into the maximum haulage capability of locomotives (Kalman and Hafele, 1969). The study looked at locomotives hauling heavy freight trains up steep gradients, but the same principle could also be applied to reduce the number of individual traction packages on multiple unit trains without reducing the maximum tractive effort available.

An alternative to increasing the absolute maximum tractive and braking effort is to aim to maintain current design maxima, which assume a given level of wheel/rail adhesion, when the train is experiencing low adhesion conditions. This has also been the subject of previous

research (Werle, 2003), again for locomotives hauling freight trains on steep gradients. Likewise, the principal justification for ECBs and the recent developments in Japan on braking systems using linear motor technology is to consistently obtain a higher level of braking effort irrespective of adhesion conditions (Sakamoto *et al.*, 2012c).

### **2.3.3. Network capacity**

Machefert-Tassin (1971) and Vollenwyder (2002) both make reference to the potential for the higher braking efforts consistently available with linear motor technology to improve the capacity of railway networks by allowing trains to safely run closer together, and the ECB development work for the TGV-NG was based on running at higher speeds within existing signal spacing distances (Raison, 1998). However, no research was found in the literature that specifically studies the potential increases in railway capacity derived from LIMs that use the running rails as their secondary. If significant improvements in capacity were found to be possible, it may help justify wider adoption of linear motor technology, as currently the benefits to individual train performance alone have generally been considered insufficient to do so.

The separation between trains (also known as headway) on a railway line is determined by the signalling system. Existing installations are typically based on fixed block signalling, where lineside signals and track-based train detection enforce the separation between trains by dividing the line into discrete blocks, within which only one train is normally permitted. The length and location of the signalling blocks must be designed to take account of the worst-case combinations of speeds and braking performance for all possible trains that may run over the route. If signalling information is displayed in the driver's cab instead of by lineside signals, it becomes more practical for a greater number of (shorter) blocks to be provided. The separation distance can then be reduced for trains running at slower speeds, and for trains with better braking performance. A further development is moving block signalling, where individual trains monitor their own locations, and the separation between trains is determined by each train's speed and braking characteristics, so that the actual separation distance between trains is no longer constrained by the location and length of infrastructure blocks and headway can remain at the minimum possible.

This suggests that in-cab or moving block signalling may be a prerequisite for taking full advantage of the potential reduction in headway offered by linear motor technology, while still respecting the requirement in Section 2.1.3 of operation on existing railway networks alongside existing rolling stock. However, in reality there are often other constraints on

capacity beyond the signalling, such as the location of stations and junctions, the service pattern in the timetable and the way in which the trains are driven, and any analysis of potential capacity gains must reflect this.

#### ***2.3.4. Conclusions***

The adoption of linear motor technology in railways has generally been limited by the costs of providing additional equipment in the track. The literature reviewed in Section 2.2 suggests that the use of a LIM with the existing running rails as the secondary is feasible when used to augment a conventional traction and braking system, rather than replace it. This arrangement would potentially allow wider adoption of linear motor technology. Increases in tractive and braking effort are made possible by increasing the vertical forces acting at the wheel/rail interface, producing longitudinal forces directly, or both.

Although passenger safety and comfort considerations are likely to prevent new rolling stock being designed with higher maximum tractive and braking efforts than existing conventional rolling stock, previous research has demonstrated that the concept offers an alternative to adding more locomotives or multiple unit traction packages to a train to achieve a given tractive effort target. The preferred option would depend on the design and operation of the rolling stock in question. Likewise, the possibility of maintaining a higher braking effort under low adhesion conditions has also been demonstrated, although the actual tractive and braking efforts used in service (rather than design maxima) must be considered to determine the potential increases that could realistically be achieved.

A higher braking effort during low adhesion conditions has the potential to provide an increase in overall railway capacity, firstly by increasing the recovery time margin in existing timetables, and secondly by reducing the separation distance required between trains. This has been highlighted in the literature, but no studies were found that investigate the potential capacity benefits in detail. A study of linear motor technology that investigates the capacity benefits in the wider railway system, rather than examining individual train performance in isolation, could therefore make a useful contribution to knowledge.

Railway capacity is affected by many different factors however. To accurately assess the potential of linear motor technology to improve capacity, a selection of actual railway networks and their operations should be analysed, so that the capacity benefits are reasonably representative of what is actually possible.

## CHAPTER 3. METHODOLOGY

### 3.1. Hypothesis

Based on the findings of the literature review in Chapter 2, the following specific hypothesis was proposed to address the research question detailed in Chapter 1:

Linear induction motors that use the running rail as their secondary component can provide a sufficient increase in the capacity of a railway network to justify adoption.

The purpose of this chapter is therefore to discuss the design a series of experiments to investigate the effect of this implementation of linear motor technology on the capacity of railway networks. This requires a strict quantitative definition of railway capacity, which is the subject of Section 3.2. The outline experimental methods to measure changes in capacity that result from this application of the technology are then developed in Section 3.3.

Should a measurable increase in capacity be found, a second requirement is then to determine whether this increase is worthwhile, to give a measure of the potential for adoption. It was suggested in Chapter 2 that moving block signalling would likely be a prerequisite to obtaining the full capacity benefits of improved braking. Moving block signalling is already considered to be a worthwhile option for increasing capacity in its own right however (Gill, 1998; Duffy, 2003). Therefore, a comparison between the influence of linear motor technology and moving block signalling (when applied together, and in isolation) is one way to provide an approximation of the value of linear motor technology.

Chapter 2 also highlighted that the lower energy efficiency of linear motors compared to their rotary counterparts is an important issue governing the adoption of the technology. Therefore, experiments to determine the feasibility and potential of linear motor technology should include an assessment of energy consumption.

Finally, a further development of the proposed experiments is to consider the circumstances in which linear motor technology would be more or less effective. This can be achieved by evaluating possible capacity benefits in a number of different railway networks, each of which should be reasonably representative of variations in design and operation between different railway systems.

### 3.2. Railway Capacity

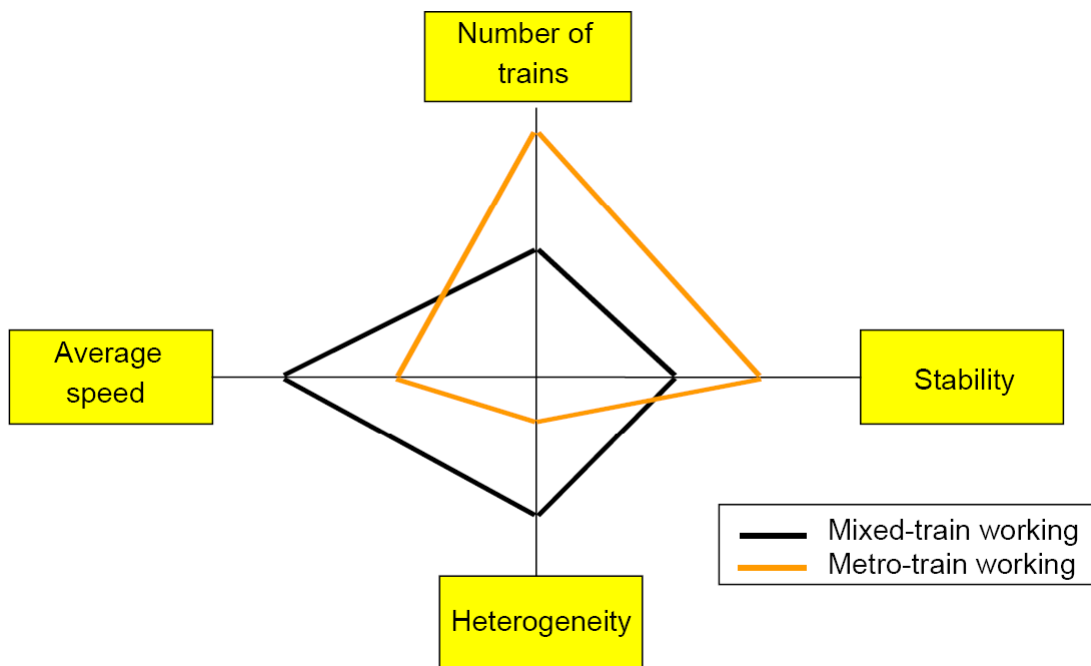
The International Union of Railways (UIC) developed a standard definition of capacity in the first edition of UIC Code 406 (2004, p. 2):

Capacity as such does not exist. Railway infrastructure capacity depends on the way it is utilised...On a given infrastructure, capacity is based on the interdependencies existing between the number of trains, the average speed, the stability and the heterogeneity.

The number of trains alone is insufficient to describe capacity within a railway network, as the maximum number of trains that can be run is affected by the characteristics of the services and rolling stock. These are defined by the timetable, which aims to cater to the demands of passengers and freight in the wider transport market.

A reduced journey time is often desirable, but increasing the train speed increases the braking distance, and hence the separation distance required between trains. Train speed and separation distance both affect the number of trains that can run on a given infrastructure over a particular time interval. A reliable and punctual service is also desirable, and an increase in the number of trains increases the likelihood that an initial delay to one train will propagate and result in other trains being delayed. An unstable timetable is defined by an initial delay to an individual train resulting in greater delays to subsequent trains. Finally, passengers and freight within a particular railway network will have different origins, destinations and expectations of service quality. As a result, railway networks usually contain a mixture of services with different rolling stock, routes, stopping locations and speeds. Increasing the heterogeneity of the services in the timetable will typically reduce the number of trains that can be run on a given infrastructure.

The trade-off between these four parameters is illustrated diagrammatically in Figure 17, comparing a mixed-traffic railway system with an urban metro system. An axis is drawn for the four parameters, with chords linking the points on the axis that represent the value of each parameter in a given railway. The perimeter of the resulting polygon then represents the capacity of that railway. For a given capacity, an increase in one or more parameters will result in a reduction in others. However, the relationship between the parameters is complex, and highly dependent on the railway system under consideration, and as such this remains a qualitative illustration.



**Figure 17:** The balance of capacity (UIC, 2004)

The number of trains, average scheduled speed and heterogeneity are set explicitly by the timetable, as well as the rolling stock specified for each train service. This implies that for a given timetable, the effects of changes to the design and operation of the railway on timetable stability can be used as a proxy to quantitatively measure changes in capacity. This meets the requirements for testing the hypothesis, as it allows the potential capacity benefits of linear motor technology and moving block signalling for existing railway networks and timetables to be evaluated. New timetables to further examine the trade-offs between the four parameters in Figure 17 would not necessarily be representative of what is possible in reality, as timetabling must satisfy many constraints beyond capacity, and as such is out of the scope of this thesis.

UIC Code 406 also detailed a common methodology to carry out capacity calculations, and this was examined in detail by Landex (2008). The calculations are based on dividing the network up into sections of plain line between nodes, such as junctions and stations. However, the results of the calculations can be affected by the choice of where to divide the network, especially in large or complex station areas, and calculations for individual line sections take no account of the influence of neighbouring sections (termed ‘network effects’). To accurately assess the interaction of multiple delays and subsequent propagation through a network, multi-train simulation is required to evaluate timetable stability (Landex, *ibid.*; Dicembre and Ricci, 2011). Furthermore, predicting the effects of linear motor technology on speed profiles and journey times of trains also requires physics-based simulation.

### 3.3. Experimental Methods

#### 3.3.1. Multi-train simulation

Landex (2008) described in detail a method to analyse delays and delay propagation in a railway network using Monte Carlo simulation. A model of the network is built in a multi-train simulation tool, the model is run a number of times with pseudorandom initial delays (based on a defined statistical distribution), and the final delays to trains on each run are measured. Siefer (2008) suggested that around 50 to 200 simulation runs are required to provide a representative indication of the network's performance, whereas Radtke and Bendfeldt (2001) suggested 50 to 100 would be sufficient.

Barter (2000) wrote a critical analysis of this method, which highlighted that a large amount of input data is required from many different disciplines across the railway to build a simulation model, and the results can be sensitive to input errors or assumptions made where data is difficult to obtain. The most critical assumptions identified were for model inputs that are influenced by human behaviour, with driving style mentioned specifically as having an important influence on simulated train movements.

Much of the basic input data for simulation models can be obtained from infrastructure and rolling stock specifications, although the tolerance on some of the data cannot necessarily be ignored. Other data may require detailed study of the actual railway under investigation, including delay distributions (Yuan, 2006) and train movements (De Fabris *et al.*, 2010; Bešinović *et al.*, 2013). The stochastic nature of the input data (and of other influencing effects that are typically ignored in simulation models, such as weather) limits the ability of simulation models to reproduce reality exactly. A further limitation is that although simulation models usually have some dispatching logic included, they are unlikely to reproduce human decision making for traffic management, especially when trains are already delayed and services may be terminated short of their destinations to recover some delay.

Strict verification and validation of completed simulation models against real world data is therefore necessary to check that they are reasonably representative (Fella *et al.*, 2010). However, Landex (*op. cit.*, p. 103) highlighted that simulation model outputs are unlikely to match corresponding results measured on the actual railway exactly:

It is difficult to calibrate simulation models to give exactly the same results as in real life operation...Often the purpose of the calibration of simulation models is to reproduce the operation of an average day to be able to examine the consequences of changes in the operation and/or infrastructure.

To account for such differences, Jacob *et al.* (2013) specified two criteria to determine whether a simulation model was sufficiently representative of reality to be used for investigating the effects of changes to the design and operation of a railway network on its capacity: less than 4% difference between simulation model results and actual measurements for train running times, and less than 8% difference for single train energy consumption. Given that real life journey times and energy consumption also show considerable day-to-day variation, a second test is to compare simulation results against a selection of measured data to determine whether the simulation results are within the spread of actual measurements.

### ***3.3.2. Application for this thesis***

The method outlined in Section 3.3.1 appeared to be a good fit to the requirements of this thesis, and was therefore adopted to test the hypothesis detailed in Section 3.1, and a three-stage experiment was devised. The following three chapters detail each stage:

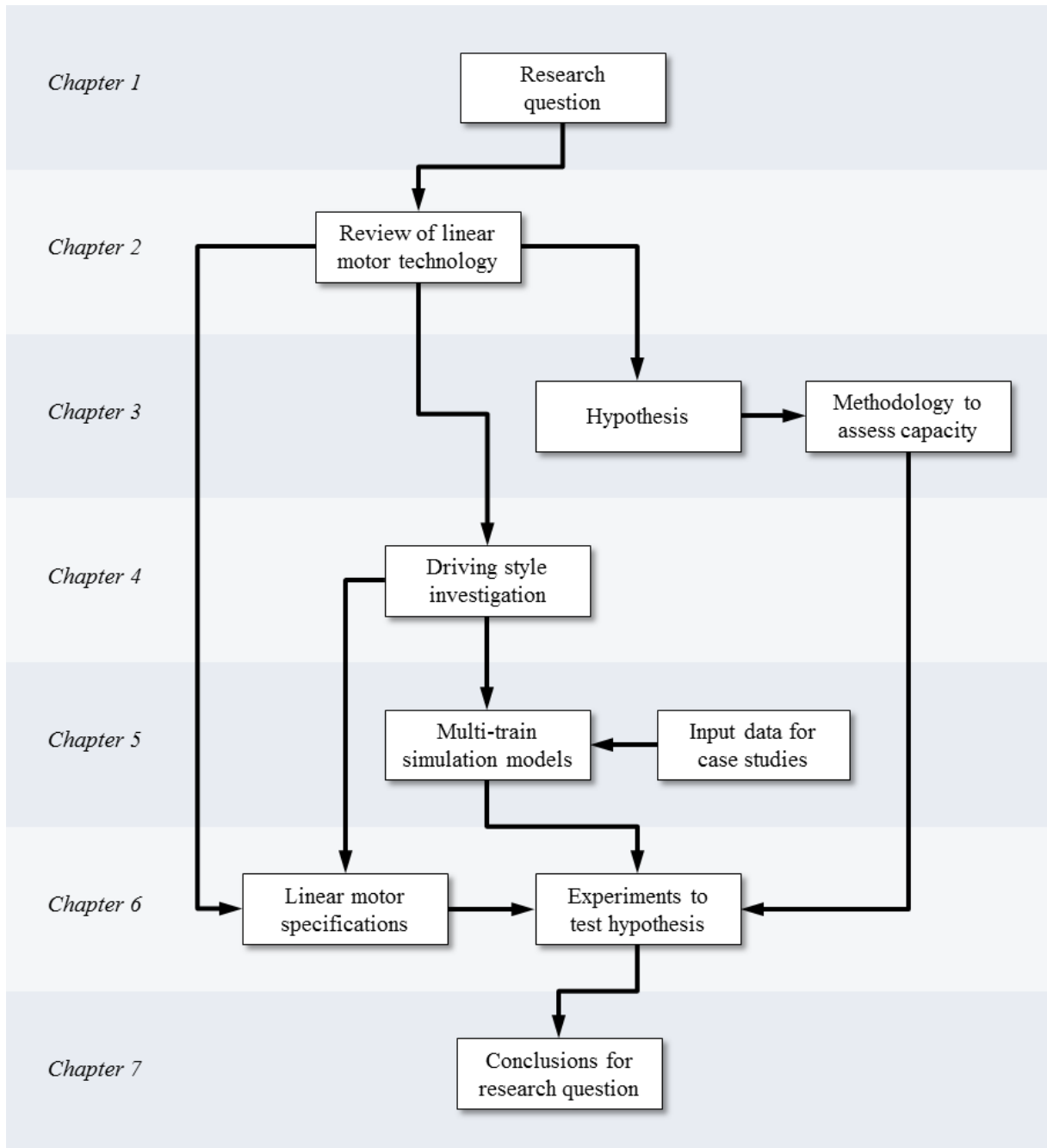
- ***Chapter 4 – Investigating train movements:*** it was suggested in Chapter 2 that the influence of linear motor technology on train movements depends on the tractive and braking efforts actually used in service, rather than the design maxima of the rolling stock used. Section 3.3.1 in this chapter also highlighted that consideration of driving style is required for an accurate multi-train simulation model. Chapter 4 therefore describes an investigation into train speed profiles and driving style, firstly as a prerequisite to building simulation models, and secondly to inform the application of linear motor technology options.
- ***Chapter 5 – Modelling train movements:*** Chapter 5 details the development of multi-train simulation models of a number of different real life railway networks, to use as case studies for testing the hypothesis.
- ***Chapter 6 – Applications of linear motor technology:*** Chapter 6 examines the influence of different applications of linear motor technology on the rolling stock and networks detailed in Chapter 5, based on the findings of the investigation into driving style in Chapter 4. The potential capacity increases from linear motor technology and from moving block signalling are evaluated and compared for each of the case studies.

Full details of the specific experimental methods, results and associated discussion for each of the three stages are contained within the respective chapters. Overall conclusions for the complete experiment are drawn in Chapter 7.



### 3.4. Summary

Figure 18 is a summary diagram of the methodology adopted, illustrating the outcomes of each chapter and the relationships between them.



**Figure 18:** Summary of thesis methodology and structure

## CHAPTER 4. INVESTIGATING TRAIN MOVEMENTS

### 4.1. Introduction

The speed profiles of individual trains within a railway system are influenced by linear motor technology, but also depend on how the trains are driven. The purpose of this chapter is therefore to investigate driving style in existing railway networks to inform the potential application of linear motor technology to conventional railways. The results also provide input data for the construction of a multi-train simulation model that can be used to evaluate the subsequent capacity benefits.

Individual train speed profiles can be characterised by four distinct operational phases:

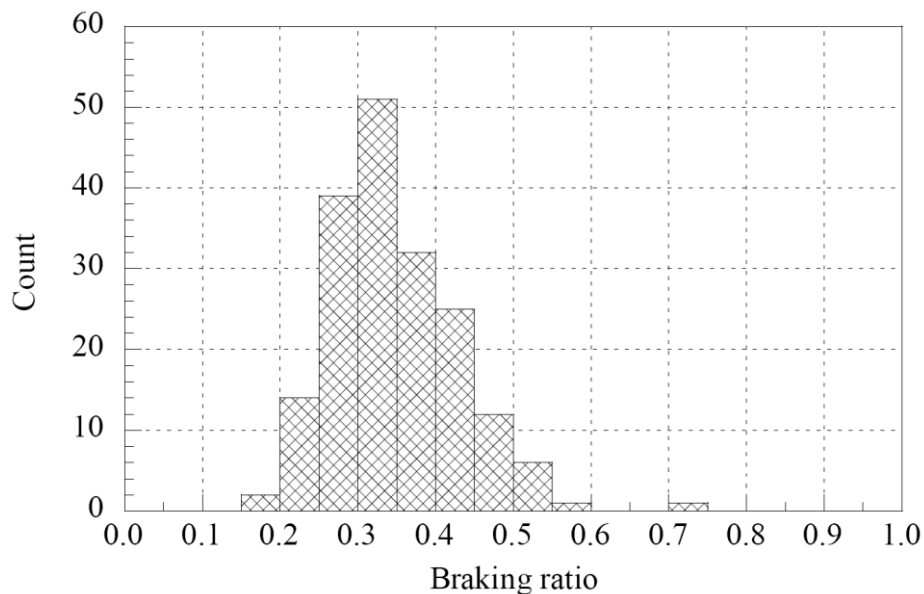
- Accelerating: apply tractive effort to achieve a particular acceleration level
- Cruising: control tractive or braking effort to maintain a constant speed
- Coasting: a period of free running, with no tractive or braking effort
- Braking: apply braking effort to reduce speed or stop

The driving style is defined here as the actions of the driver in operating the train's controls to achieve the desired level of tractive or braking effort (this also applies to the control system for ATO - automatic train operation). Note that the speed may be reducing on a steep uphill gradient, even if full tractive effort is being developed. Likewise, changes in speed during the coasting phase will also depend on the track gradient. The length of the transitions between the phases varies with the driver and rolling stock concerned; transitions are likely to be very short for passenger multiple unit trains (a few seconds or less), but much longer on long freight trains where changes in air pressure in the braking system take some time to propagate along the full length of the train. In-train forces for long freight trains must also be managed to prevent damage to cargo or to the couplers between vehicles (Cole, 2006).

Section 4.2 reviews some existing studies that used measured data to quantify driving style in several different railways. Sections 4.3 to 4.5 describe an experiment to gather more data to support this thesis, with some conclusions for the application of linear motor technology to conventional railways within Section 4.6.

## 4.2. Literature Review

A comprehensive study into train movement was carried out on freight trains in Sweden by Lukaszewicz (2001). Instrumentation was installed on an SJ Rc4 electric locomotive, and data from a full year of operation was acquired and analysed. Part of the study involved quantifying driving style. The powering ratio was defined for the acceleration phase as the ratio of actual measured tractive effort to the maximum tractive effort possible for the locomotive, and the measured values had a mean of 0.6. However, it was observed during test runs that the driver frequently set the controller to demand maximum tractive effort, but the effort actually delivered was limited by adhesion (especially at low speeds) and voltage drops in the power supply network. A mixture of cruising and coasting was observed, and when considered over all of the operational phases, the proportion of the total distance spent coasting formed an approximately normal distribution with a mean of 0.25 and standard deviation of 0.10. During braking phases, a mean braking ratio of 0.35 was measured, with a range of 0.15 to 0.75, suggesting that drivers generally chose to brake at a much lower level than the capabilities of the rolling stock. The distribution is illustrated in Figure 19.

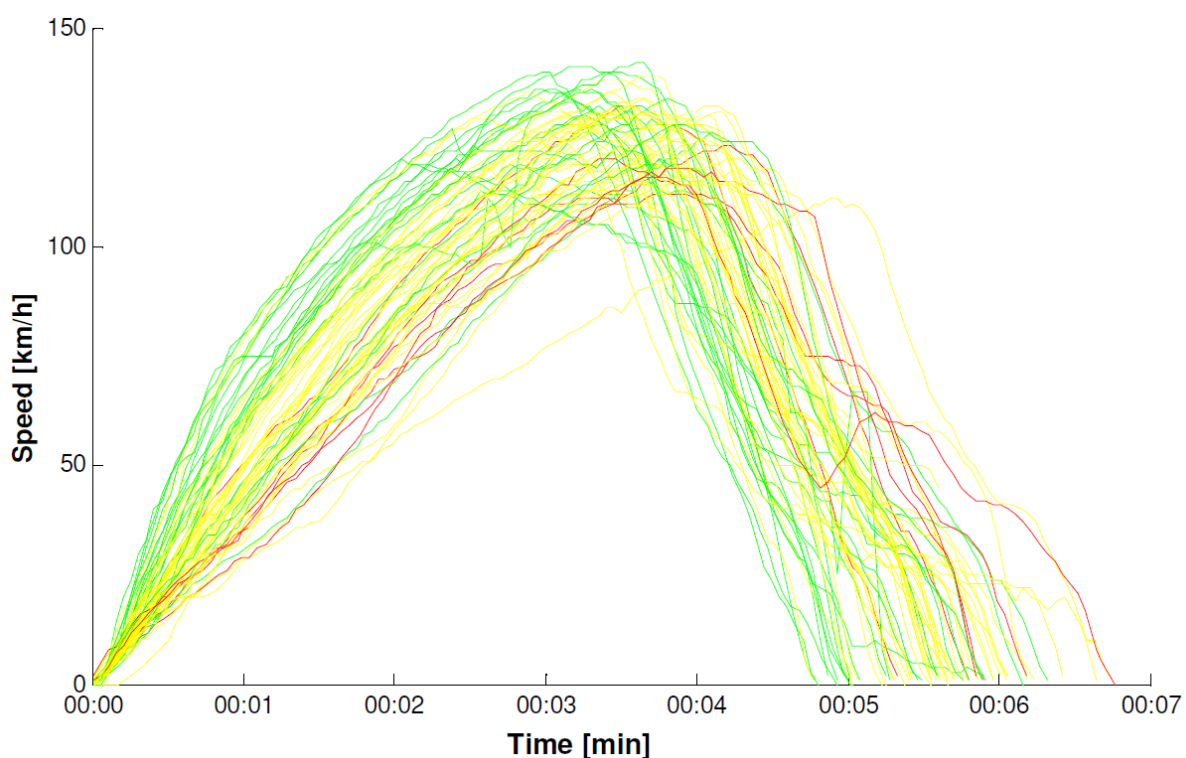


**Figure 19:** Distribution of braking ratio for Swedish freight trains (Lukaszewicz, 2001)

This distribution shows some positive skew. The mean value of 0.35 corresponds to a braking effort that provides a deceleration of approximately  $0.32 \text{ m/s}^2$ . However, the brake application and release times (around ten seconds and thirty seconds respectively for a braking ratio of 0.35) mean that the average deceleration over the full length of the braking phase would be lower, with the exact value depending on the duration of the braking phase, track gradient and resistance to motion of the complete train.

An alternative methodology was proposed by Bešinović *et al.* (2013), where speed profiles and driving strategy are approximated from signalling section occupation data and rolling stock characteristics. Although the results are less accurate than direct measurement, it does remove the need to instrument rolling stock, and provides large data sets where signalling data can be made available. A case study was carried out on the Rotterdam-Delft corridor in the Netherlands with a VIRM intercity electric multiple unit (EMU). During the accelerating phase, drivers appeared to set the throttle close to or at the maximum level at higher speeds, and at a somewhat lower level at slow speeds. The line in question is very busy by comparison with freight lines in rural Sweden, and as a result the timetable required drivers to cruise at close to the line speed limit with little opportunity for coasting. The distribution of deceleration due to braking ranged from 0.17 to 0.75 m/s<sup>2</sup> with a most probable value of 0.26 m/s<sup>2</sup>. This value is less than half of the 0.66 m/s<sup>2</sup> assumed by NS (Dutch Railways) for timetabling purposes. The effect of this assumption is an error of around forty seconds in a ten-minute journey, which illustrates the potential sensitivity of simulation models to input data that describes driving style.

These results can be compared with another Dutch study carried out by van Steenis (2010), which analysed data gathered directly from instrumented VIRM EMUs on a different set of routes. Some speed profiles measured in November 2008 are illustrated in Figure 20, with the yellow and red profiles indicating low or very low adhesion conditions.



**Figure 20:** Measured VIRM EMU speed profiles (van Steenis, 2010)

The results of the study confirmed that VIRM drivers generally do not set the throttle to the maximum value at the start of the accelerating phase, but tend to increase it progressively to the maximum value as train speed increases. Low adhesion conditions reduce the maximum tractive effort that can be transmitted at the wheel/rail interface, resulting in lower acceleration, and potentially extending journey times. The station spacing on the routes studied was rather shorter than the Rotterdam-Delft corridor, and as a result there was little or no cruising, and relatively short periods of coasting between the accelerating and braking phases. The profiles in Figure 20 do show that the amount of coasting does vary significantly between individual runs however. The average deceleration due to braking (not including the resistance to motion) was  $0.32 \text{ m/s}^2$ , with a similar positively skewed distribution to that already reported.

The study also provides some illustrative examples of increases in journey time due to low adhesion conditions. It found that the accelerating phase had the greatest influence on this increase, as the adhesion demands while accelerating are higher: only 25% of the axles on the train are powered, but all are braked. One of the important findings was that drivers tend to use significantly lower braking efforts than the design maximum of the train at all times, but the choice of tractive effort varied in response to actual adhesion conditions. These findings can be observed directly in Figure 20, as the different colour lines tend to diverge during the acceleration phase, but appear to be largely parallel during the braking phase.

A third possible source for driving style data is the design of an ATO system, and the example of the London Underground Central Line ATO was described by Rowe (2009). This is designed to maximise the capacity of the line, and so the ATO aims to use the maximum acceleration and deceleration values possible. The trains have all axles motored, and maximum acceleration is  $1.3 \text{ m/s}^2$ , which requires an adhesion level of around 0.15. Around a third of the line is underground, and the target deceleration values during braking are  $1.15 \text{ m/s}^2$  in tunnels and  $0.75 \text{ m/s}^2$  when running above-ground, requiring adhesion values of around 0.13 and 0.09 respectively. During low adhesion conditions, which are typically a result of leaf fall in the autumn, a reduced target deceleration of  $0.55 \text{ m/s}^2$  was found to be necessary on the open air sections to reduce the risk of station and signal overruns or wheelset damage.

Some limited driving style data for trains in Great Britain can also be derived from two reports written for the Department for Transport. A study into rail freight emissions by AECOM (Clarke and van Kalles, 2011) measured the time spent in each throttle notch by different drivers on a given journey with a Class 66 diesel locomotive hauling an intermodal

train. On average, 37% of the complete journey time was spent in idle, 20% in one of the intermediate notches (1 to 7), and 43% at full throttle (notch 8). This suggests that drivers predominantly use notch 8 during the acceleration phase.

A report by Ricardo and TRL (Bower *et al.*, 2012) included similar data for a Class 159 diesel multiple unit (DMU), and some example speed profiles. Two different duty cycles were considered: an intercity service between London Waterloo and Salisbury with few stops and long periods of cruising at a maximum speed of 90 mph, and a local service between Salisbury and Exeter St. David's with more frequent station stops. The intercity service has eight stops in 83 miles, with an average speed of 61 mph; the local service has thirteen stops in 89 miles, with an average speed of 54 mph. For the intercity duty cycle, 23% of the journey time was spent at idle, 33% at an intermediate notch (1 to 6), and 44% at full throttle (notch 7). By comparison, the figures for the local duty cycle were 39%, 11% and 49% respectively. Based on the stopping patterns and speed profiles, it can be inferred that drivers generally use notch 7 for the majority of the accelerating phase, and lower notches for cruising. Little coasting was observed, and insufficient data were available to draw conclusions about braking.

It can therefore be concluded from the literature that drivers generally aim to use the maximum tractive effort available for the majority of the accelerating phase, but significantly lower braking efforts than can be achieved. This is consistent with the use of defensive driving strategies, which aim to minimise the risks associated with low adhesion conditions. The consequences of low adhesion are less severe when accelerating compared to braking: the former typically only results in an extension in journey time, whereas the latter increases the risk of station overruns, SPADs (signals passed at danger) or even collisions, and wheel slide is usually more damaging to trains and infrastructure than wheel spin (*Managing Low Adhesion*, 2004). The choice between the amounts of cruising and coasting is generally constrained by a combination of the timetable and the choice of effort demanded during the accelerating and braking phases.

The experimental work described in this chapter is therefore focused on measuring the decelerations actually achieved by different trains when braking, to compare against the capabilities of the rolling stock in question. Data collection was carried out throughout the autumn, where wheel/rail adhesion is typically lowest, so that the results reflect the limitations imposed by adhesion on the achievable year-round performance of current railway networks.

### 4.3. Experimental Methods

#### 4.3.1. Outline

Analysis of measured speed-time profiles was adopted to provide the best possible accuracy out of the various methods outlined in Section 4.2. The speed profiles required for investigations of this nature are not always readily available however, and different methods of data collection were required for this study: gathering data directly from vehicle odometry, GPS and video analysis. These are described further in Sections 4.3.2 to 4.3.4. Train running data from timetable and signalling systems, as well as infrastructure details such as line speed limits and the distance between stations, were also used for validation.

The braking phases were identified within each of the speed profiles obtained, which provided a total of 283 individual braking phases for analysis. The average deceleration for each braking phase was then estimated from the change in speed over the full duration of that phase. This method therefore includes braking effort, resistance to motion and the influence of gradients. Section 4.5.1 illustrates this process in more detail.

#### 4.3.2. Vehicle odometry

The most accurate source of speed profiles for individual trains is direct measurement by on-board equipment that interfaces with the traction system. Two different sets of data were collected; the first set was derived from the On Train Monitoring Recorder (OTMR) data from Class 158 DMUs during November 2015. Secondly, some of the Tyne and Wear Metro rolling stock has been fitted with energy meters that also record train speed, and speed profile data from September to November 2012 was extracted from data provided by the operator. Figure 21 illustrates an example speed profile from the Tyne and Wear Metrocar data set.

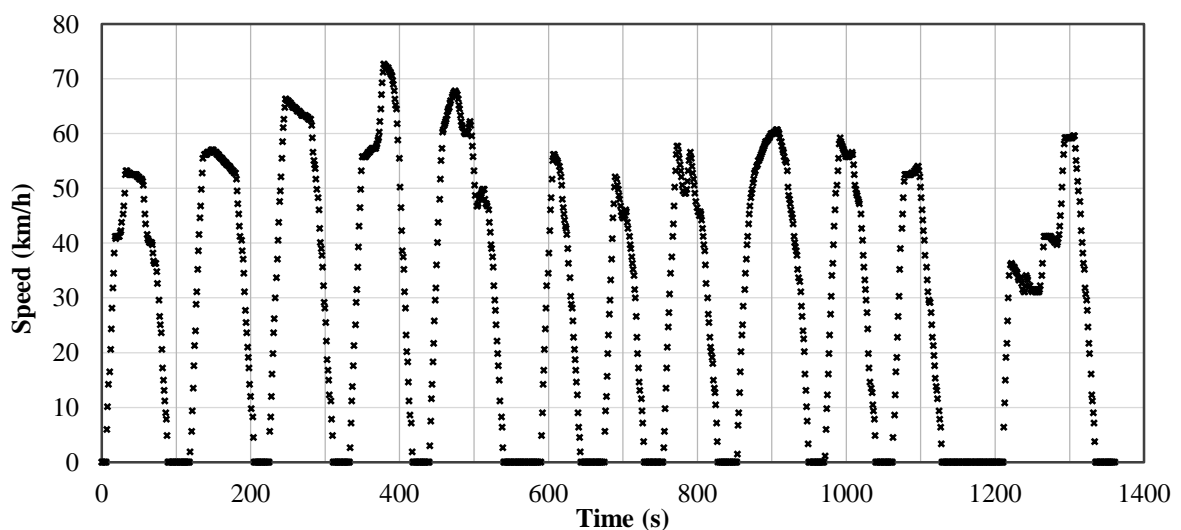


Figure 21: Example speed profile from vehicle odometry

### 4.3.3. GPS data

An alternative method is the use of a GPS device to record the location of the train at a particular time, and subsequently derive the speed profile. For this study, a number of different journeys were measured directly as a passenger with a handheld GPS device between September and November 2014. Data sets were obtained from Class 43 diesel locomotives with Mark 3 coaches, Class 91 electric locomotives with Mark 4 coaches, and Class 142, 156, 180 and 185 DMUs. Figure 22 illustrates the data from a service on the East Coast Main Line as an example.

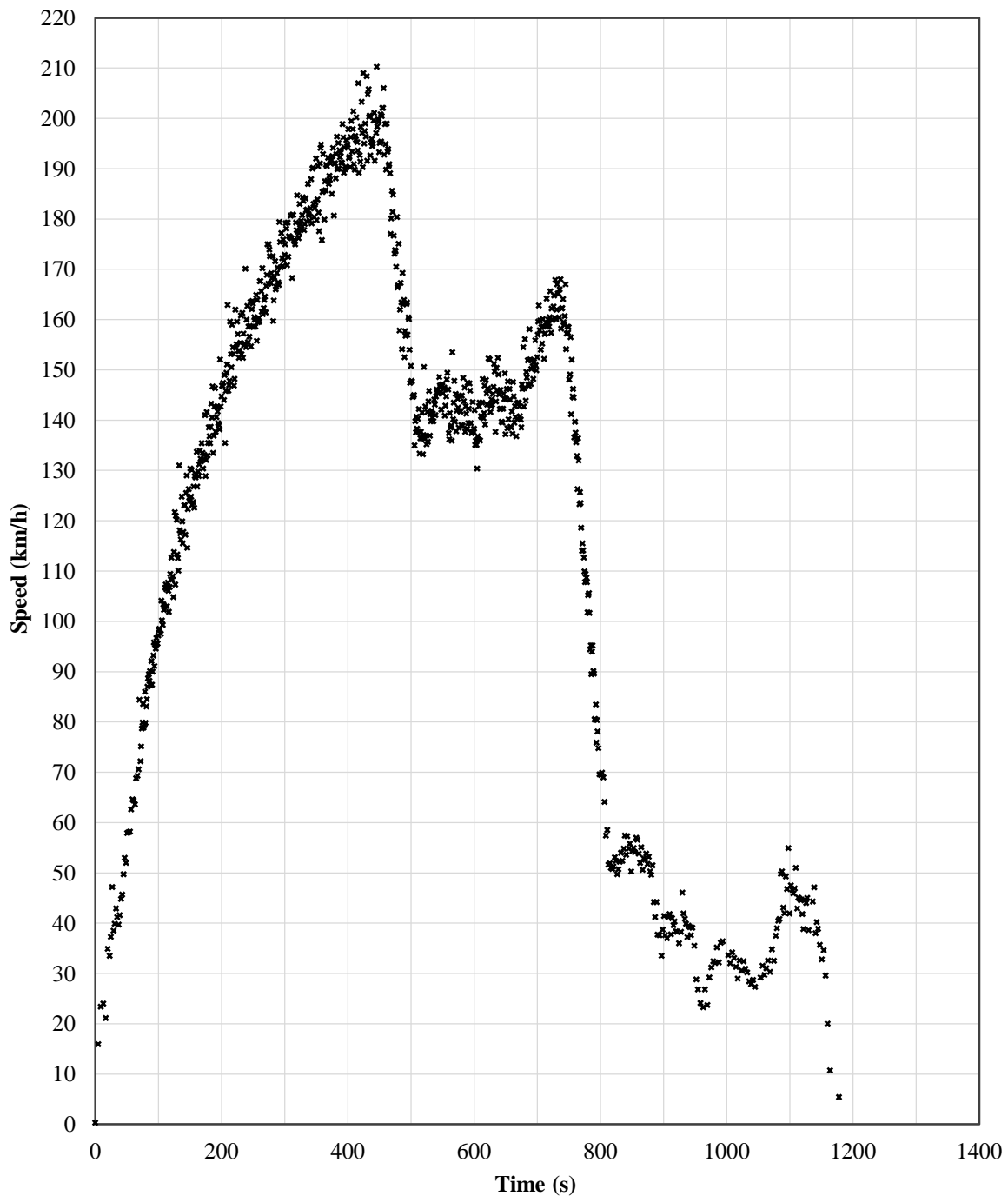


Figure 22: Example speed profile from GPS data



It can be seen by comparison with Figure 21 that speed measurements derived from GPS data have a higher degree of scatter than data collected from on-board odometry. The GPS device also recorded a data point once a fixed distance had elapsed from the last data point, rather than the fixed time interval of the odometry data.

#### 4.3.4. Video analysis

Finally, a third option is to analyse in-cab video from a forward facing camera, to derive a distance-time profile using junctions, station platforms, level crossings, signals, bridges and other such infrastructure features as reference points. The average speed between two adjacent features can then be calculated to derive a speed-time profile. A number of freight trains hauled by Class 66 diesel locomotives were analysed for this study, based on route learning videos available, and an example profile derived from one journey is illustrated in Figure 23.

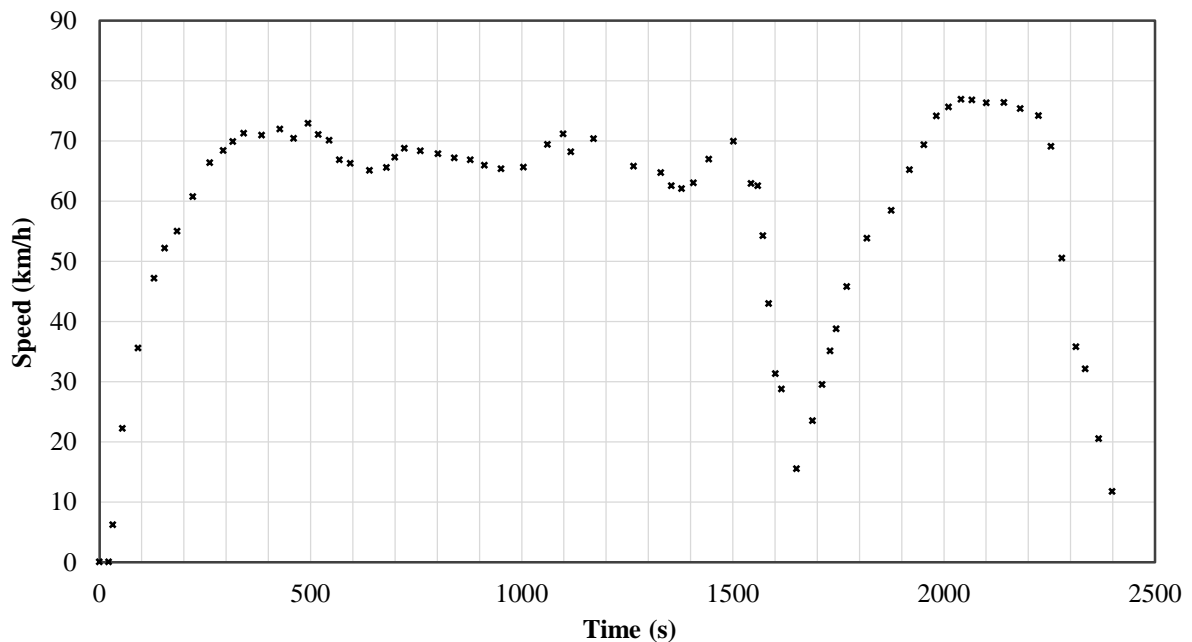


Figure 23: Example speed profile from video analysis

The sampling frequency for video analysis using this method is considerably lower than vehicle odometry or GPS. The number of suitable videos available was also rather limited, and as a result journeys from all year round were analysed, although this did include several recorded during the autumn. The trains investigated for this study included laden bulk cargo trains, empty bulk cargo trains, and intermodal trains with a mixture of empty, laden and part-laden wagons.

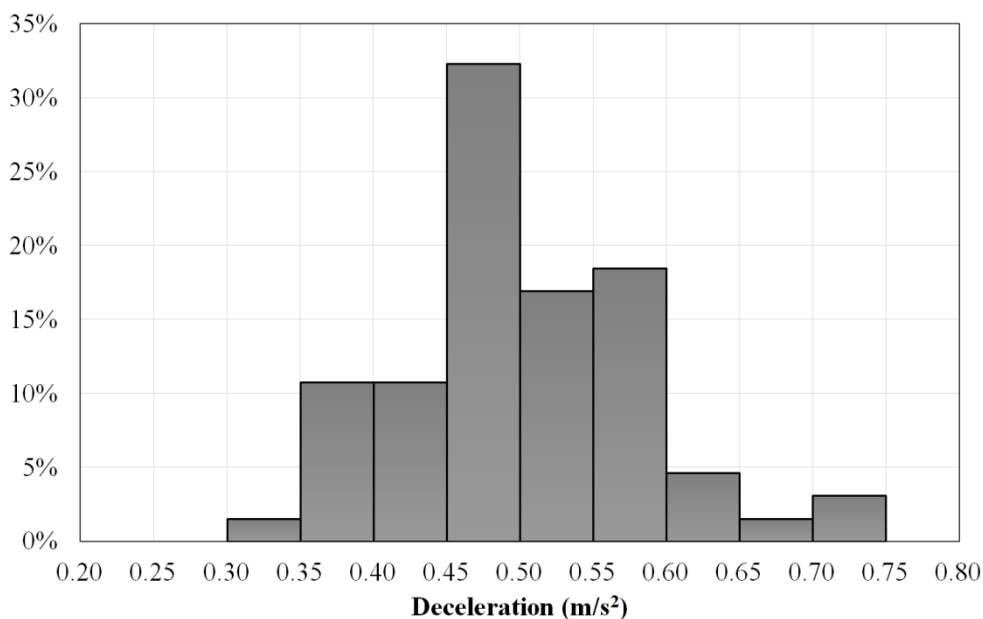
#### 4.4. Results

Table 1 summarises the mean, standard error of the mean (SE) and the range of the decelerations estimated by the three methods. The train services were broadly classified into four different service types: initially split into passenger and freight, the passenger services were then subdivided into metro, regional and intercity. Intercity services were nominally defined as those with maximum speeds of 100 mph (161 km/h) or more and tens of kilometres between stops. The maximum speeds of regional services are lower: typically 90 mph (145 km/h) or less, with more frequent station stops. Metro station spacing in urban rail networks is even closer; typically a few hundred metres to a few kilometres, and consequently speeds are lower still.

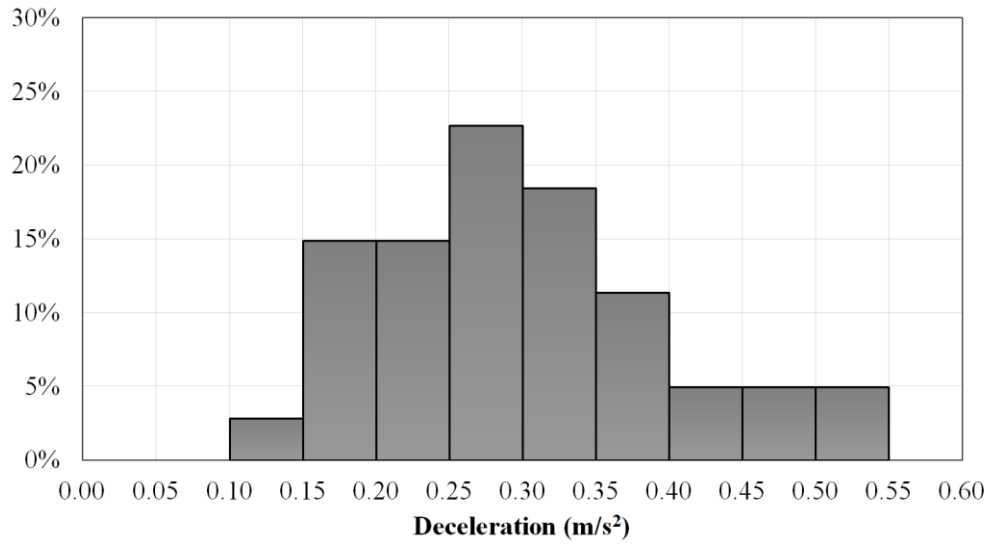
	Deceleration (m/s <sup>2</sup> )			Total braking phases analysed
	Mean	SE	Range	
<b>Metro</b>	0.50	0.010	0.35 - 0.73	65
<b>Regional</b>	0.29	0.008	0.11 - 0.55	141
<b>Intercity</b>	0.31	0.011	0.13 - 0.51	55
<b>Freight</b>	0.12	0.007	0.08 - 0.19	22

**Table 1:** Summary of measured decelerations

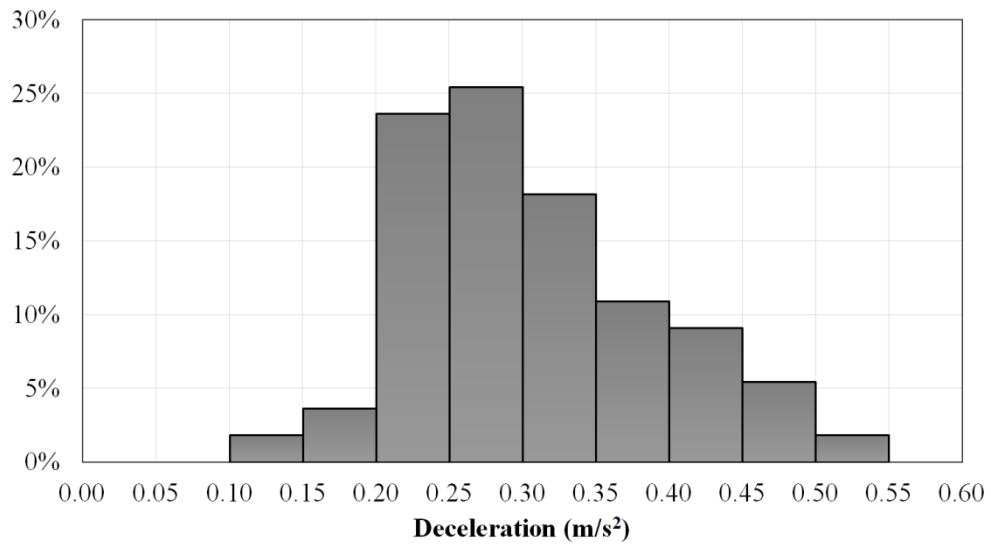
The distributions of the measured decelerations achieved are illustrated by Figure 24 to Figure 27 for the four service types.



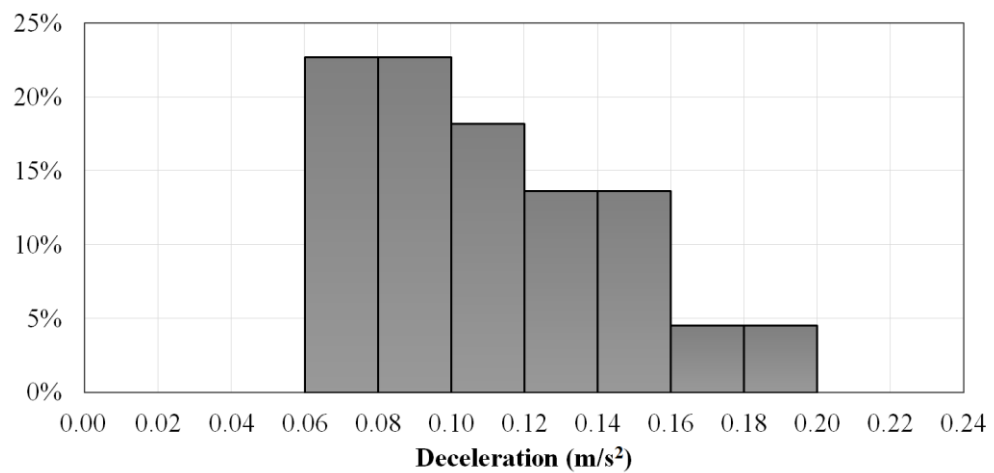
**Figure 24:** Metro deceleration distribution



**Figure 25.** Regional passenger train deceleration distribution



**Figure 26:** Intercity passenger train deceleration distribution

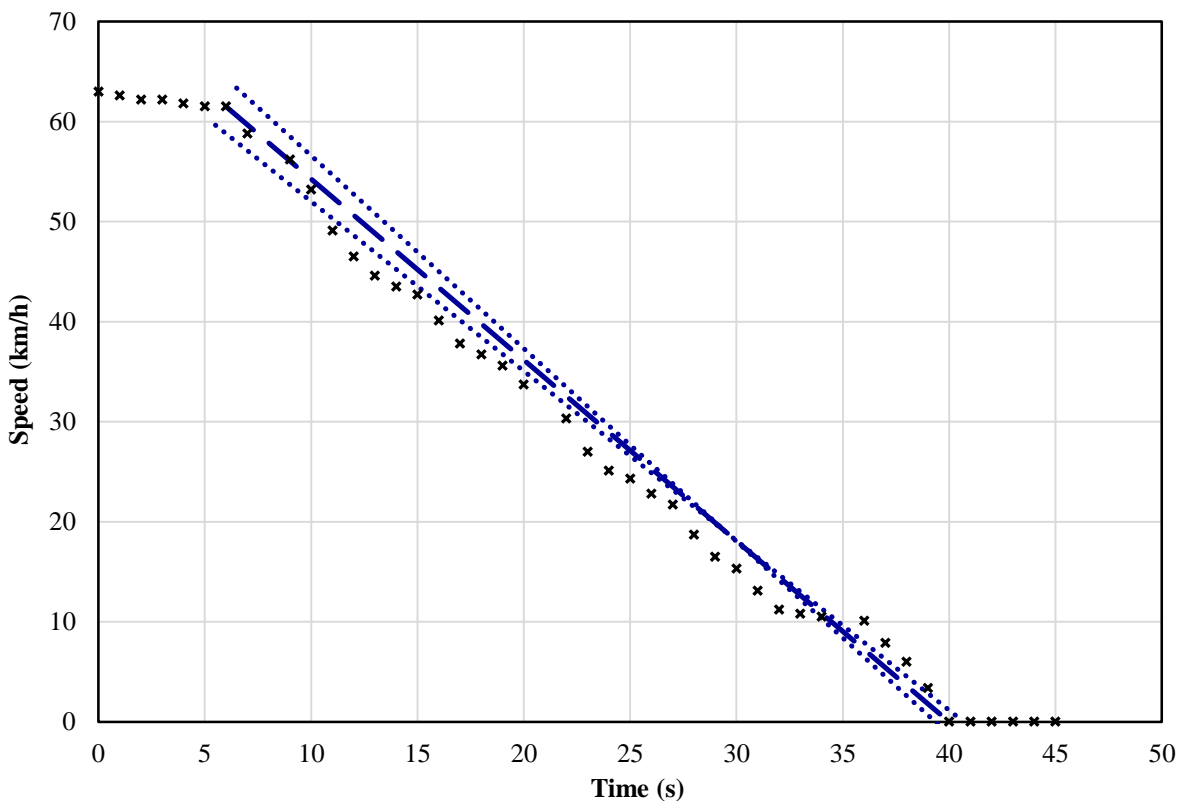


**Figure 27:** Freight train deceleration distribution

## 4.5. Discussion

### 4.5.1. Accuracy

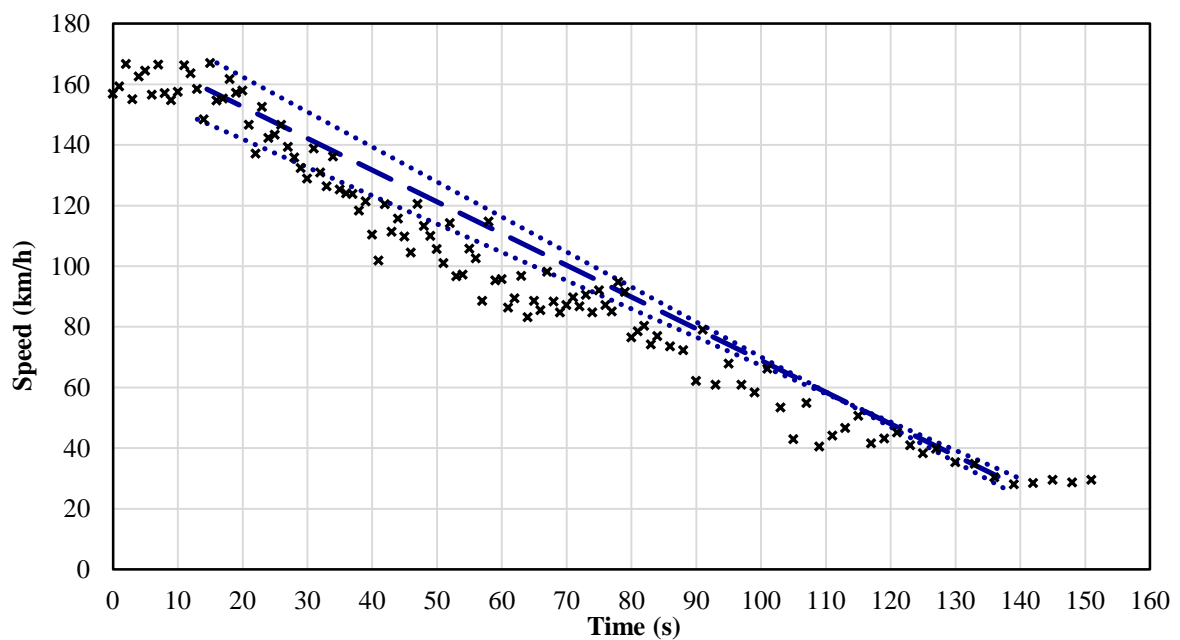
The total distance for journeys measured by the on-board odometry was compared to the value given by the infrastructure specifications to provide a measure of the accuracy. For the data in this study, the two values were within 3% of each other. The sample rate was approximately once per second, also with a one second resolution. Figure 28 illustrates the influence of these experimental uncertainties on the method outlined in Section 4.3.1. The example used was chosen as a reasonably representative example of a braking phase measured by vehicle odometry: the duration of this braking phase and the measured deceleration are both close to the overall average for the service type.



**Figure 28:** Accuracy of vehicle odometry data

The heavy dashed line is the deceleration measurement estimated from this braking phase:  $0.50 \text{ m/s}^2$ . It represents the average deceleration over the entire phase, rather than attempting to follow the exact speed profile as the braking effort is varied by the driver, and therefore does not necessarily pass through all of the measured data points between the start and end of the phase. The dotted lines represent extreme estimates of the minimum ( $0.47 \text{ m/s}^2$ ) and maximum ( $0.54 \text{ m/s}^2$ ) possible deceleration values for this phase, based on the worst case of  $0.5 \text{ s}$  error in the time measurement and 3% error in speed measurement.

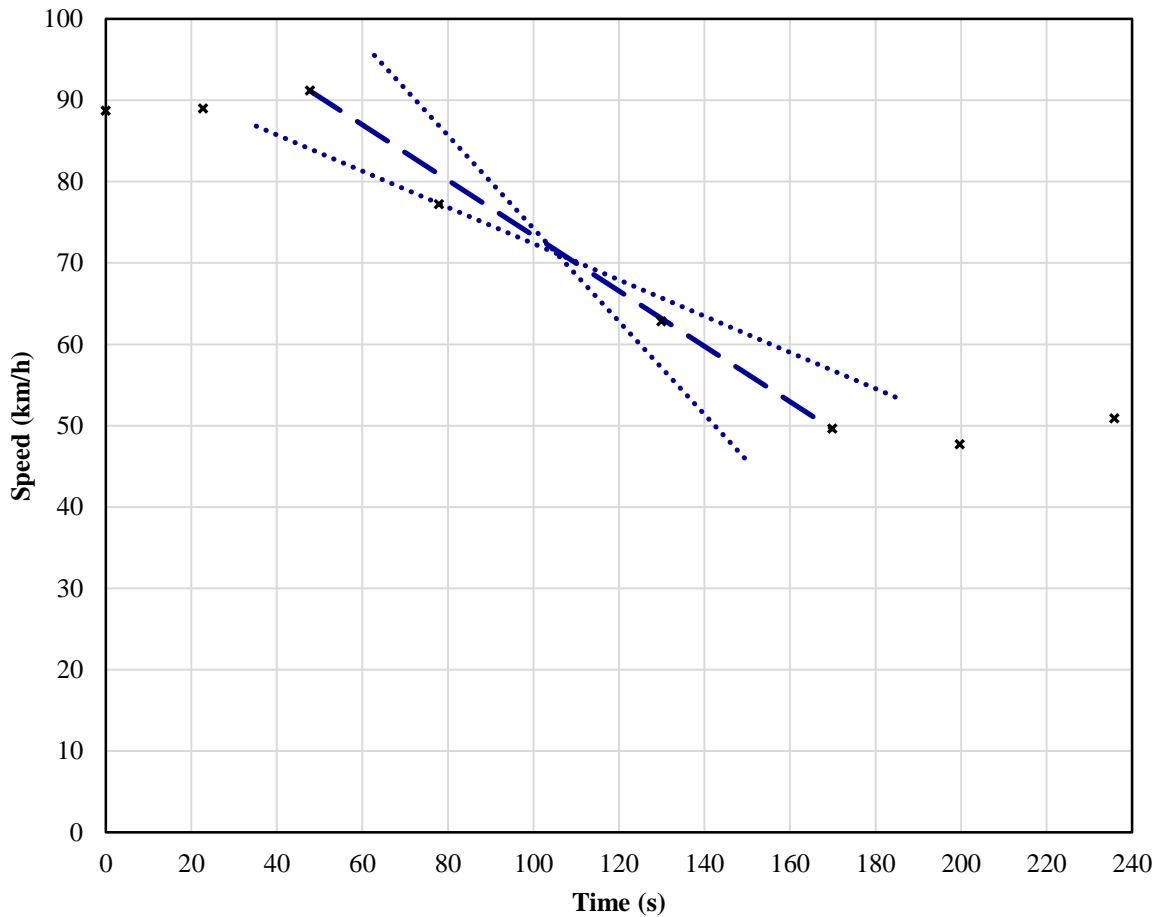
Figure 22 demonstrates that the GPS data has a greater scatter in the speed profile than the odometry data, and this scatter allows the uncertainty in speed to be estimated directly. It does however tend to make it more difficult to define exactly where individual braking phases start and finish. As the data was sampled by distance rather than time, the resolution is generally better at higher speeds. This has the effect of smoothing out some of the scatter at lower speeds, but means that few data points were collected at very low speed. Figure 29 illustrates an example of the accuracy for GPS data, again aiming to use a reasonably representative case. As before, the dashed line indicated the estimated average deceleration for this phase ( $0.29 \text{ m/s}^2$ ), and the dotted lines the minimum ( $0.26 \text{ m/s}^2$ ) and maximum ( $0.32 \text{ m/s}^2$ ) estimates.



**Figure 29:** Accuracy of GPS data

The sample rate of the video analysis data was much lower, and depended on the presence of suitable infrastructure features to use as reference points. The location of these features was derived from a combination of infrastructure specifications and measurements of aerial photographs. The cumulative distance measured along the complete route using aerial photographs matched the infrastructure specifications to within 2%. However, the positional accuracy of individual features varies where aerial photographs are stitched together, and an accuracy of 20 m was used as a reasonable estimate for the potential errors (Ubukawa, 2013). This fixed measurement error has a significantly greater influence on shorter distances between infrastructure reference points. The number of reference points (and hence the sample rate) is therefore a compromise between measuring a sufficient number of data points, the number of suitable infrastructure features and the distance between each data point. The video could be viewed frame-by-frame, and the frame rate of the videos was high enough for

errors in time measurement to be negligible by comparison with location errors. Comparing the derived speed profiles against infrastructure specifications for the routes in question suggested that the speeds derived were reasonable, although significant uncertainty remained about the exact timing of the transitions between different phases.



**Figure 30:** Accuracy of video analysis data

Figure 30 illustrates an example, with a measured deceleration estimated to be  $0.09 \text{ m/s}^2$ , a minimum of  $0.06 \text{ m/s}^2$  and maximum of  $0.16 \text{ m/s}^2$ . As may be expected, this level of uncertainty is rather higher than the odometry and GPS cases.

The deceleration measurements derived using this method are influenced by track gradients. Correcting individual deceleration values to account for the gradient at the location that they were measured indicated that a sufficient number of measurements were taken for the uphill and downhill gradients in the results to roughly balance each other out, and the overall effect on the mean decelerations and ranges for each of the four service groups was small by comparison with the experimental uncertainties. In addition, it is the actual decelerations (rather than the resistance to motion and braking effort) of individual trains that is of interest for determining train movements and railway system capacity.

#### ***4.5.2. Interpretation***

The average deceleration achieved by the freight trains in the study is significantly lower than the passenger service types; the difference is several times larger than the typical experimental uncertainties derived in Section 4.5.1. This result is likely to be partly due to the brake application and release times referred to previously, and the need to manage in-train forces to within acceptable limits.

The average decelerations achieved by regional and intercity passenger services are similar at around  $0.3 \text{ m/s}^2$ , in good agreement with the findings from the literature. The maxima of around  $0.55 \text{ m/s}^2$  are significantly lower than achievable from a full service brake application, which would result in decelerations approaching  $0.9 \text{ m/s}^2$  (a full service brake application is where the design maximum brake effort is applied). Although the typical operating speeds of intercity and regional services are different, the deceleration due to the resistance to motion of the trains hauled by Class 91s or Class 43s at their maximum operating speed of 200 km/h is nevertheless similar to that of Class 142 and 156 DMUs at their maximum of 120 km/h (Swift et al., 1990). For comparison, resistance to motion represents a maximum contribution of around  $0.09 \text{ m/s}^2$ , reducing as a quadratic function of speed.

The average deceleration measured on the Tyne and Wear Metro is higher at  $0.50 \text{ m/s}^2$ , with minimum and maximum values also around  $0.2 \text{ m/s}^2$  higher than the intercity and regional cases. This is also below a full service brake application of around  $1.1 \text{ m/s}^2$ . The Tyne and Wear Metro shares tracks with heavy rail services between Newcastle and Sunderland, and around a third of the metro, regional and freight results were gathered on this route. The typical experimental uncertainties for passenger services are lower than those for the freight services, and are small enough for these conclusions to remain valid.

Figure 24 to Figure 27 display positively skewed distributions, which are a good match to the distributions found within the literature. In each case, the magnitude of the range is also large relative to the magnitude of the mean values. The largest measured values are also rather lower than the design maxima for the rolling stock. Examining the variation of the instantaneous (rather than average) deceleration value within individual speed profiles suggests that the positive skew is a result of a conscious decision by drivers to target the lower deceleration values. If the contribution from resistance to motion and gradients is subtracted from the deceleration values measured, to give a measure of braking effort demanded rather than deceleration achieved, this result (and the positive skew) does not change. These findings are consistent with the use of defensive driving.

## 4.6. Conclusions

Drivers generally aim to use the maximum tractive effort available while accelerating. Low adhesion conditions reduce the effort available, but over the course of an entire year the effects on the running times of all services is relatively small. By contrast, the general adoption of defensive driving strategies when braking means that drivers tend to use significantly lower braking efforts than the design maxima at all times, rather than exclusively when low adhesion conditions are present. The difference between the measured data and assumptions for timetabling by NS raise the possibility that the potential reduction of capacity from the adoption of defensive driving in recent years has not necessarily been accounted for. The use of cruising and coasting varies between individual train services, but is ultimately determined by the efforts actually achieved during acceleration and braking, along with the journey time constraints of the timetable.

The experiments outlined in this chapter investigated braking in more detail. The measured mean values for the decelerations actually achieved by different trains in service were found to be considerably lower than the maximum values measured in the data, which in turn were lower than the designed maxima of the rolling stock. The distributions of the measured values were positively skewed. These results are consistent with existing research in the literature, and can be used as input data for improving the accuracy of multi-train simulation models.

The mean, range and maximum instantaneous values of decelerations observed were highest for urban metro services, including on routes where the track is shared with heavy rail passenger and freight services. This supports the findings in Section 2.3 and 4.2 that the trade-off between system capacity, risk of wheel slip and passenger comfort is different for different service types. It also suggests that adhesion may not be the most critical constraint on the average decelerations achieved by freight trains.

Chapter 2 indicated that a principal benefit of linear motor technology is to increase the deceleration achieved during braking, although it was noted that it must remain acceptable to passengers. Therefore, it is proposed that a suitable target for application of the technology would be to allow drivers to consistently brake at the top end of the ranges of deceleration values measured in this experiment, without increasing the adhesion demand above that for the current measured average decelerations. This could potentially provide an increase in system capacity, while still respecting existing defensive driving requirements and in-train force constraints.



## CHAPTER 5. MODELLING TRAIN MOVEMENTS

### 5.1. Introduction

This chapter describes the development of multi-train simulation models of a number of different real life railway networks. The aim is to simulate train movements and interactions with sufficient accuracy to allow the effect of different linear motor technologies on capacity and energy consumption to be compared and analysed.

Chapter 3 stated that potential case studies should include a variety of infrastructure and train service characteristics between them, to test potential applications of linear motor technology in a variety of different applications. Ideally, the railway networks in the case studies would also be busy enough that more capacity would be desirable. Detailed specifications and information about current operations should also be available, to allow an accurate simulation model to be built.

Three different representative case studies were chosen that met these requirements:

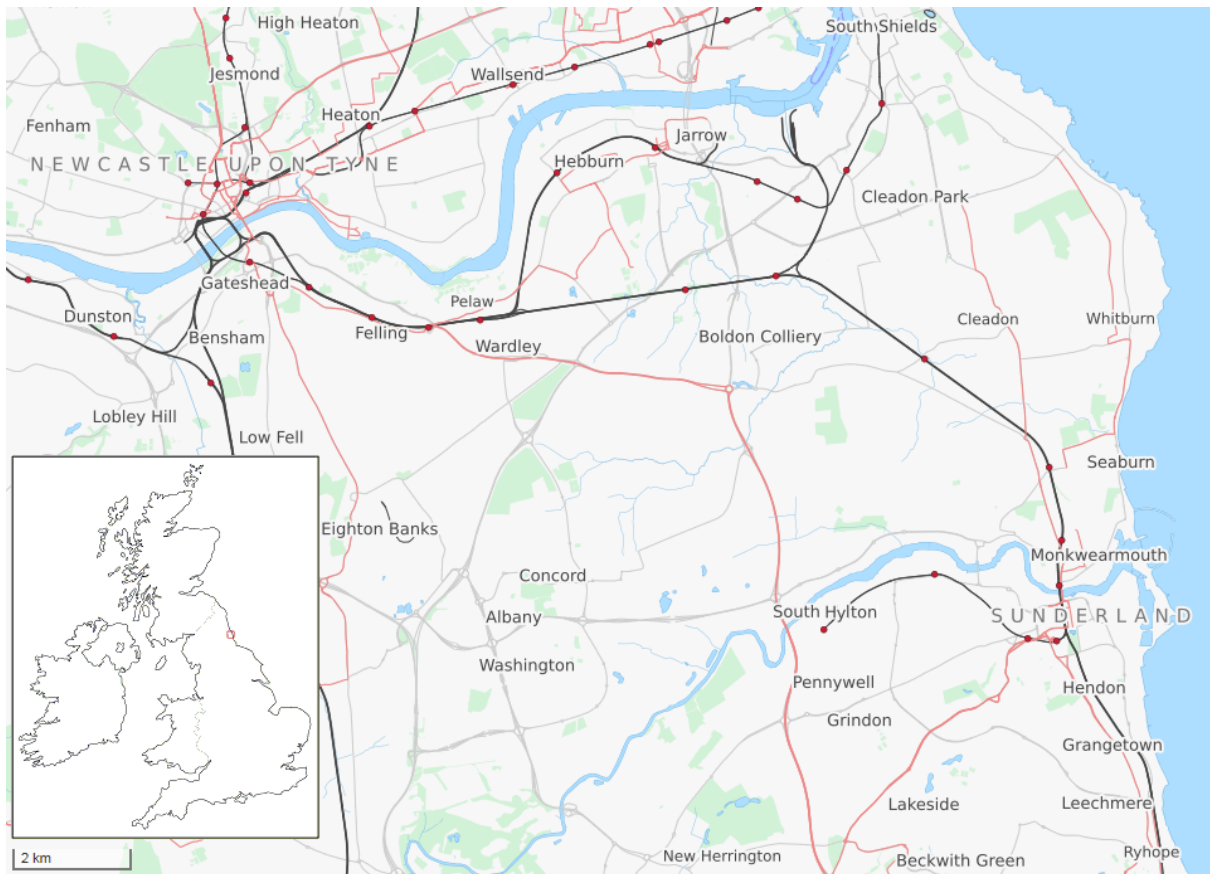
- **Case study 1 – Tyne and Wear:** the first case study is intended to examine the influence of linear motor technology on both metro/suburban and mixed traffic railway operation in urban areas.
- **Case study 2 – Swindon:** the second case study considers intercity services running at higher speeds (up to 200 km/h), alongside local and freight services within a larger railway network.
- **Case study 3 – Highland Main Line:** the third case study looks at a more rural railway with a mix of regional, intercity and freight traffic, where large sections of single-track infrastructure provide a different set of operational constraints.

A more detailed description of each case study is given in Section 5.2. The remainder of the chapter details the methods used to develop the multi-train simulation models of each case study, and the results of the validation of these models.

## 5.2. Case Studies

### 5.2.1. Tyne and Wear

The first case study is based on the section of the railway between Newcastle upon Tyne and Sunderland in the north-east of England, illustrated in Figure 31.



**Figure 31:** Newcastle upon Tyne – Sunderland railway corridor

The main railway between Newcastle and Sunderland was opened as part of the Brandling Junction Railway between Gateshead and Monkwearmouth in 1839, although the area already had a number of wagonways running from collieries to staithes on the River Tyne or River Wear. Further passenger and freight lines were opened in subsequent decades to build up a substantial network, but most of the lines were closed and demolished during the twentieth century with the decline of the coal industry. The line from Pelaw to South Shields (via Hebburn) was converted to form part of the Tyne and Wear Metro in the early 1980s, including overhead electrification at 1500 V DC. In 2002 the Metro was extended from Pelaw to South Hylton (including extension of the overhead electrification to this section), sharing tracks with the heavy rail services between Pelaw and Sunderland. The route therefore now carries a mixture of Metro, regional and intercity passenger traffic, and a number of different freight flows.

The double-track main-line route from Newcastle Central station meets the Metro route (which runs in a separate tunnel under Newcastle city centre) at Gateshead Stadium, and they run in parallel as a quadruple-track railway to Pelaw. There are goods loops on the main line here, and sidings on the Metro lines for terminating trains. After Pelaw, the Metro diverges from the South Shields route across a flat junction, and joins the main line via a flying junction (Pelaw Metro Junction). There are also flat junctions on the main line for the disused line through Wardley and the single line to the oil terminal at Jarrow. This freight-only line runs parallel to the Metro route to South Shields, but there is no connection between them. The line to Sunderland is then double track, with the line to the freight terminals at Tyne Dock diverging at single-track flat junctions (Boldon East Junction and Boldon West Junction), forming a triangle at Boldon North Junction. This line runs under the Metro route to South Shields in a short tunnel, and there is no longer a connection between them. At Sunderland South Junction, there is another flat junction where the Metro line to South Hylton and the main line to the south diverge. The whole route is currently operated as track circuit block, with four-aspect colour light signalling.

The double-track section between Pelaw Metro Junction and Sunderland South Junction is the focus of this case study. This is effectively bordered by quadruple-track sections at either end, and contains the single-line flat junctions for the line to Tyne Dock. As such, this section is the most likely to constrain the capacity of the overall route. To model train behaviour immediately adjacent to the section under consideration, the boundaries of the case study were chosen to be Heworth in the west (between Pelaw and Felling), Green Lane Junction on the Tyne Dock branch, South Hylton, and Ryhope Junction to the south. The case study therefore includes mixed-traffic, freight-only and Metro-only sections.

The Tyne and Wear Metro runs five trains per hour per direction through the day on this section, reducing to four early in the morning and late at night. These are operated by a fleet of 90 twin-section articulated Metrocars, built for the system's opening in 1980, which typically run in pairs. Statistics published by the UK Department for Transport (2014) give the average loading on the Metro as 54 passengers per train.

Northern Rail operate an hourly regional passenger service on the route, with an additional service in the morning and evening peaks, using a mixture of Class 142 and Class 156 DMUs. At the time of writing, the Class 142 units are anticipated be withdrawn in the next few years, and so the Class 156 units were modelled for the case study. Specific passenger numbers for the journey between Sunderland and Newcastle were not available, and are therefore assumed to be the same as the Metrocar loadings.

Grand Central operates five intercity passenger services per day between Sunderland and London. Although these run south from Sunderland via the Durham Coast line, the first two up trains of the day run empty from Heaton depot (in Newcastle) to Sunderland, and vice versa for the last two down trains. The three remaining services during the day run empty from Sunderland to either Pelaw Goods Loops or Ryhope Junction and back, due to a lack of space for stabling at Sunderland station in the time between arrival from, and return to, London. Passenger numbers are of the order of 10,000 per week, and so an average of 147 per train was assumed. These services are operated interchangeably with either a pair of Class 43 diesel-electric locomotives operating in push-pull mode with Mark 3 coaches (otherwise known as an HST set) or Class 180 DMUs. Given that the Class 180 traction system is very similar to the Class 156, albeit with a more powerful engine and higher rated transmission, the HST was chosen for the case study so that it could illustrate the effects of linear motor technology on a greater variety of rolling stock. At the end of 2015, after the modelling had been completed, Virgin started operating one return HST service per day between Sunderland and London, running via Newcastle rather than the Durham Coast.

There are occasional freight trains carrying cement or spent nuclear fuel running over the route, but the majority of the freight trains carry imported coal or biomass from Tyne Dock to power stations across the north of England, joining the route at the junctions around the former Boldon Colliery and running via either Sunderland or Newcastle. These are hauled by Class 66 diesel-electric locomotives, with most trains operated by GBRf. The Tyne Dock services were used for the case study, as there are one or two trains per hour, compared to less than one train per day for cement or nuclear trains.

### ***5.2.2. Swindon***

The second case study is of a set of routes converging on Swindon, located on the Great Western Main Line in the south-west of England. The area is illustrated in Figure 32.

The railway through Swindon dates back to 1841, built as part of the original Great Western Railway (GWR) between London and Bristol (via Bath). Additional routes were added over the following decades, and Swindon became an important interchange station. The GWR also built its locomotive and carriage works there in 1843, although this was closed in 1986. Current services are a mixture of intercity and local passenger trains, as well as a variety of freight traffic. At the time of writing, the Great Western Main Line was undergoing extensive modernisation work, including electrification at 25 kV AC and eventual fitment of ETCS Level 2 signalling.



**Figure 32:** Railway routes around Swindon

The main line through Swindon and Chippenham towards Bristol (via Bath) is double track, with additional lines through Swindon station, including a flat junction for the line through Kemble (towards Cheltenham Spa). There is a flat junction at Wootton Bassett for the double-track line to Bristol (via Badminton), and another at Thingley Junction for the single line through Melksham (towards Westbury). The Cheltenham line was redoubled between Swindon and Kemble in 2014 as part of the route modernisation - the route was originally double track, but was singled between Kemble and Swindon in the 1960s. The 2013 layout was used in the case study, reflecting the infrastructure before the current modernisation programme. The signalling in the model is also the 2013 arrangements: track circuit block with a mixture of two-, three- and four-aspect colour light signals.

The boundaries of the case study approximate the area controlled by the former Swindon Panel signal box (which closed at the end of 2013). The eastern boundary is at Uffington, beyond which the line changes from double to predominantly quadruple track towards London. The other boundaries are at Kemble, Hullavington goods loops (on the Badminton line), the western portal of Box Tunnel (on the Bath line) and Bradford Junction (on the line towards Westbury). As for the first case study, the precise locations for the boundaries were

chosen with the aim of avoiding speed restrictions, steep gradients or likely capacity bottlenecks immediately outside the area boundary. The area modelled includes long stretches of line with speed limits significantly higher than the maximum speed of the freight and local passenger trains, as well as flat junctions with a variety of speed limits. These sections provide different types of capacity constraints to complement those modelled in the first case study.

There are four intercity trains per hour throughout the day on the route between London, Bristol and further west into South Wales and Devon/Cornwall (via both Bath and Badminton), and trains every two hours towards Cheltenham (via Kemble). The vast majority of these trains are operated by HST sets, with a few services operated by Class 180 DMUs, but HSTs were again chosen for the case study. There is also one overnight sleeper train in each direction per day (the Night Riviera), with a Class 57 locomotive hauling Mark 3 sleeper coaches. A Class 66 locomotive was substituted for the case study, because more data was available for this locomotive. Both are six-axle diesel-electric locomotives, the services are timed at a maximum speed of 75 mph, run during a quiet period during the night and overall represent less than one percent of the number of services in the case study. As such, the effects of this change are considered negligible.

There is also one local passenger train per hour that runs between Cheltenham Spa and Westbury, with some services extended further. This runs via Kemble and Melksham, and reverses direction at Swindon. This service is typically operated by Class 150 DMUs. Statistics for individual passenger train loading were not available, and the case study therefore assumed all intercity and local passenger trains to be at their defined laden weight.

The principal freight flows are intermodal and aggregate trains, although steel, coal and Ministry of Defence traffic is also present. Most of these trains run through the area, but some start or finish their journeys at Swindon Cocklebury sidings or the aggregates terminal at Wootton Bassett. The majority of the freight trains are hauled by Class 66 diesel-electric locomotives. Some of the heavier aggregates trains may be hauled by Class 59 locomotives (on which the Class 66 was based), which have a lower top speed but higher maximum tractive effort. Class 60 and Class 70 locomotives also occasionally feature. For the case study, the day chosen did not include the heaviest loaded aggregate trains timetabled, and so Class 66 locomotives were chosen as a representative locomotive for all of the freight trains.

### 5.2.3. Highland Main Line

The third case study is the Highland Main Line between Perth and Inverness in the north of Scotland, illustrated in Figure 33.



**Figure 33:** Highland Main Line between Perth and Inverness

The first direct line between Perth and Inverness was opened in 1863, but the present route was not completed until 1898, when the direct line between Aviemore and Inverness was opened by the Highland Railway (trains had previously run via Granttown on Spey and Forres). The Highland Railway owned the tracks as far as Stanley Junction, where it joined the Caledonian Railway line that ran between Perth and Aberdeen via Forfar. The line between Aviemore and Forres and the line between Forfar and Aberdeen were both closed in the 1960s, along with a number of minor branch lines. The section between Stanley Junction and Forfar was retained for occasional freight trains, but also closed in 1982. In 1978, a section of the former Aviemore to Forres line was reopened as a heritage line, the Strathspey Railway.

The complete route between Perth and Inverness was modelled for the case study, including the areas within the immediate vicinity of each station. The route is predominantly single track, with passing loops and sections of double track at Perth, between Blair Atholl and Dalwhinnie, and at Inverness. The route has severe gradients, climbing from sea level at Inverness to 401 m at Slochd Summit in a distance of 35 km, with a ruling gradient of 1 in 60. Druimuachdar Summit is also the highest point on the British main-line railway network at 452 m above sea level. The signalling is absolute block between Stanley Junction and Kingussie (tokenless block for the single line sections), and track circuit block elsewhere. Signals are a mixture of two- and three-aspect colour light signals and semaphore signals.

Most of the services are regional passenger trains, running between Inverness and either Glasgow or Edinburgh. These services mainly use three-coach Class 170 DMUs, although a few services use two-coach Class 158 DMUs instead. For the case study, all trains were assumed to be worked by Class 170 units. The Class 158 is relatively similar to the Class 156 already modelled, although with a higher power engine and a top speed of 90 instead of 75 mph, and a small increase in mass. The Class 170 is significantly heavier, as well as being more powerful again, with a top speed of 100 mph. As for the Swindon case study, the defined laden weight of the trains was assumed.

There are two intercity trains per day to London – an HST set to London King’s Cross via the East Coast Main Line during the day, and a sleeper train to London Euston via the West Coast Main Line overnight (the Caledonian Sleeper). At the time of writing, this train consisted of Mark 3 sleeper coaches hauled by a four-axle Class 67 diesel-electric locomotive. This was replaced in the case study by the newer Class 68 diesel-electric locomotive, which is a higher-powered development of the Class 67 design.

There is a daily intermodal freight train to Inverness that transports supermarket produce, and occasional other freight trains such as cement, pipelines or nuclear flasks. The intermodal train was modelled for the case study as the only regular working. It is typically hauled by either a Class 66 or Class 68 locomotive, and the Class 68 was chosen to provide a contrast with the Class 66-hauled freight trains in the other case studies.



## 5.3. Methods

### 5.3.1. Simulation tool

There are many existing multi-train simulation tools available that can simulate train movements within a railway network. A review of some of these tools was carried out by Barber *et al.* (2007). OpenTrack was one of the software packages within the review that was highlighted by Landex (2008) as suitable for assessing delays and timetable stability within a railway network, and as such was adopted to model the case studies for this thesis.

OpenTrack is a microscopic synchronous simulation tool using an object oriented programming language, intended to answer a variety of questions about railway operations. Originally developed as part of a doctoral thesis (Hürlimann, 2001), it was subsequently released as a commercial product. It simulates the behaviour and interactions of the elements of the railway (infrastructure, rolling stock and timetable) in a mixed continuous/discrete simulation process. The overall structure of the software is illustrated in Figure 34.

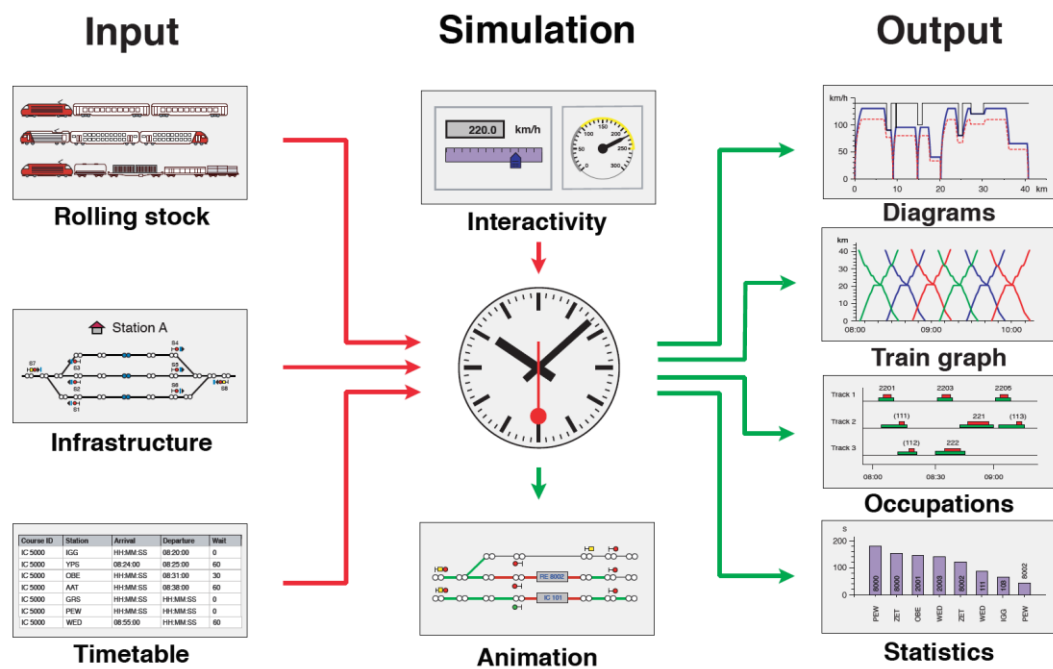


Figure 34: OpenTrack software elements (Nash and Hürlimann, 2004)

The modelling used OpenTrack version 1.7.5. Sections 5.4 to 5.6 describe the three principal inputs (rolling stock, infrastructure and timetable) for each of the three case studies in more detail.

### ***5.3.2. Verification and validation***

Chapter 3 highlighted that verification and validation of the output is essential when carrying out multi-train simulation. Although OpenTrack itself is an existing and proven product, the models of the three case studies are new, and therefore had to be checked to make sure the results are reasonably representative of reality. The case studies required a large amount of input data to describe the rolling stock, infrastructure and timetable, and a large number of published and unpublished sources were used, referenced in the following sections where possible. Some of the sources were not necessarily comprehensive, and a combination of sources and methods was sometimes necessary to describe a particular element. The sensitivity of detailed multi-train simulations to errors or inaccuracies in their input data further strengthens the requirement for verification and validation of the results.

Verification was carried out at two stages. Firstly, as part of the process of building the model, the input data was checked at intervals to look for data entry errors. Once the model was complete, the rolling stock, infrastructure and timetable data was then exported from OpenTrack and this output compared against the original data sources. The model was also run with different combinations of trains to check that the signalling was exhibiting the correct behaviour.

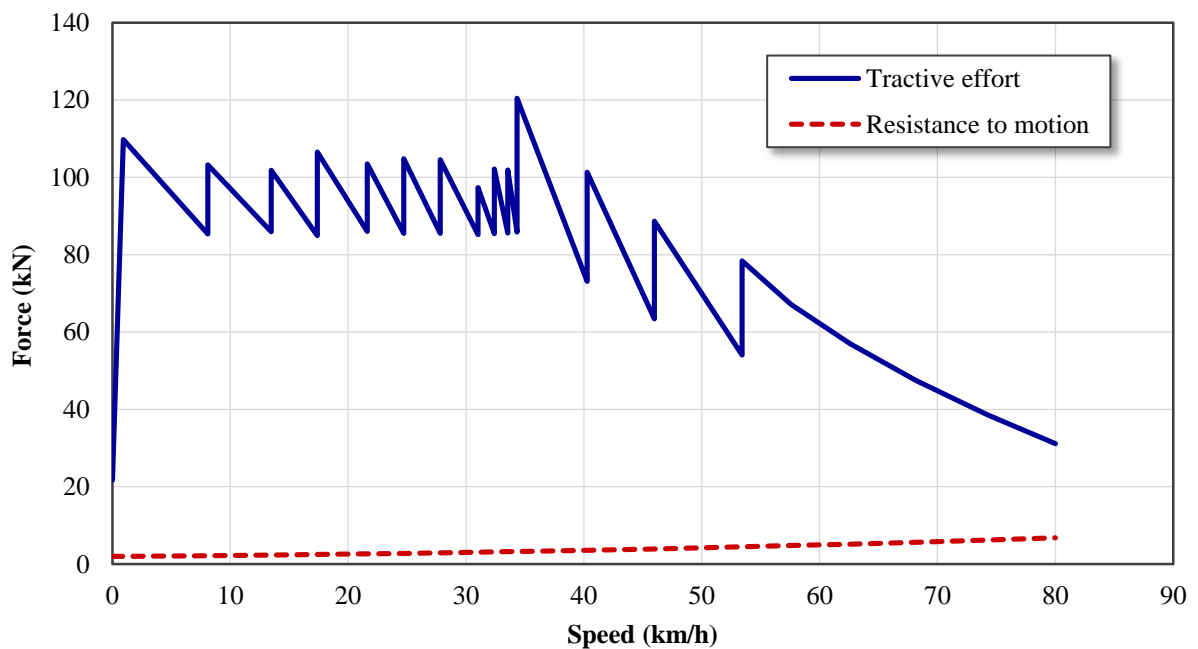
To validate the models, results for the two outputs of train movement and energy consumption were compared against actual measured data. The criteria for acceptance (effectively whether the model is indeed reasonably representative of reality) were defined in Chapter 3: less than 4% difference between simulation model results and actual measurements for train running times, and less than 8% difference for single train energy consumption, or alternatively either could be within the spread of results for a set of measured values. Section 5.7 details the results of the validation carried out for each of the three case studies.

## 5.4. Rolling stock

### 5.4.1. Tyne and Wear Metrocar

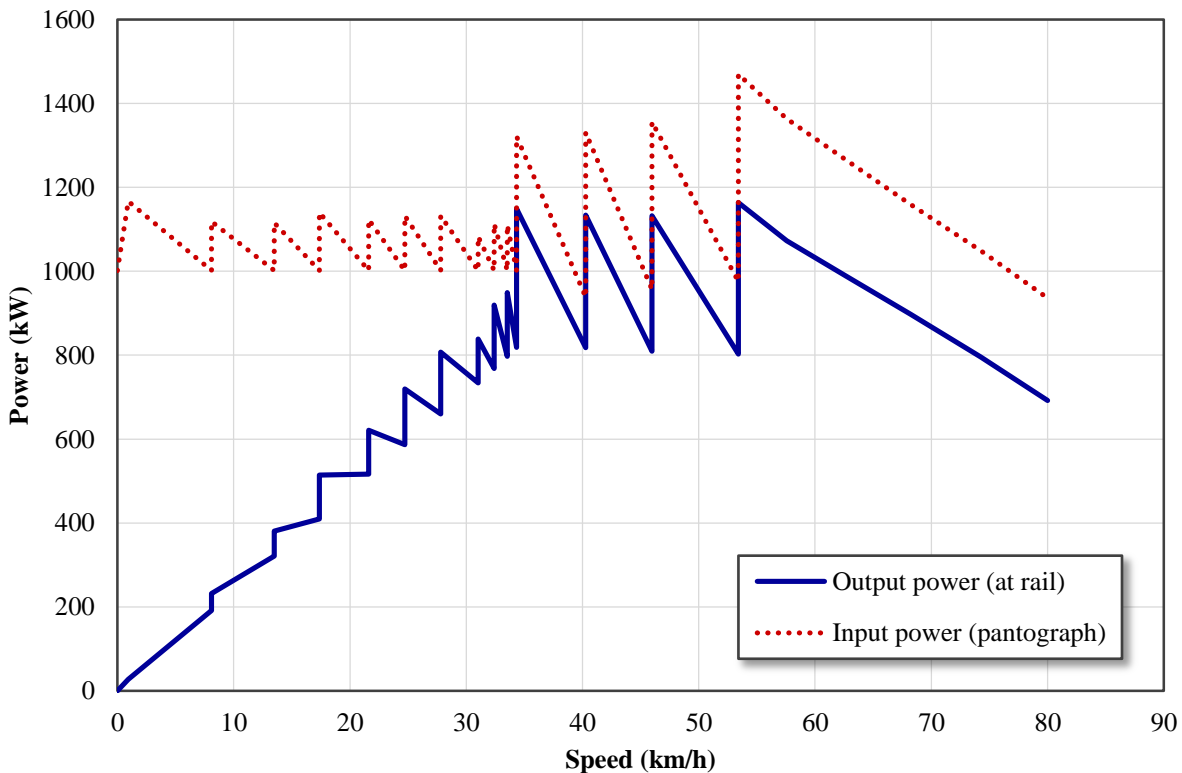
The Tyne and Wear Metrocars are twin-section articulated vehicles, with a total length of 28 m and a tare weight of 40 t. They were built by Metro-Cammell in the late 1970s, with electrical equipment by GEC Traction and bogie/articulation design by Düwag. The fleet was refurbished between 1995 and 2000, and underwent life extension work between 2010 and 2015 to run until the mid-2020s. The majority of the technical details were provided by DBTW (DB Regio Tyne and Wear).

The vehicles are fed with 1500 V DC from overhead wires, with a 185 kW series-wound DC monomotor on each outer bogie, resistance-controlled by camshaft. The two motors in each Metrocar are connected in series when motoring (there is no series-parallel transition), and there are four stages of field weakening. Figure 35 illustrates the design tractive effort and resistance to motion for a pair of Metrocars, with part-worn wheels and line voltage of 1350 V, running above-ground rather than within a tunnel.



**Figure 35:** Metrocar tractive effort and resistance to motion (two-unit train)

The power output at the rail for maximum tractive effort and the input power drawn from the overhead lines are illustrated in Figure 36. The input power is measured at the pantograph and so excludes power losses in the overhead lines and supply system, which show considerable dependence on the infrastructure and other nearby trains, but does include vehicle traction equipment losses and auxiliary loads. The energy consumption of these auxiliary loads was determined by a study that analysed on-board energy meter data (Powell *et al.*, 2014).



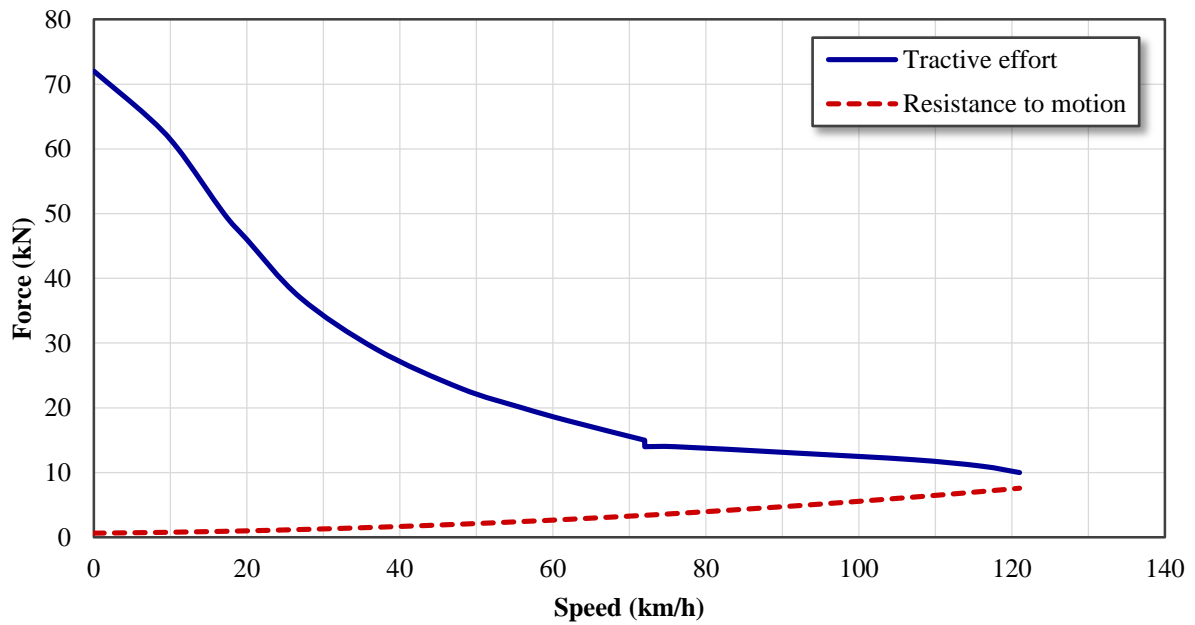
**Figure 36:** Metrocar power input/output (two-unit train)

Braking is a mixture of friction (pneumatically-operated disc) and rheostatic, with motors cross-connected in parallel and no field weakening. Regenerative braking into the overhead line is not possible. The friction brakes on the unpowered bogie are always used, and the friction brakes on the motor bogies are automatically blended with the rheostatic brake at low speeds. There are four notches on the brake controller up to and including full service braking, as well as magnetic track brakes for use in emergencies. The maximum deceleration under full service braking is  $1.15 \text{ m/s}^2$  (and  $2.1\text{-}2.6 \text{ m/s}^2$  for emergency braking), but the average deceleration of  $0.5 \text{ m/s}^2$  measured in Chapter 4 was used for the OpenTrack model to better match the actual driving style.

#### 5.4.2. Class 150 DMU

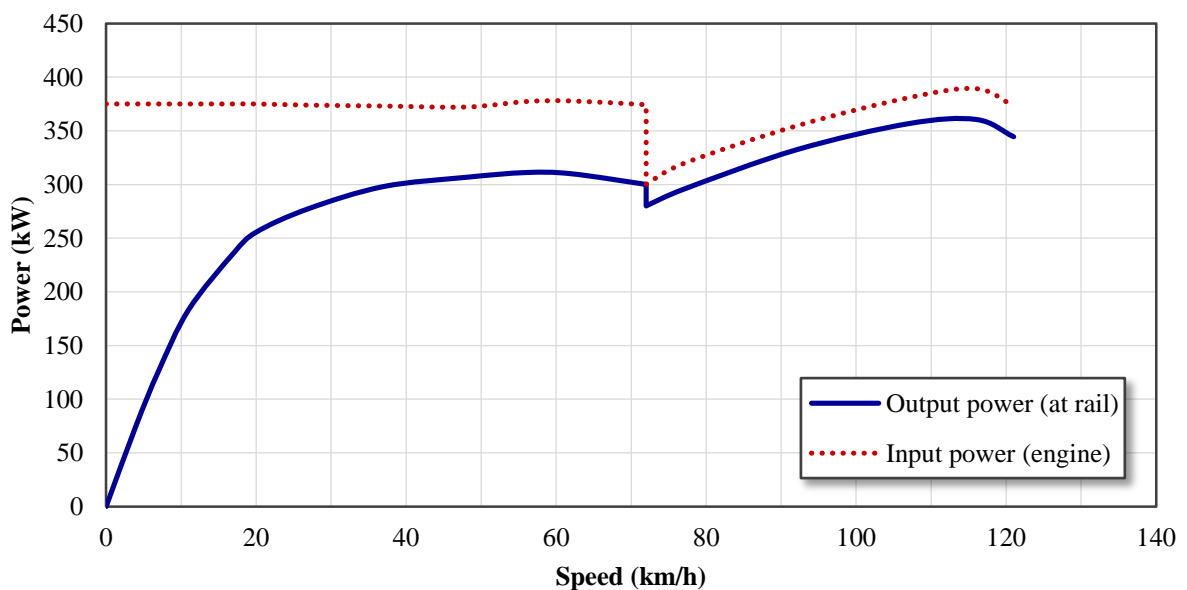
A Class 150 Sprinter is a diesel multiple unit made up of two or three 20 m coaches, with a tare weight of around 36 t per vehicle. They were designed and built by British Rail/BREL between 1984 and 1987.

Each vehicle is powered by a 213 kW Cummins NT-855-R5 diesel engine, with Voith T211r hydrodynamic transmission and Gmeinder final drive on both axles of one bogie. The tractive effort and resistance to motion of a two-coach unit are illustrated in Figure 37 (Shore, 1987; Swift *et al.*, 1990).



**Figure 37:** Class 150 tractive effort and resistance to motion (two-coach train)

Although well-to-wheel energy efficiencies of electric and diesel traction are roughly similar (Spring, 1982; Hoffrichter *et al.*, 2012), conversion of primary energy (and the associated losses) occurs on board diesel trains, as opposed to at a distant power station for electric trains. The input power was therefore measured at the output shaft of the diesel engines, so that electric and diesel rolling stock energy consumption in the same simulation would be reasonably comparable. In both cases, this definition accounts for vehicle transmission losses and auxiliary energy consumption, but not the losses in converting and transmitting primary energy into a form that can be used on the vehicle. The resulting input/output power is illustrated in Figure 38.



**Figure 38:** Class 150 power input/output (two-coach train)

The units are fitted with Westinghouse three-step pneumatically-operated tread brakes, with three service braking notches and one emergency notch. Based on Chapter 4, a deceleration of  $0.29 \text{ m/s}^2$  was used for the model, compared to the service braking maximum of around  $0.7\text{-}0.8 \text{ m/s}^2$ .

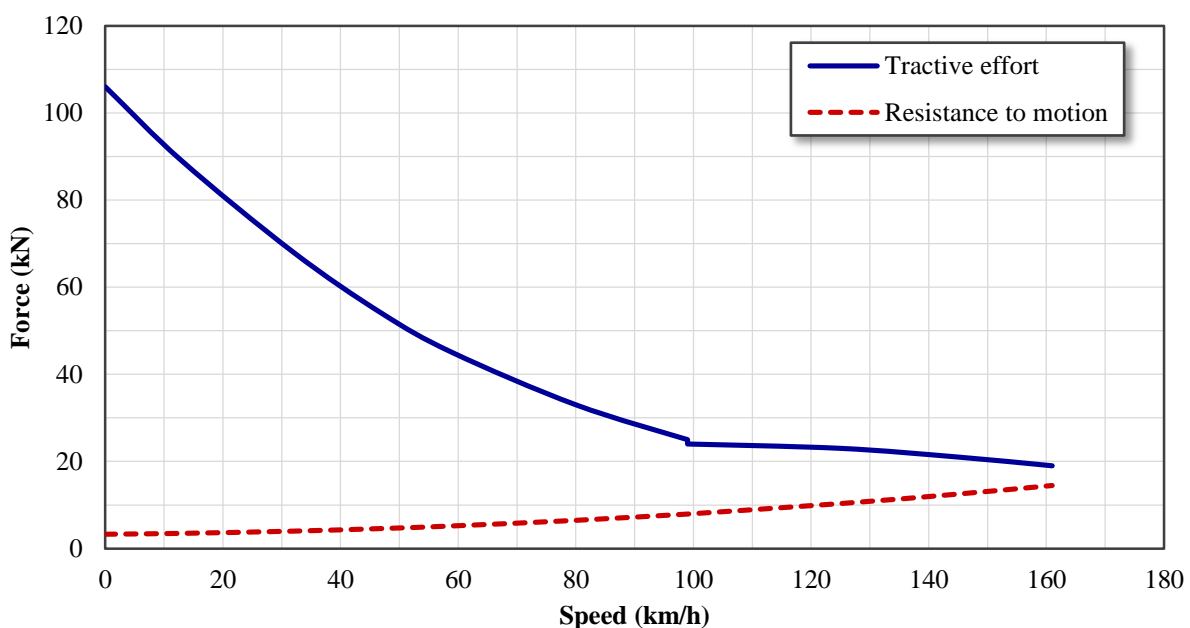
#### 5.4.3. Class 156 DMU

The Class 156 Super Sprinter was a further development of the Sprinter family of trains, with 23 m long bodysells and single-leaf end doors. The two-coach units were built by Metro-Cammell between 1987 and 1989. The traction and braking system is identical to the Class 150 units, and overall tare vehicle masses are similar. Therefore, the only modification to the OpenTrack input data required was slight adjustments to mass and resistance to motion to reflect overall train length and passenger loading in the respective case studies.

#### 5.4.4. Class 170 DMU

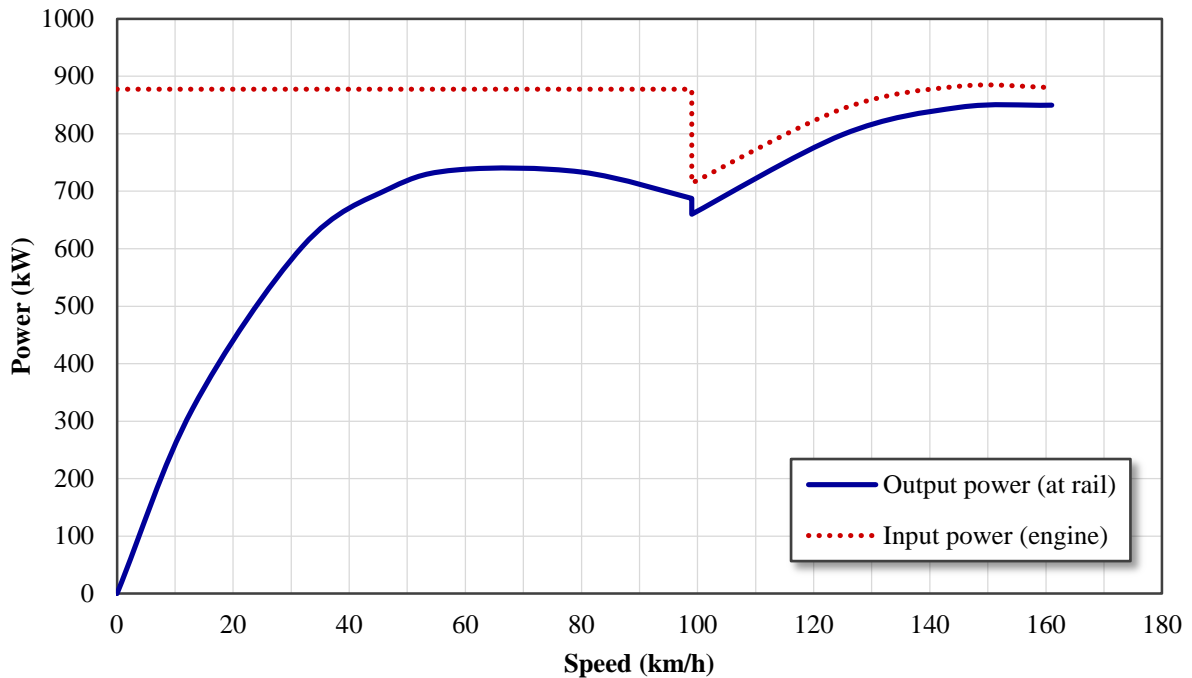
The Class 170 Turbostar diesel multiple unit also has 23 m long coaches, but is heavier at around 45 t per vehicle. Built by Adtranz (later Bombardier) between 1998 and 2005, units may be formed of two, three or four coaches.

The traction system is similar to the Class 150/156 units, but with the more powerful MTU 6R183TD13H diesel engine (rated at 315 kW). This is coupled to a Voith T211rzze hydrodynamic transmission and ZF final drive, again to both axles of one bogie. The tractive effort and resistance to motion of a three-coach unit are illustrated in Figure 39 (Read *et al.*, 2011).



**Figure 39:** Class 170 tractive effort and resistance to motion (three-coach train)

Figure 40 illustrates the power at the diesel engine output shafts and the power at rail (Read *et al.*, *ibid.*).



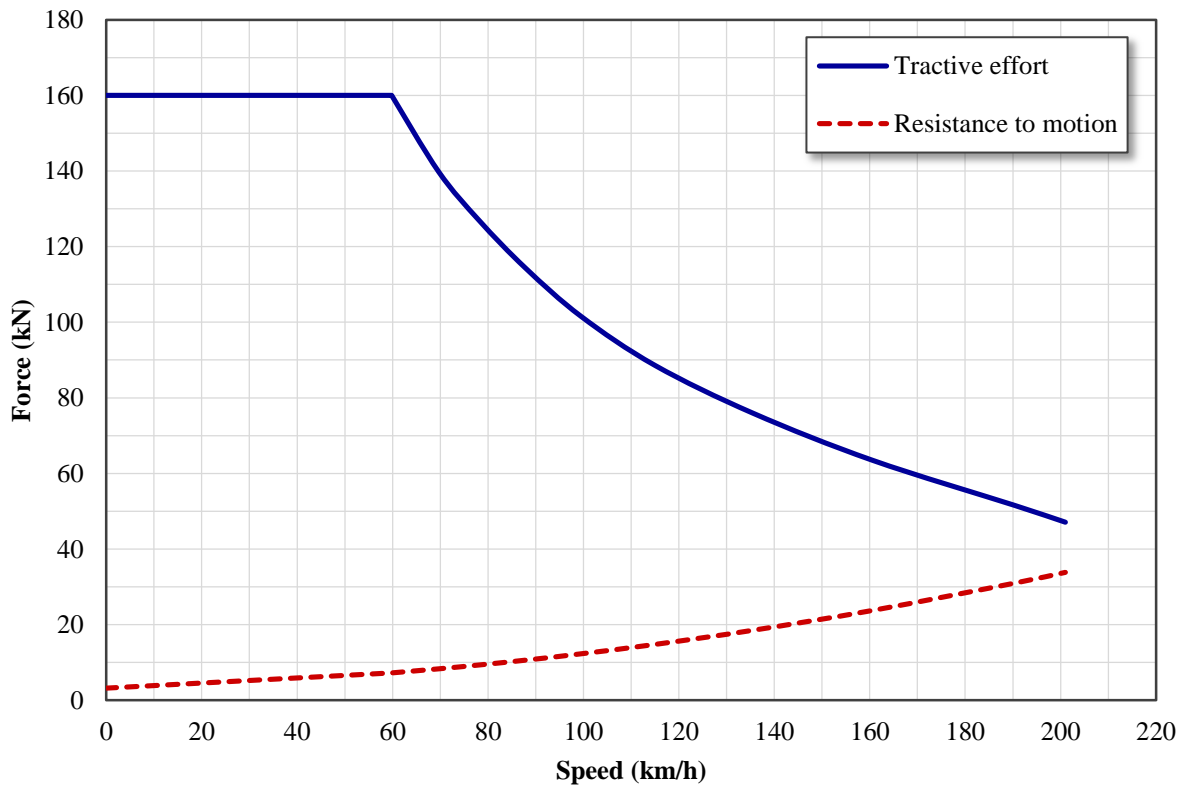
**Figure 40:** Class 170 power input/output (three-coach train)

The units are fitted with Westinghouse three-step pneumatically-operated brakes, acting on wheel-mounted discs rather than the wheel tread. There are three service braking notches and one emergency notch. This provides a maximum service braking deceleration of around  $0.9 \text{ m/s}^2$ , but the OpenTrack model used the deceleration of  $0.31 \text{ m/s}^2$  derived in Chapter 4.

#### 5.4.5. Class 43 locomotive (HST)

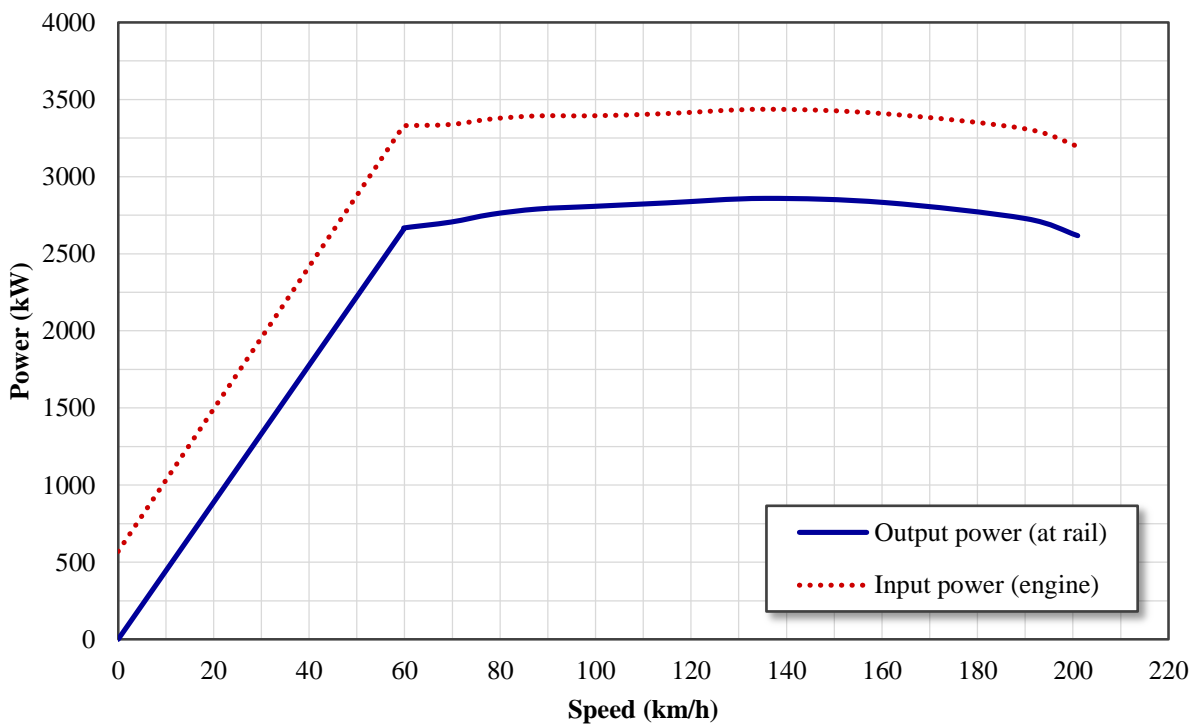
The HST was developed by British Rail in the early 1970s, and consists of two Class 43 diesel-electric locomotives (power cars) at either end of a number of Mark 3 coaches. The complete HST sets have also been given the DEMU classification of Class 253 or 254 in the past. They were built by BREL between 1975 and 1982, and are in service with a number of operators with different coach formations. For the Tyne and Wear case study a six-coach formation was used, eight for the Swindon case study and nine on the Highland Main Line.

The power cars were originally fitted with a 1680 kW Paxman Valenta 12RP200L diesel engine, driving a Brush BA1001 alternator and four DC traction motors (either Brush TMH68-46 or GEC G417AZ). The diesel engines have been replaced in recent years, with most power cars being fitted with MTU 16V4000 engines, and a few with Paxman 12VP185 engines. The tractive effort and resistance to motion of an eight-coach formation are illustrated in Figure 41 (Hoffrichter, 2012).



**Figure 41:** HST tractive effort and resistance to motion (eight-coach train)

Figure 42 illustrates the estimated energy consumption for an eight-coach train, measured at the rail and the engine output shafts. Where the number of coaches varies, the auxiliary energy consumption and resistance to motion were adjusted accordingly (Swift *et al.*, 1990).



**Figure 42:** HST power input/output (eight-coach train)



The braking system consists of pneumatic disc brakes, electrically controlled from each power car with Davies and Metcalfe equipment. As with the Class 170, the maximum service braking deceleration is around  $0.9 \text{ m/s}^2$ , but the OpenTrack model used the deceleration of  $0.31 \text{ m/s}^2$  derived from Chapter 4.

#### 5.4.6. Class 66 locomotive

Class 66 diesel electric locomotives were built between 1998 and 2004 by General Motors, derived from the earlier Class 59 design. They are currently the most numerous locomotive in service in Great Britain. HYA hoppers were chosen as a reasonably representative example of the wagons used for coal trains, and FKA container flats likewise for intermodal trains.

The locomotives are fitted with a 2460 kW EMD 12N-710G3B diesel engine, AR8 alternator and six D43 traction motors (DC). The estimated tractive effort curves and resistance to motion of different freight trains is illustrated in Figure 43. Laden HYA wagons are limited to 60 mph (97 km/h), but empty wagons can run at 75 mph (121 km/h).

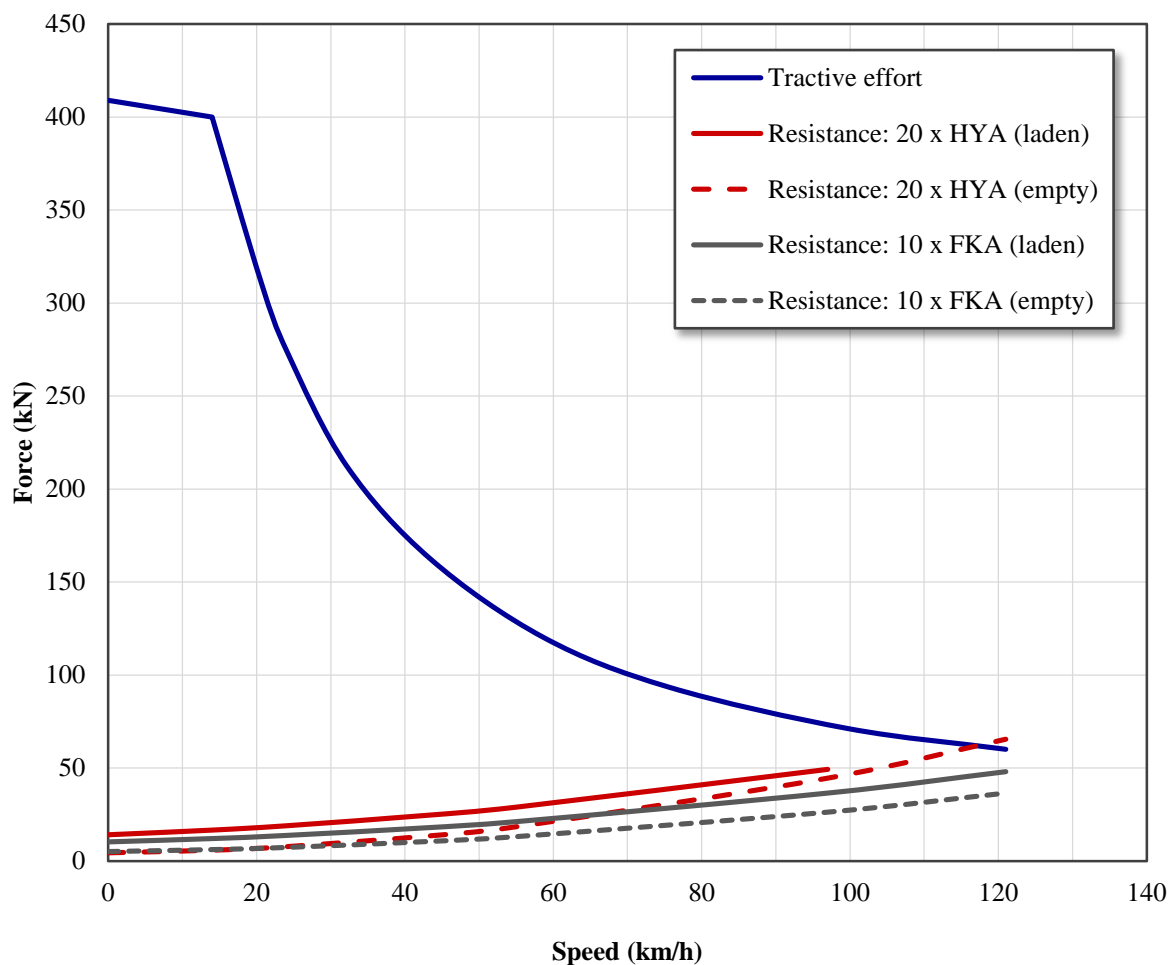
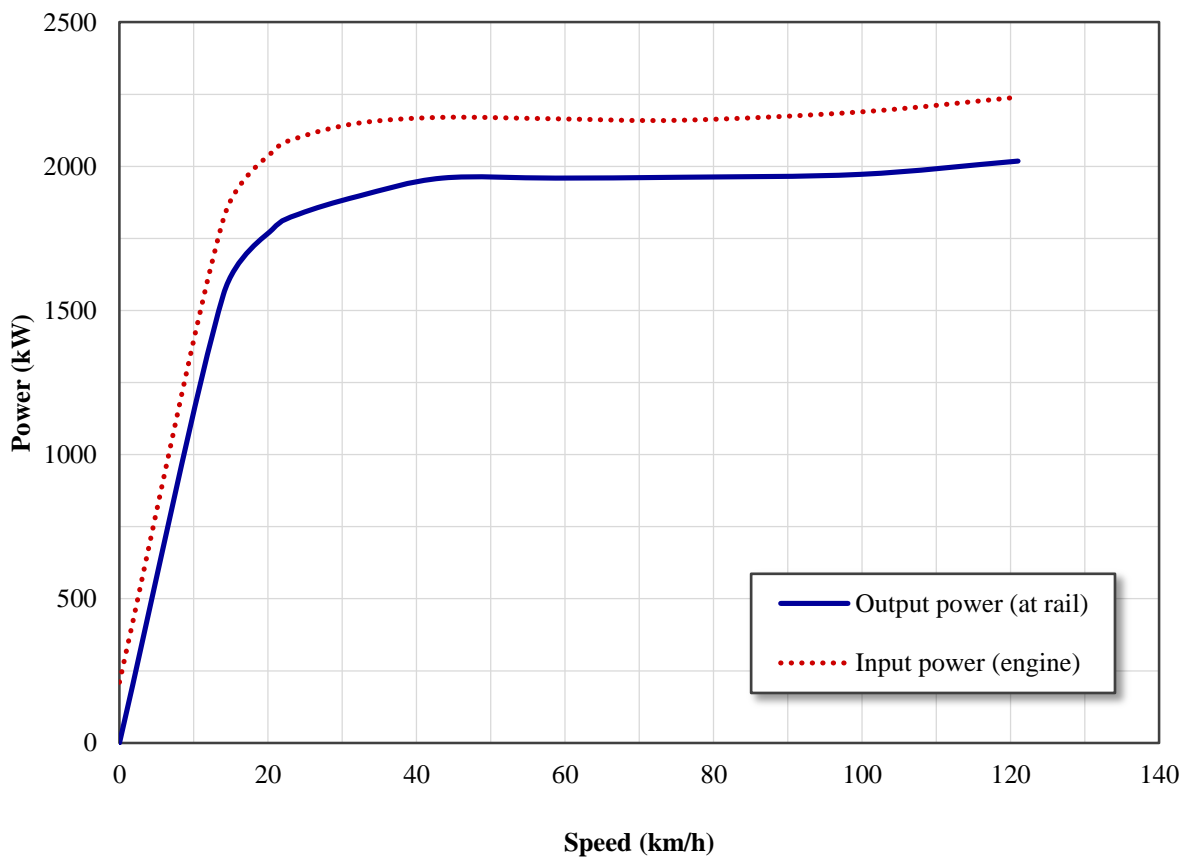


Figure 43: Class 66 tractive effort and resistance to motion

The estimated energy consumption is illustrated in Figure 44.



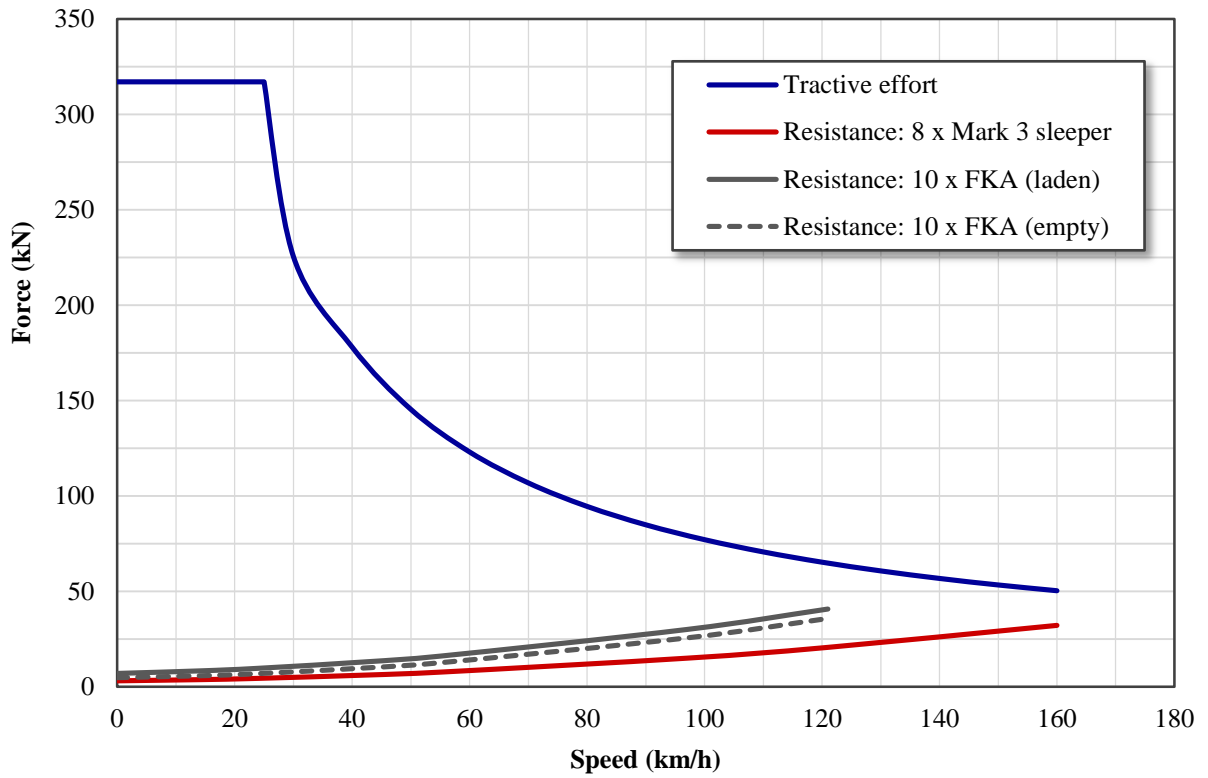
**Figure 44:** Class 66 locomotive power input/output

Freight train braking is pneumatic, with a mixture of tread and disc brakes. Although the average deceleration measured in Chapter 4 was  $0.12 \text{ m/s}^2$ , this was increased to  $0.15 \text{ m/s}^2$  for the case studies, to avoid braking phases of simulated trains (in response to adverse signal aspects) starting in advance of sighting the relevant signal. This increase remains within the margin of uncertainty from the experimental errors.

#### 5.4.7. Class 68 locomotive

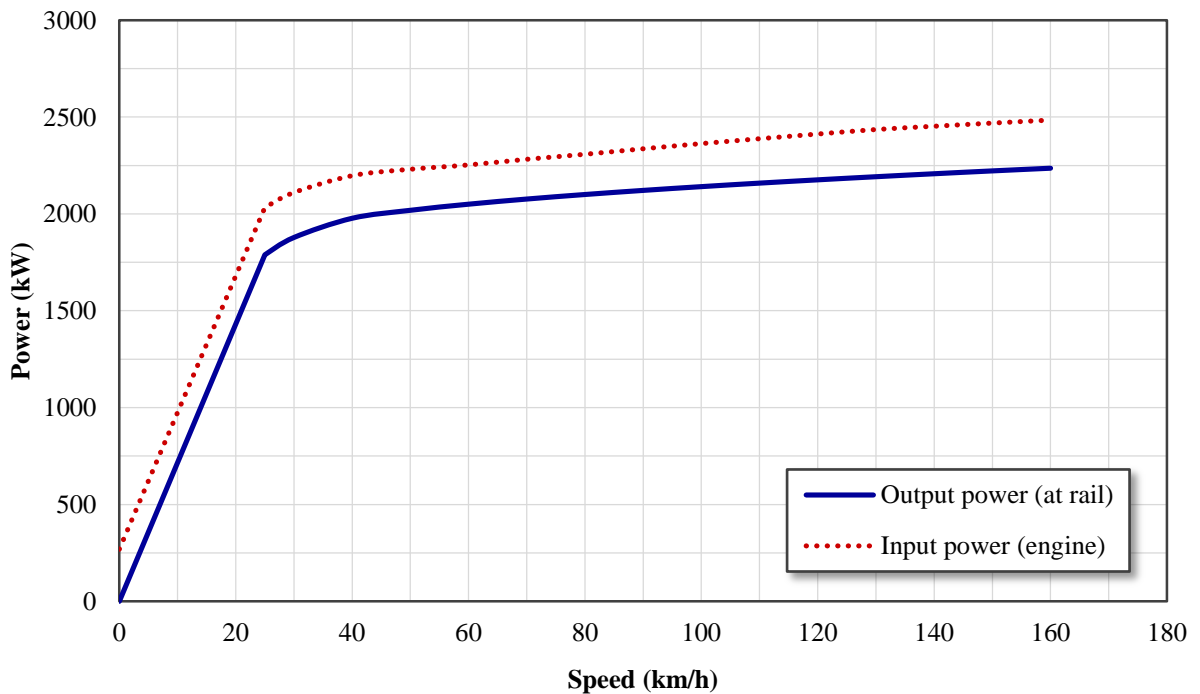
Production of Class 68 diesel electric locomotives by Vossloh started in 2013, are at the time of writing are still being manufactured, although the factory in Spain had since been sold to Stadler. The design is a further development from the Class 67 produced by the same factory, then under Alstom ownership.

The engine in the Class 68 is a 2800 kW Caterpillar C175-16, with an ABB WGX560 alternator and four ABB 4FRA6063 traction motors (asynchronous AC). The estimated tractive effort and resistance to motion (when hauling an eight-coach Mark 3 sleeper formation) is illustrated in Figure 45.



**Figure 45:** Class 68 tractive effort and resistance to motion (sleeper train)

The estimate energy consumption is illustrated in Figure 46.



**Figure 46:** Class 68 locomotive power input/output

The deceleration defined for the freight trains was the same as for the Class 66 at  $0.15 \text{ m/s}^2$ , with  $0.31 \text{ m/s}^2$  for the sleeper train. As well as the pneumatic brakes, electric braking is also possible, feeding energy into the locomotive's auxiliaries or a resistor.

## 5.5. Infrastructure

The infrastructure models were built using information provided by Nexus, DBTW and Network Rail. These specifications included the track layout, speed limits, gradients, signals and track circuits. Further information to assist in the construction of the model was taken from other publically accessible data, aerial photographs and directly from videos, photographs and observations in person.

The default OpenTrack dispatching rules were retained, with signals at stations kept at danger until trains calling at that station were ready to depart. For moving block, a safety distance of 70 m was used, based on Network Rail specifications. Discrete blocks were retained as required around junctions, stations and bi-directional sections of track to prevent deadlocks. Point switching times were assumed to be five seconds for motorised points, and three seconds for manually operated points. Route reservation and release times were assumed to be one second for electronic interlockings. Route reservation times were assumed to be ten seconds for absolute block where communication between signal boxes is required, three seconds for reservation of routes under the full control of one signal box, and three seconds for release.

The completed OpenTrack model of the Tyne and Wear case study is illustrated in Figure 47.

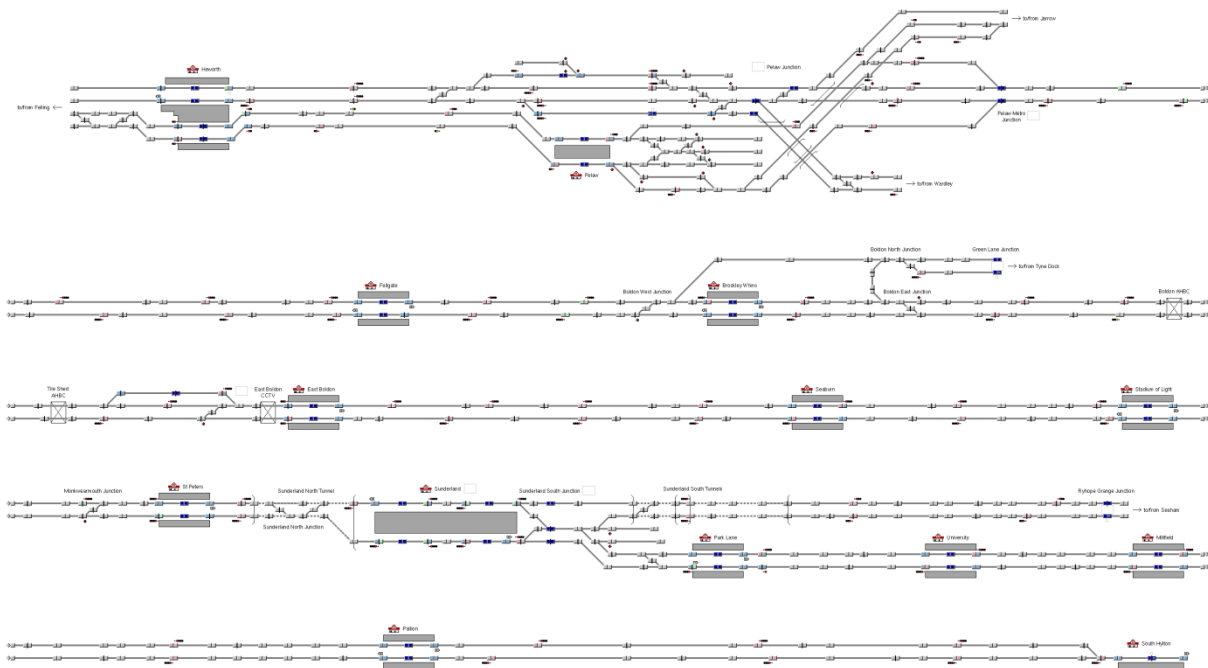


Figure 47: Tyne and Wear model

Figure 48 illustrates the OpenTrack model of the area around Swindon. It is divided up into the former Swindon Panel interlockings. The sections with a light grey background are areas controlled by adjacent signal boxes (Westbury and Bristol), and are included to meet the boundaries defined in Section 5.2.2. Freight sidings are not modelled in detail.

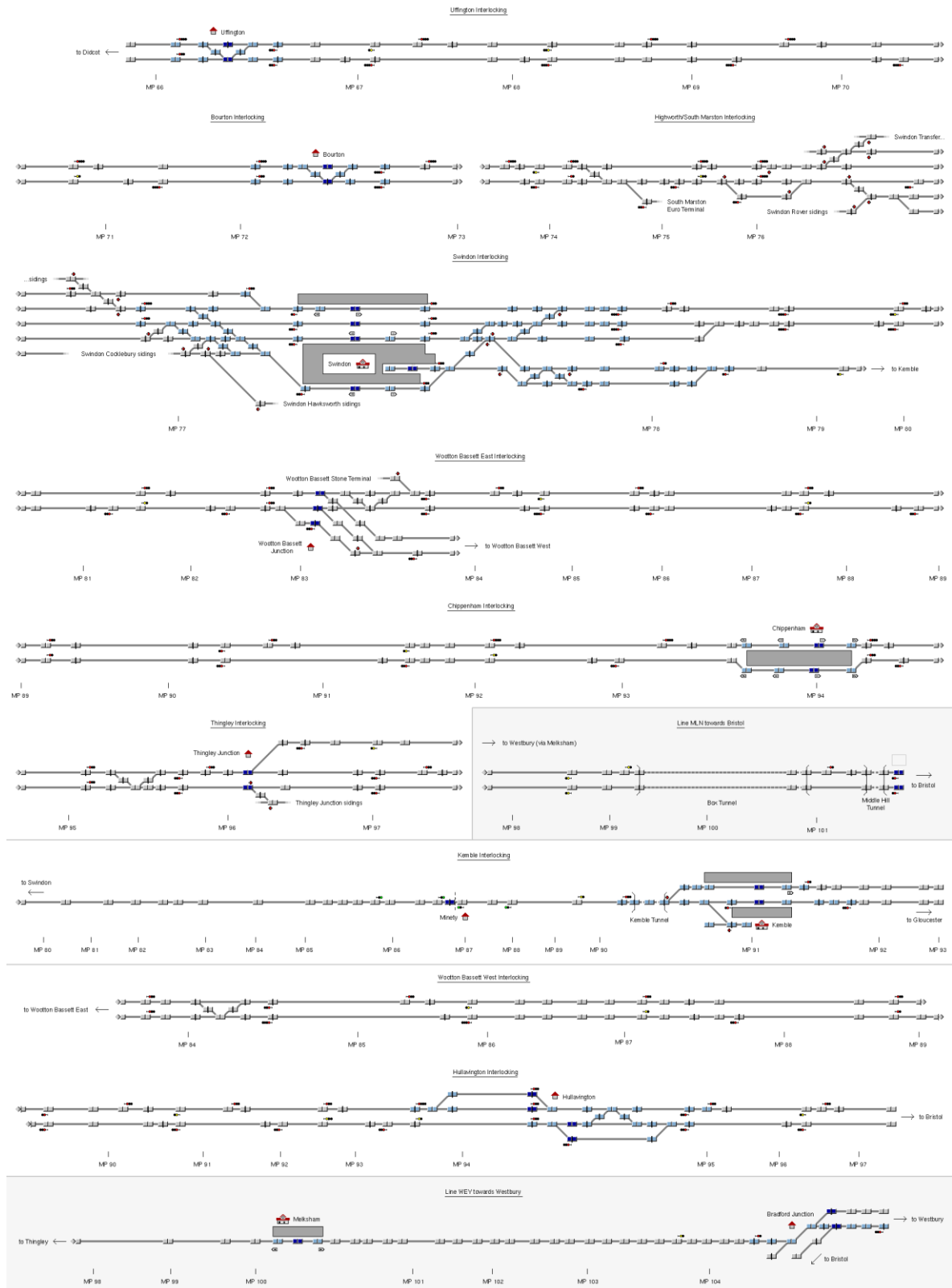


Figure 48: Swindon model

Figure 49 illustrates the OpenTrack model of the Highland Main Line. There are a large number of sidings around Perth and Inverness that are not modelled in detail, because they are either disused or not necessary for the modelling carried out.

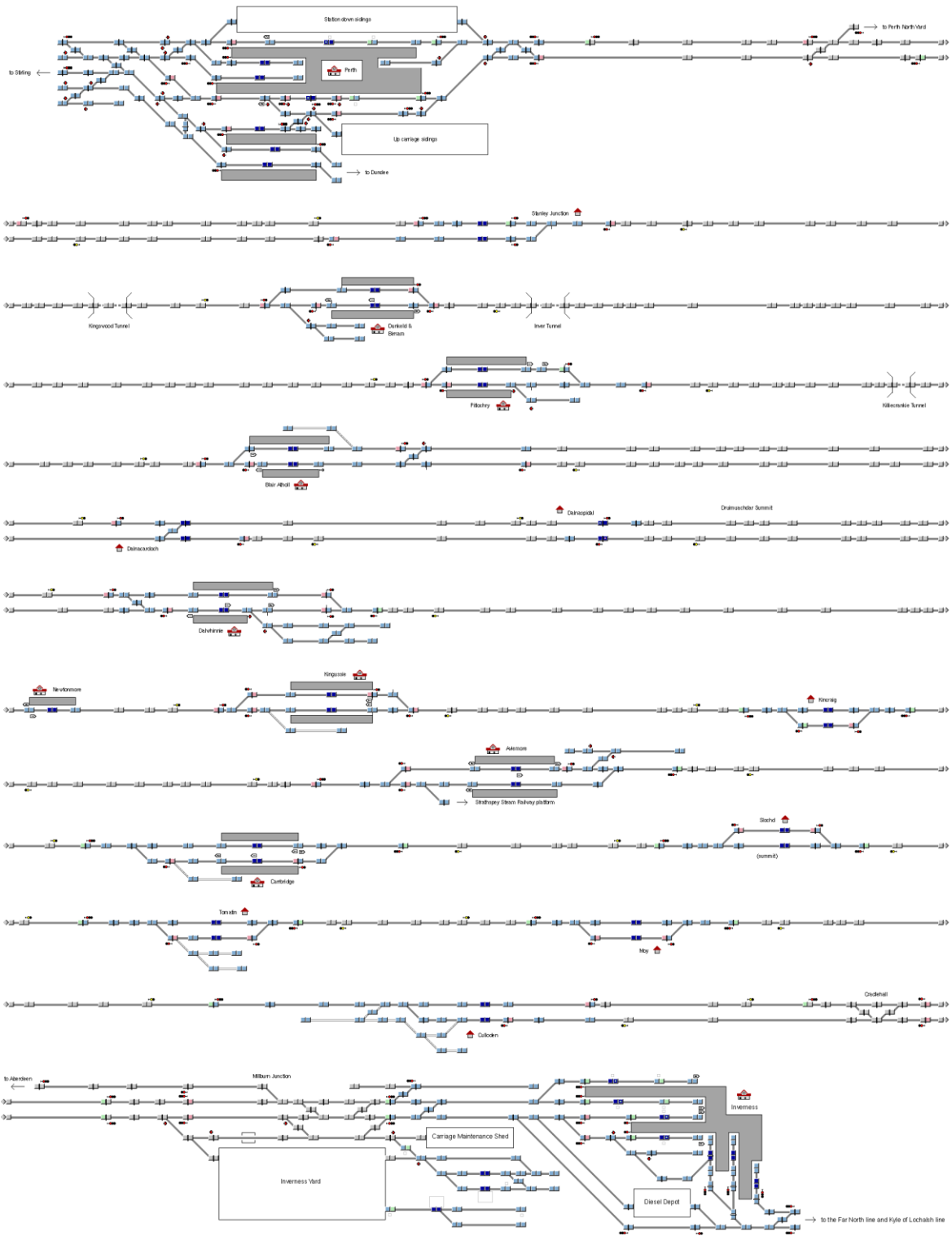
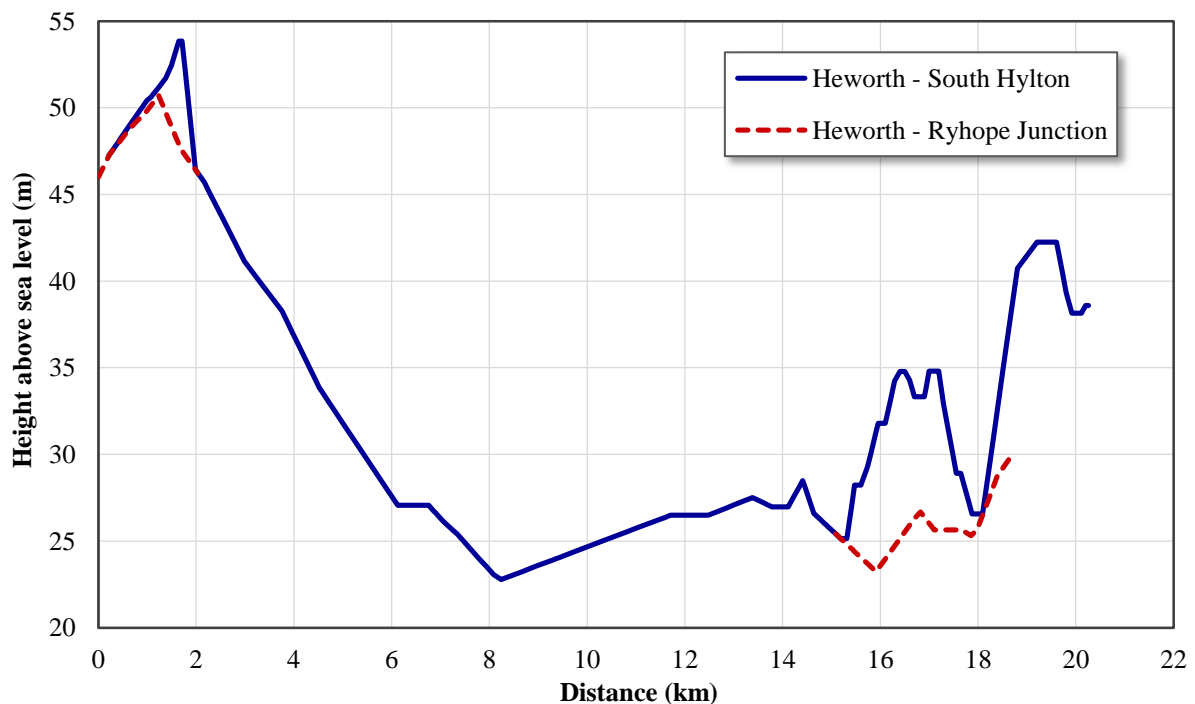


Figure 49: Highland Main Line model

For comparison, the track layouts derived from the Network Rail Sectional Appendix for each of the case studies are provided in Appendix B. The Sectional Appendix also includes the speed profiles of the lines, in miles per hour. In each case study there are differential line speeds for some track sections, which allow different rolling stock to run at different speeds. Differential speed limits are generally imposed to restrict the speed of heavier trains over particular infrastructure features such as bridges and tunnels, or to allow certain types of train with a better braking performance to run at higher speed for a given signalling layout. This offsets some of the disadvantages of fixed-block lineside signalling compared to in-cab moving block. The differential speed limits are as follows:

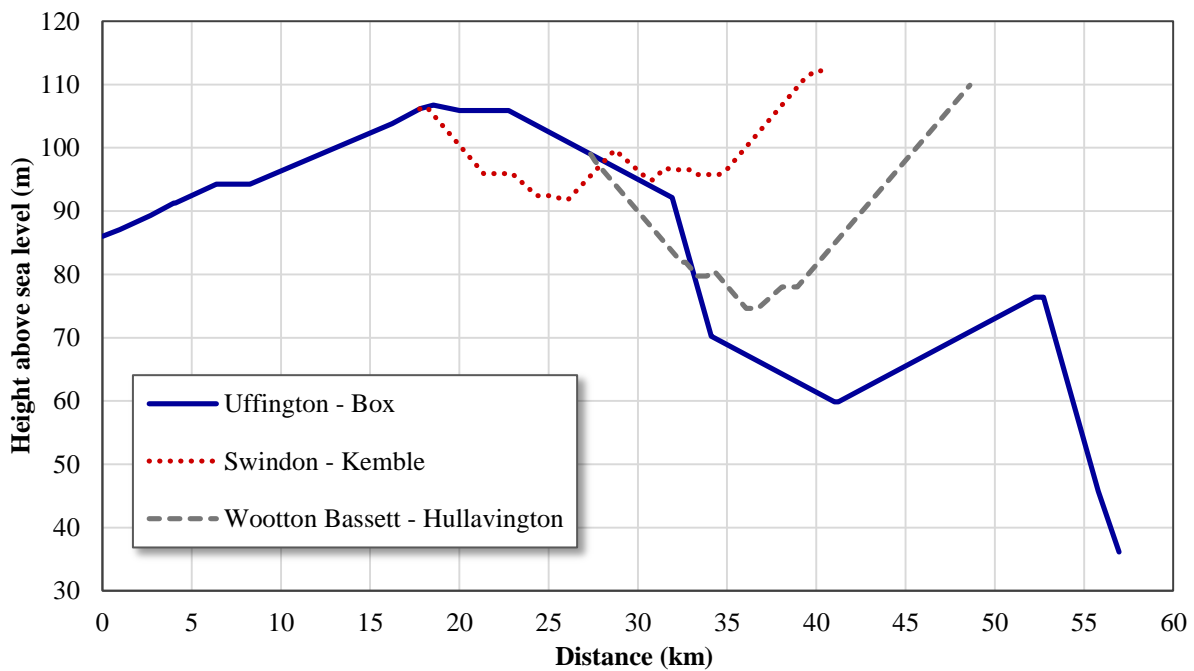
- **Tyne and Wear:** the line speed is different for freight, passenger and Metro trains; the Metro speed limits are the only limits given in km/h.
- **Swindon:** there are higher differential speed limits for HSTs at Kemble, and lower differential speed limits for freight trains through Swindon station and Melksham.
- **Highland Main Line:** there is a higher SP (Sprinter) differential speed limit for DMUs with relatively low axle loads, currently defined as including all DMUs between Class 150 and Class 172.

Figure 50 illustrates the height above sea level of the route of the Tyne and Wear case study, providing an indication of the track gradients on the route.



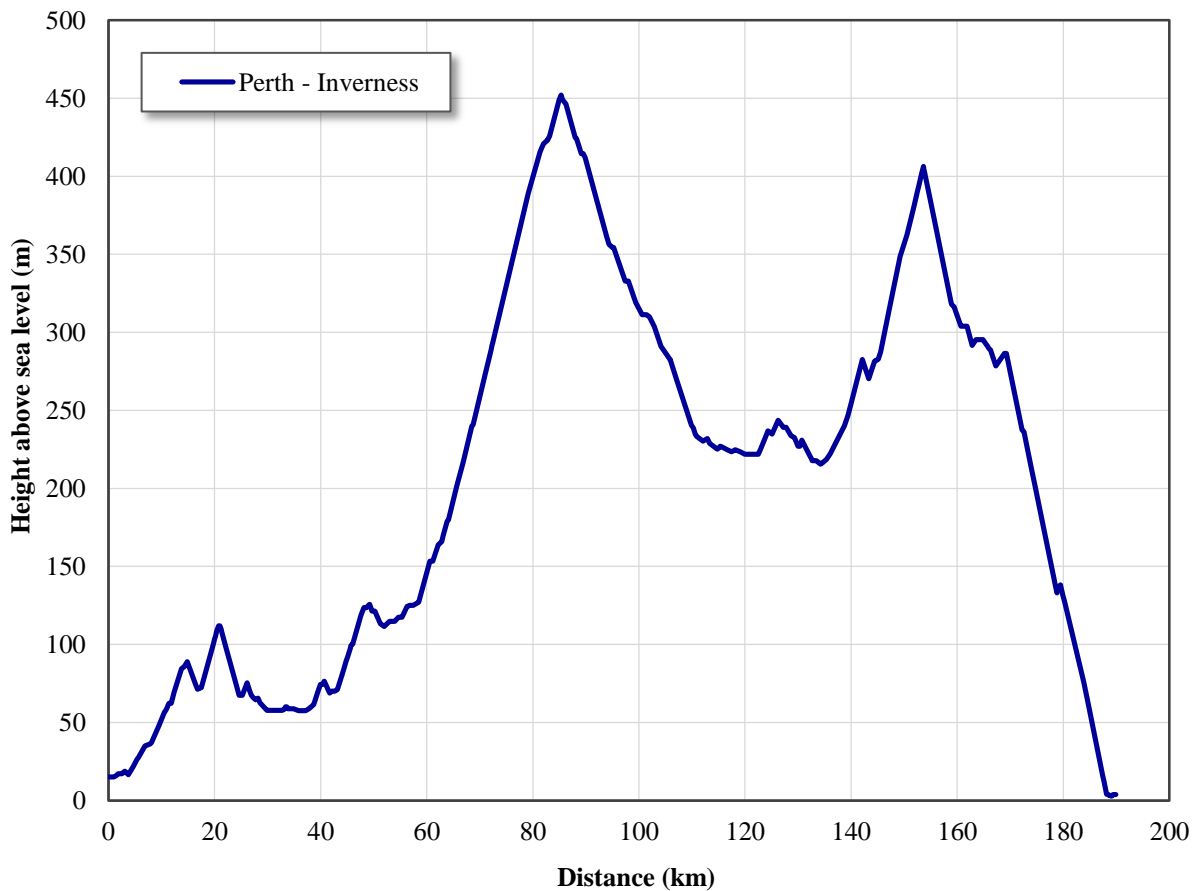
**Figure 50:** Height above sea level of the Tyne and Wear case study route

Figure 51 illustrates the gradients of the main routes in the Swindon case study.



**Figure 51:** Height above sea level of Swindon case study routes

Figure 52 illustrates the gradients between Perth and Inverness on the Highland Main Line.



**Figure 52:** Height above sea level of the Highland Main Line case study route



## 5.6. Timetable

### 5.6.1. Working timetable

A full 24-hour timetable for each case study was built from the relevant weekday Network Rail working timetables. The start and finish time was chosen to ensure that there were no train movements within the boundaries of the case study, which was 02:00 for the Tyne and Wear case study, 03:00 for Swindon and 00:00 for the Highland Main Line.

Typically, only some of the timetabled freight train paths in the timetable are actually used, as trains only run where there is sufficient demand. Therefore, the trains that actually ran on the routes were monitored over a period of several months during 2015, using data available from Real Time Trains<sup>3</sup>, to estimate an average for the proportion of freight paths actually used and identify which trains ran most often:

- **Tyne and Wear:** on average, 26 out of the 62 paths were actually used. The cement and nuclear trains did not run often, and so all of the modelled trains are coal hoppers to and from Tyne Dock (some of these may in fact be carrying biomass, but this distinction was not made for the model).
- **Swindon:** the proportion of freight paths actually used was lower in this case, with an average of 28 out of 92.
- **Highland Main Line:** the only regular freight working was the daily intermodal train: service 4H47 from Mossend to Inverness, and its return working 4D47.

The completed timetables used for each case study are illustrated by the train graphs in Appendix C. These were derived from the OpenTrack models, with no initial delays specified.

### 5.6.2. Driving style

Driving style in OpenTrack is modelled by a ‘performance’ value (a percentage), which modifies tractive effort during acceleration, cruising speed and deceleration values. OpenTrack was used to simulate single train runs, and hence determine the performance value that gave the closest match to the required journey times for the services in each case study.

Representative mean inter-station journey times and dwell times were derived from measurements of real journeys, using the metering data previously mentioned in Section 4.3.2 for the Tyne and Wear Metro and the running data from Real Time Trains for other passenger trains mentioned in Section 5.6.1. The Tyne and Wear data has a greater resolution, with arrival times correct to the nearest second, compared to the nearest fifteen seconds for the

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<sup>3</sup> <http://www.realtimetrains.co.uk/>

Real Time Trains data. However, the inter-station journey times for main-line trains in the case studies are typically of the order of tens of minutes, rather than one or two minutes for the Metro. As a result, the lower resolution of the Real Time Trains data is not a significant problem. To establish the turnaround times at locations where trains terminate, the minimum dwell time of late running trains was used rather than the mean dwell time.

OpenTrack allows a different performance value to be specified when trains are delayed. This accounts for drivers exploiting running time margins present in timetables to recover from the delays. To establish this late-running performance, the minimum journey times from the measured data were used as the target for the single train simulation runs instead of the mean journey times. The values are less than 100% because the trains are manually driven, and it is unlikely that drivers can maintain the train cruising speed exactly at the limit. For the Tyne and Wear Metrocars, the camshaft control makes it more difficult to maintain a specific cruising speed compared to the notched controllers of the diesel rolling stock, and as a result the late-running performance is lower. Freight train mass and driving styles (and hence running times) show significant day-to-day variation compared to passenger trains, and the data available was more limited. As such, a blanket figure of 90% was used, based on studies by Imrie (2015) and a comparison of single train runs to the timetabled paths.

Table 2 summarises the final performance figures used in each of the three case studies.

Case study	Rolling stock	On-time performance	Delayed performance
Tyne and Wear	Tyne and Wear Metrocar	94	94
	Class 156	90	98
	HST (six coaches)	90	98
	Class 66, twenty HYA wagons	90	90
Swindon	Class 150	95	98
	HST (eight coaches)	91	98
	Night Riviera (sleeper)	96	98
	Class 66, twenty HYA wagons	90	90
	Class 66, ten FKA wagons	90	90
Highland Main Line	Class 170	98	98
	HST (nine coaches)	98	98
	Caledonian Sleeper	98	98
	Class 68, ten FKA wagons	90	90

**Table 2:** OpenTrack train performance values for driving style

### 5.6.3. Delays

The studies of train running data outlined in Section 5.6.1 and 5.6.2 also monitored the punctuality of all trains passing the boundaries of the case studies (or starting/finishing within them). The threshold for trains to be defined as late at each timing point was typically either fifteen or thirty seconds. These figures were then used to build up a representative distribution of the delays to trains in each case study. The results for the initial delays (trains either starting their journeys or entering the area) for each case study are given in Table 3.

Case study	Service type	Proportion of trains delayed	Average delay	Maximum delay
Tyne and Wear	Metro	79%	82 s	300 s
	Other passenger	91%	135 s	540 s
	Freight	50%	44 s	420 s
Swindon	Intercity passenger	64%	136 s	915 s
	Local passenger	53%	83 s	255 s
	Freight	32%	268 s	930 s
Highland Main Line	(all trains)	22%	315 s	3240 s

**Table 3:** Initial delay distributions

These initial delay distributions were used for the experiment described in Chapter 6. The low average delay of freight trains masks both large delays and trains running much earlier than timetabled, as freight trains are not strictly limited to a timetabled path in the same way that passenger trains are. This means that simulation models are less representative of actual freight train movements compared to passenger train movements. Together with the greater variation in running times highlighted in Section 5.6.2, this suggests that the effects of freight train timetabling and running on the wider network performance may be a suitable subject for future research.

## **5.7. Validation Results**

### **5.7.1. Overview**

Speed profile and energy consumption data collected for the experiment described in Chapter 4 was used for validation of the three case studies. Individual journeys within this data set were used for either defining the driving style or validating the model, but not both, to avoid calibrating the model with the same data that would be used to validate it.

Six journeys between Heworth and South Hylton (three in each direction) were chosen at random from the Metrocar energy metering data provided by DBTW, although different times of day and different seasons were specifically chosen. The speed-distance and energy-time profiles are illustrated in Figure 53 to Figure 56 in Section 5.7.2, along with profiles generated by the OpenTrack model of this case study.

For the Swindon case study, some HST speed profiles measured in July 2015 were provided by First Great Western. Twelve individual speed profiles were obtained: three in each direction between Uffington and either Box or Hullavington. As noted in Section 5.2.2, the case study is based on the 2013 layout, but the Kemble line underwent extensive modifications during 2014 as part of the wider Great Western Main Line modernisation programme. These speed-distance profiles are illustrated in Figure 57 to Figure 60 in Section 5.7.3, together with the OpenTrack output. However, no energy consumption data were available for comparison in this instance.

GPS measurements for a single HST journey between Aviemore and Perth were taken in October 2014, and the speed-distance profile is illustrated in Figure 61, together with the OpenTrack equivalent. Energy consumption figures for an HST running between Perth and Inverness were published by the iRFP in Germany, as calculated by their FBS software (iRFP, 2006). This provides an alternative way to help validate the OpenTrack model, and a comparison between the results is made in Section 5.7.4. Finally, Figure 62 illustrates Class 170 speed profiles between Inverness and Perth, comparing the OpenTrack output with GPS measurements taken in September 2015.

Although speed profiles and energy consumption data were not available for all of the rolling stock modelled, it is the methods used to build the models that are being validated, rather than all of the possible outputs from it. The verification process made sure that the all parts of the model were built in the same way, and therefore it is not unreasonable to work on the basis that a successful validation using the data that is available means the models are reasonably representative of reality (which is the ultimate requirement for their use in Chapter 6).

### 5.7.2. Tyne and Wear Metrocar results

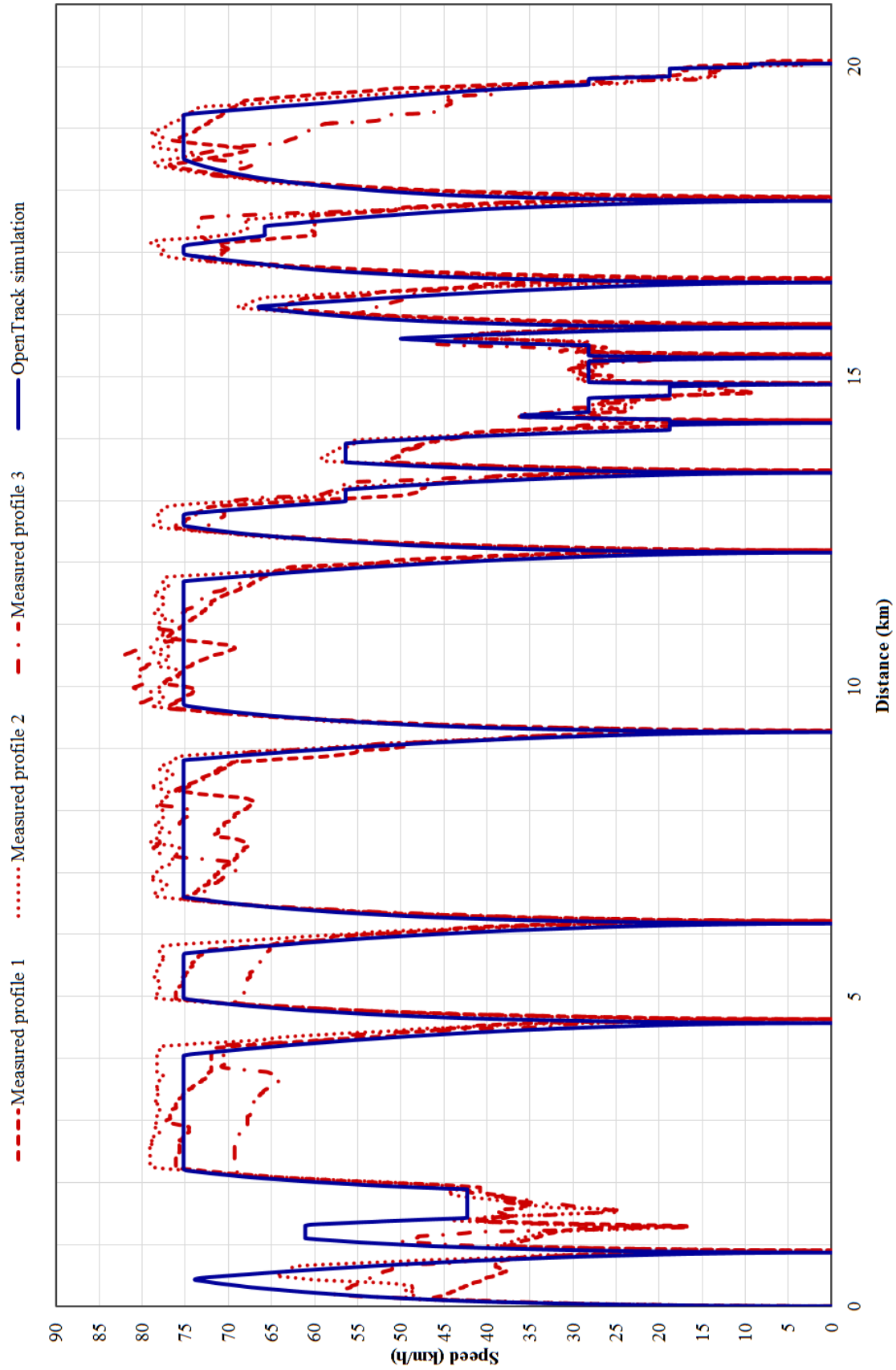
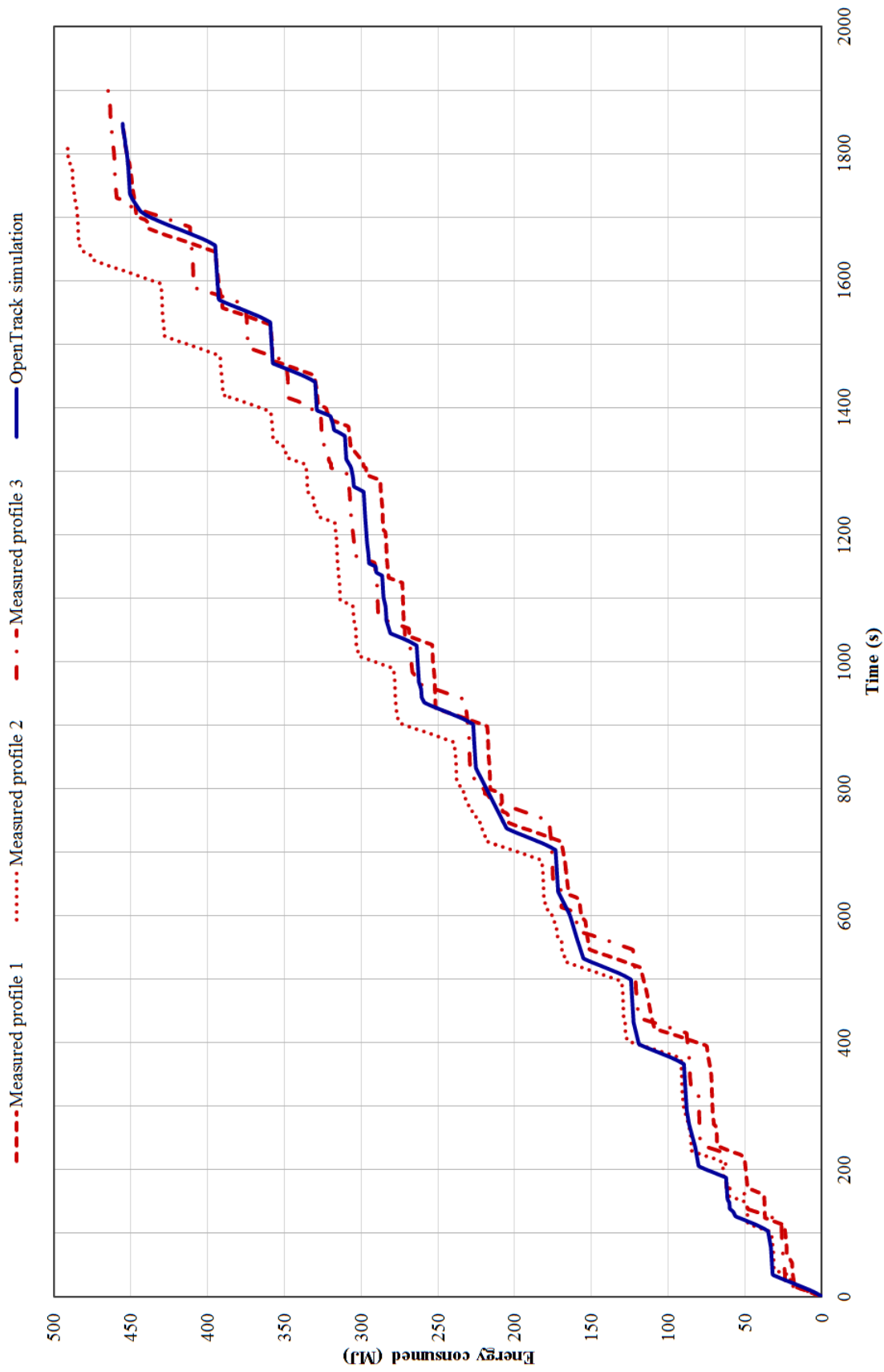
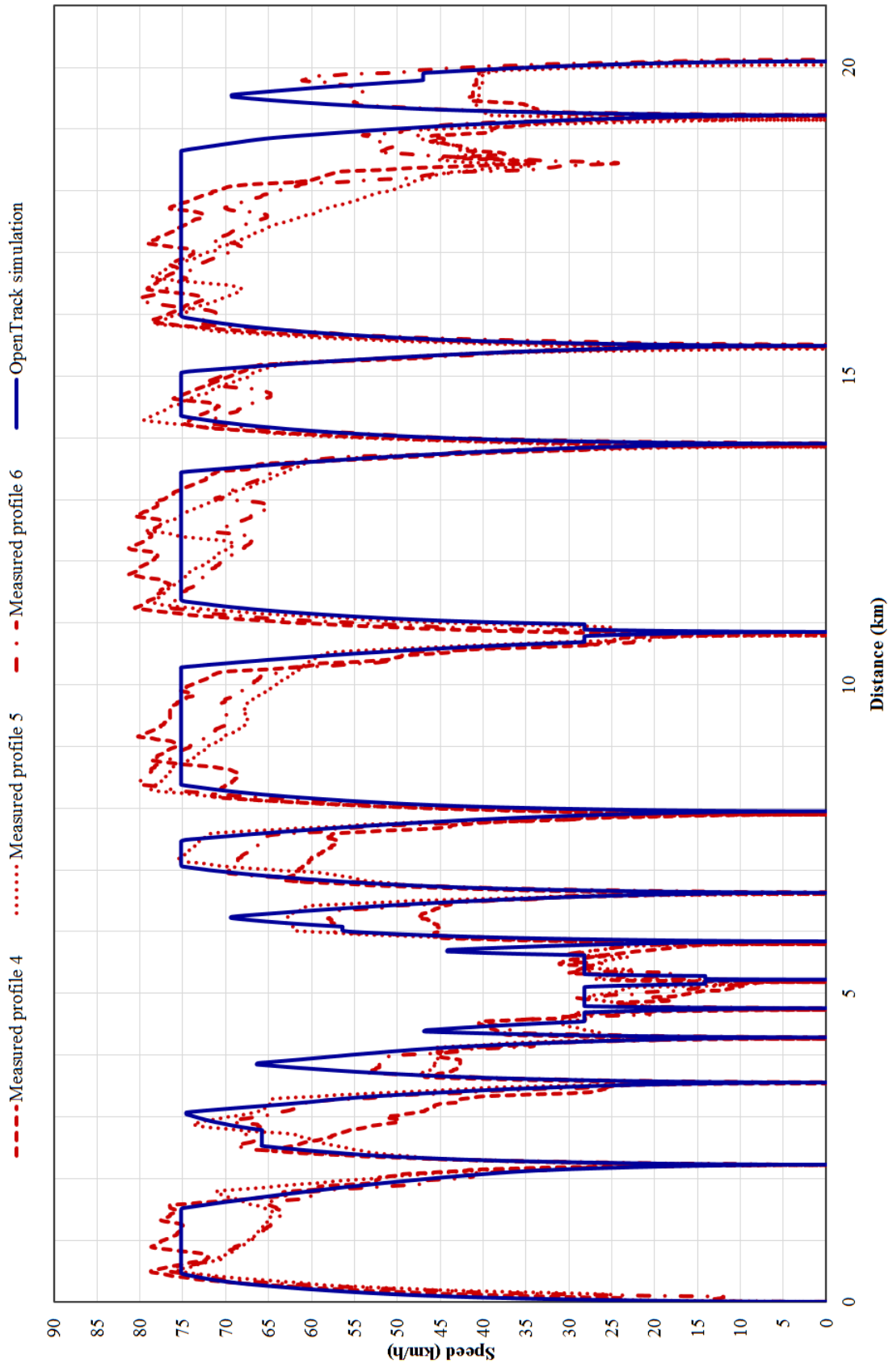


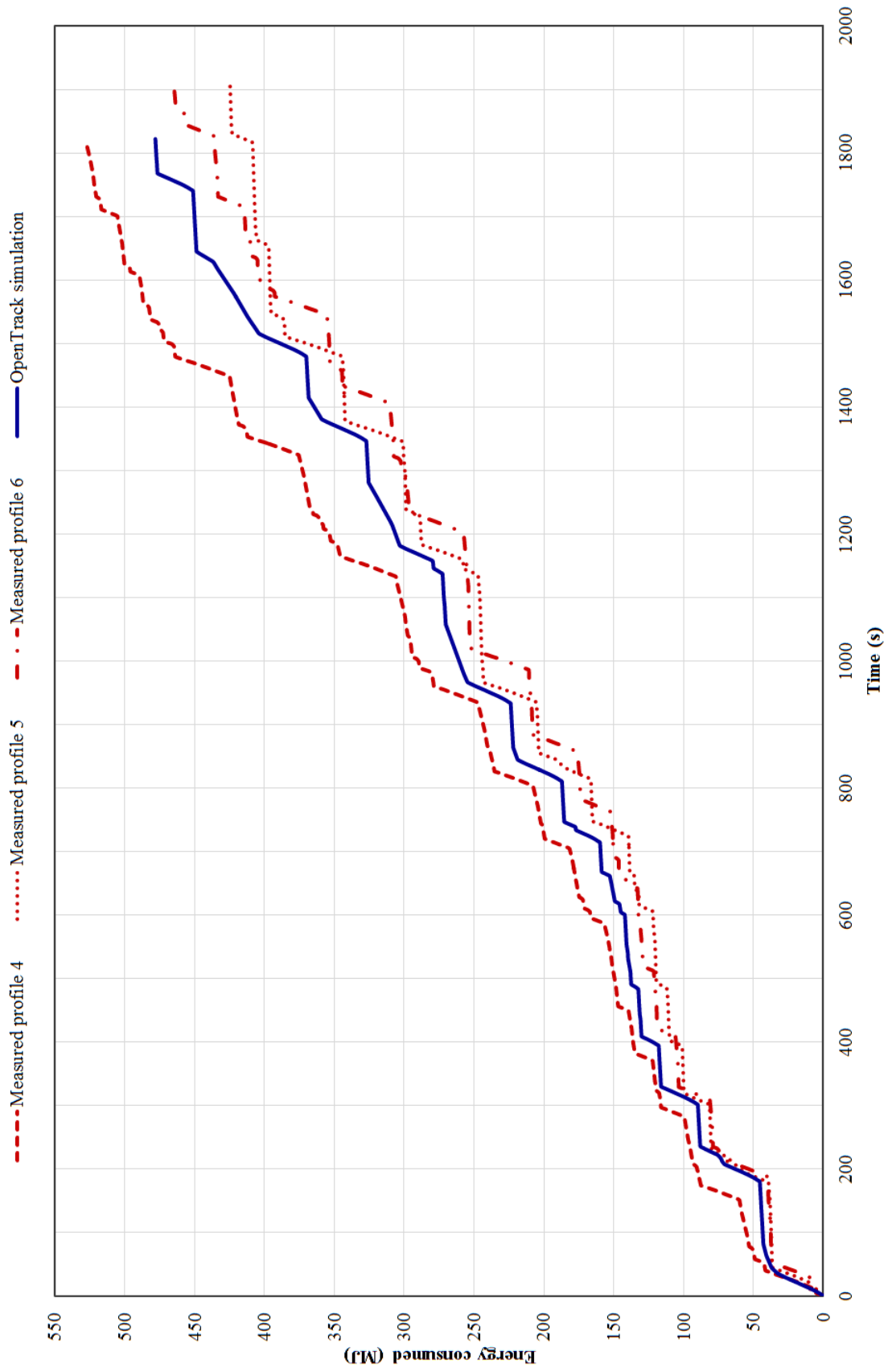
Figure 53: Metrocar speed-distance profiles (Heworth – South Hylton)



**Figure 54:** Metrocar energy-time profiles (Heworth – South Hylton)



**Figure 55:** Metrocar speed-distance profiles (South Hylton – Heworth)



**Figure 56:** Metrocar energy-time profiles (South Hylton – Heworth)



The results for journey time and energy consumption from the OpenTrack simulation show good agreement with the measured profiles, with a difference in inter-station journey times of 2-3% between the simulation results and the average of each of the three measured runs. This is within the 4% criterion defined in Chapter 3, and also less than the magnitude of day-to-day variation seen in the measured profiles.

One immediate difference that can be observed in the speed-distance profiles is driving style. It was noted in Section 5.6.2 that the performance setting in OpenTrack changes the cruising speed and the percentage of tractive effort while accelerating, and coasting is not used. In reality, the Metro drivers are constrained by the camshaft control and use a mixture of maximum tractive effort and free running, resulting in the sawtooth profiles seen. There is also a systematic difference in the speed profiles between Pelaw and Pelaw Metro Junction. Observations suggest that drivers are often subject to signal checks on this section, and as a result tend to coast at lower speeds before these signals rather than run close to the line speed limit. The difference that this makes to the station-to-station time between Pelaw and Fellgate is typically only around fifteen seconds over a four-minute journey, a difference of around 6%. The method for determining the driving style outlined in Section 5.6.2 will tend to average out such variation in driving style over the entire journey.

The match between the OpenTrack energy-time profile and measured profile number 1 is very good. Profile 2 is closer to all-out running, resulting in a reduced journey time but increased energy consumption. The relationship is not exact however: profile 3 has a longer journey time but also increased energy consumption, as longer dwell times provide a longer journey time in this case despite the driving style also being closer to all-out running than the OpenTrack profile.

Profile 4 also shows a large increase in energy over the modelled profile, including increased power draw while stopped at stations. This can be attributed to the weather as well as driving style: this journey was during a snowstorm with strong winds and low temperatures. Profiles 5 and 6 are both slower, and consumed less energy than the modelled profile, but again the exact relationship between journey time and energy consumption is affected by dwell times and weather. A further factor that may have an influence is differences in passenger numbers: although the load weighing system means the effect on journey times is minimal, it will affect energy consumption. Nonetheless, the percentage difference between the energy consumption calculated by the OpenTrack simulation and the average of the measured results was 1-3%, which is well within the day-to-day variation between measured profiles.

5.7.3. HST results (Swindon)

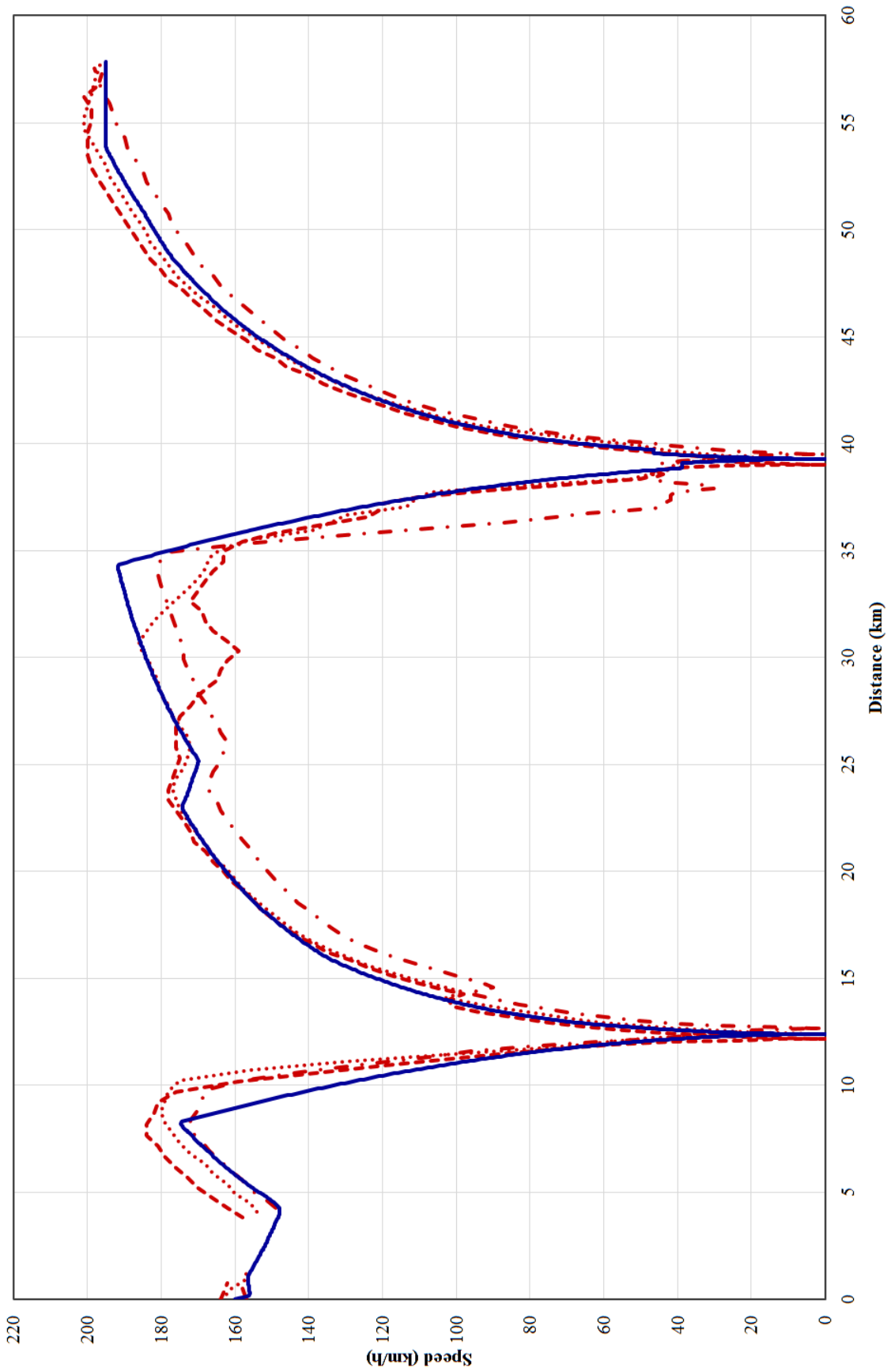
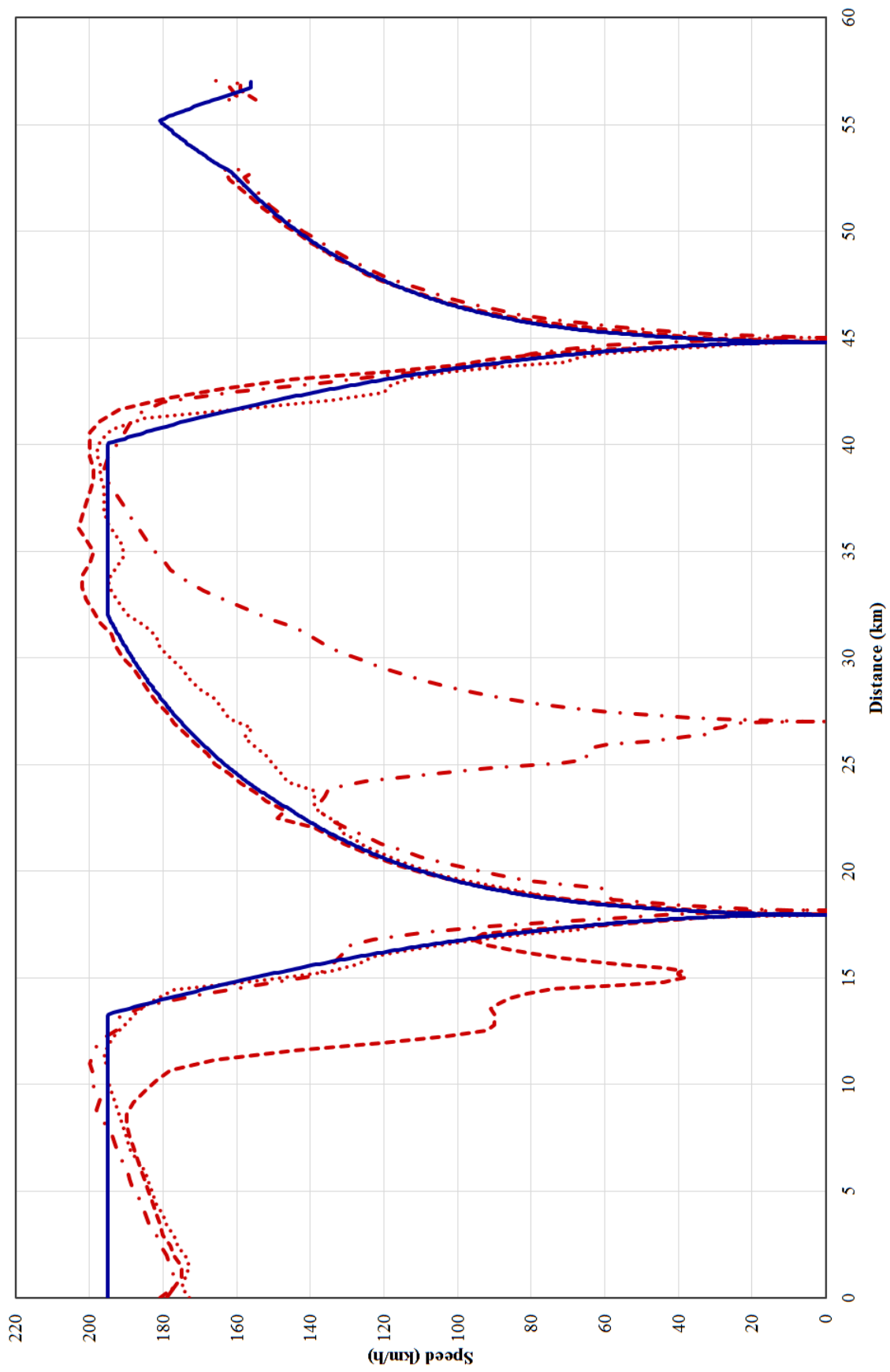
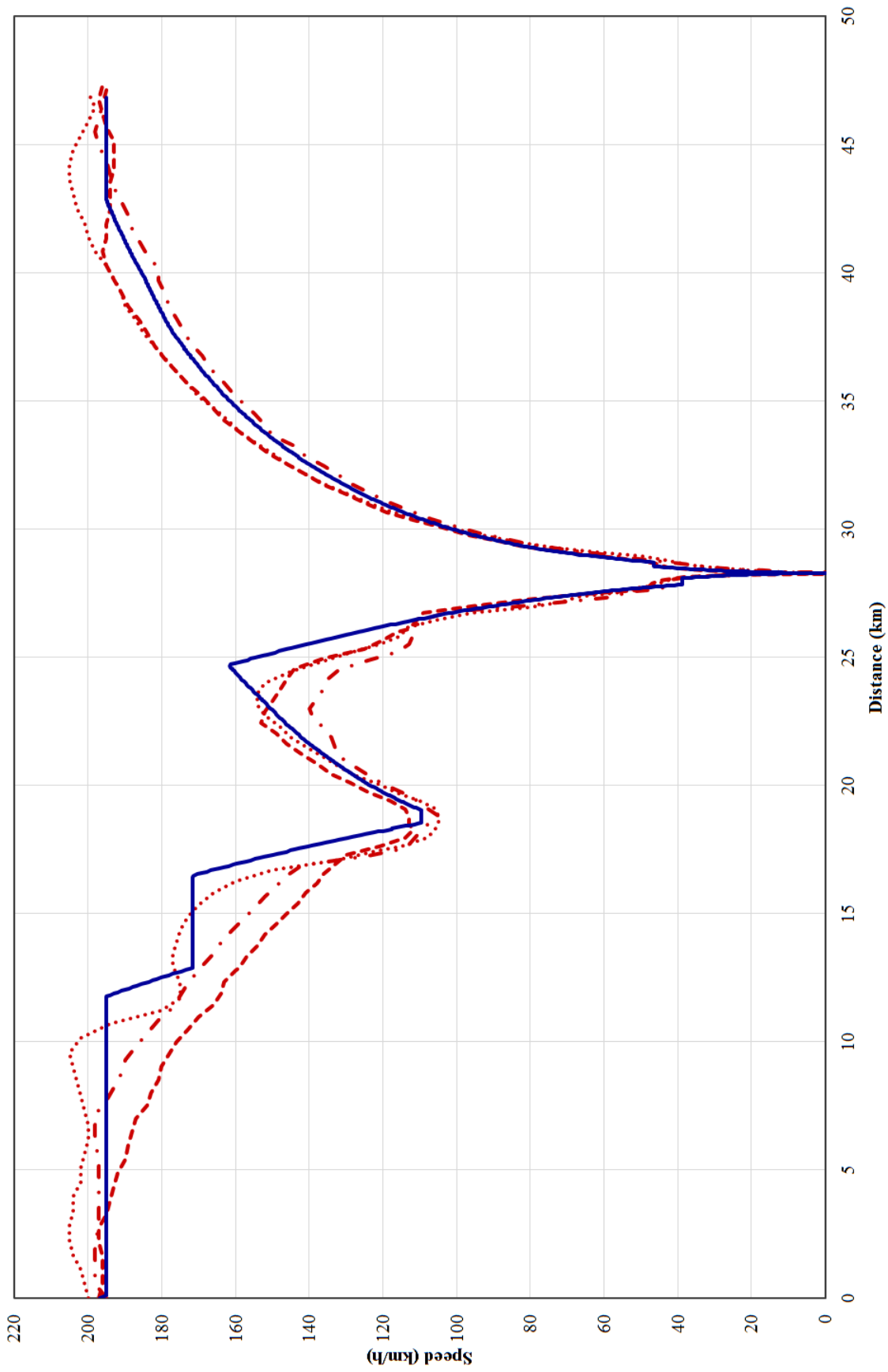


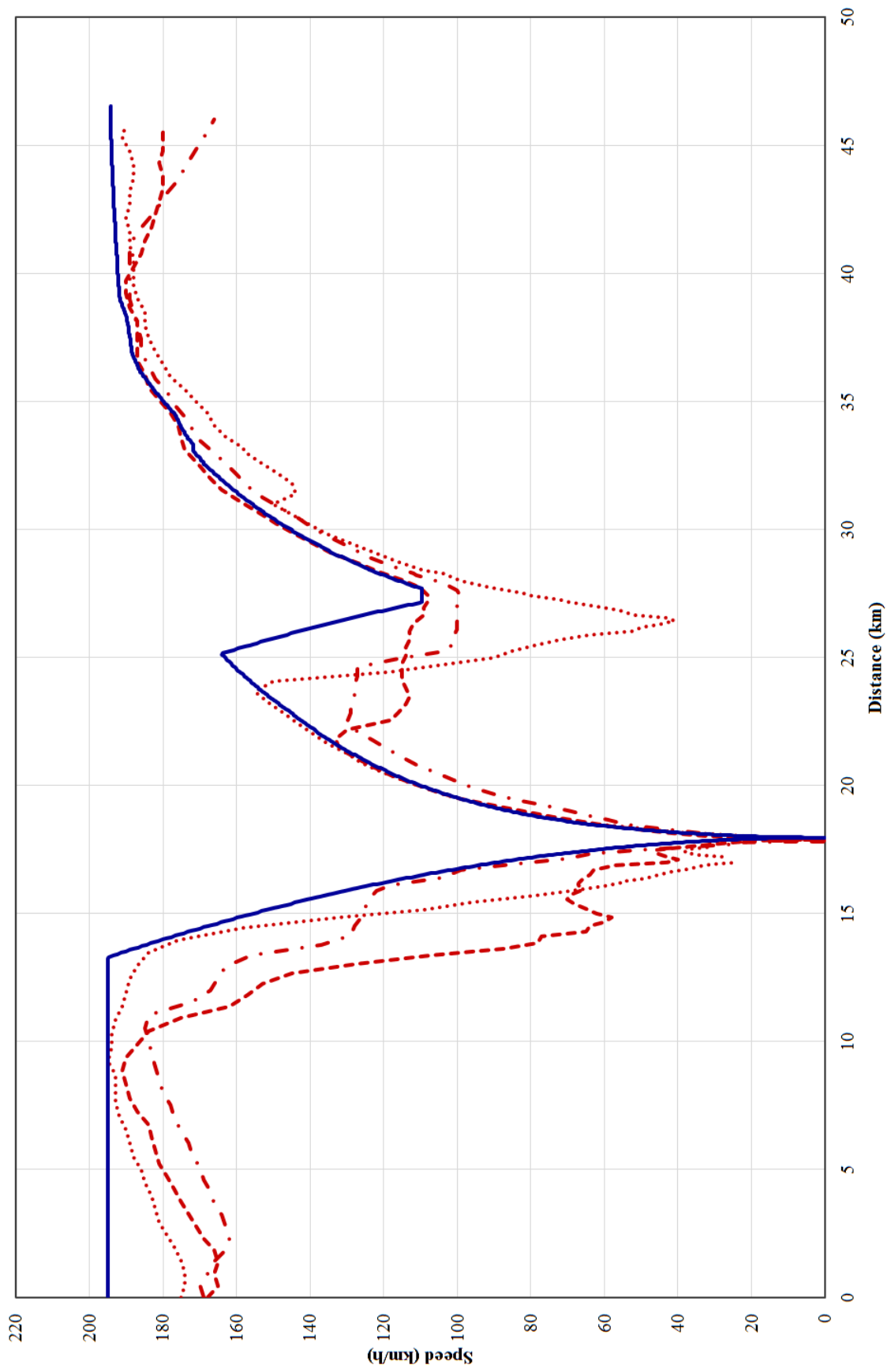
Figure 57: HST speed-distance profiles (Box – Uffington)



**Figure 58:** HST speed-distance profiles (Uffington – Box)



**Figure 59:** HST speed-distance profiles (Hullavington – Uffington)



**Figure 60:** HST speed-distance profiles (Uffington – Hullavington)

The HST profiles also show considerable variation in the measured speed profiles, and hence in the journey times that result. When compared to the Tyne and Wear Metro, the higher speeds and longer distances between stations, combined with the notched driver's throttle controller in the HST, mean that the OpenTrack approximation of cruising at constant speed is a generally a closer match to the HST profiles than the sawtooth profiles observed in the Metrocar data. However, it is clear from the profiles that coasting is also used.

The speed-distance profiles for the section between Box and Uffington illustrated in Figure 57 show a reasonable match between the OpenTrack results and measured profiles. A higher deceleration is consistently chosen when braking for Chippenham station, but the deceleration for the stop at Swindon is a close match to the OpenTrack model. One of the profiles features a slower approach to Swindon station, most likely due to adverse signals. The differences in journey times between the OpenTrack model and measured data are 2.6% to 4.7%.

In the reverse direction between Uffington and Box (illustrated in Figure 58), trains are also subject to unscheduled brake applications and stops, with adverse signals again the most likely reason. The difference in the journey time of the unaffected speed profile and the OpenTrack results is 1.4%. The measured profiles show trains passing Uffington and entering the area of the case study rather below the maximum line speed; this was due to a temporary speed restriction (TSR) in force immediately east of Uffington at the time the data was collected. Measured data was not available inside Box Tunnel.

The Hullavington to Uffington profiles illustrated in Figure 59 show the variation between different drivers in the amount of coasting on the approach to Wootton Bassett Junction, which resulted in journey times with a difference of 0.9% to 4.4% to the OpenTrack results. The deceleration during the braking phases for both Wootton Bassett Junction and Swindon is generally a good match to the value used for the OpenTrack model.

Figure 60 illustrates that trains running between Uffington and Hullavington were also subject to unscheduled brake applications, most likely due to adverse signals on the approaches to Swindon and Wootton Bassett Junction. The only measured profile not affected by these had a journey time difference of 4.8% to the OpenTrack results. The trains also appeared to be coasting from outside the case study boundary on the approach to the TSR at Uffington, and the choices made by different drivers for braking and coasting showed variation at both Wootton Bassett Junction and Hullavington. Overall, the OpenTrack journey times are within the ranges of the measured journey times, and within 4% of the average of the measured profiles not affected by delays due to signals or temporary speed restrictions.

5.7.4. Highland Main Line results

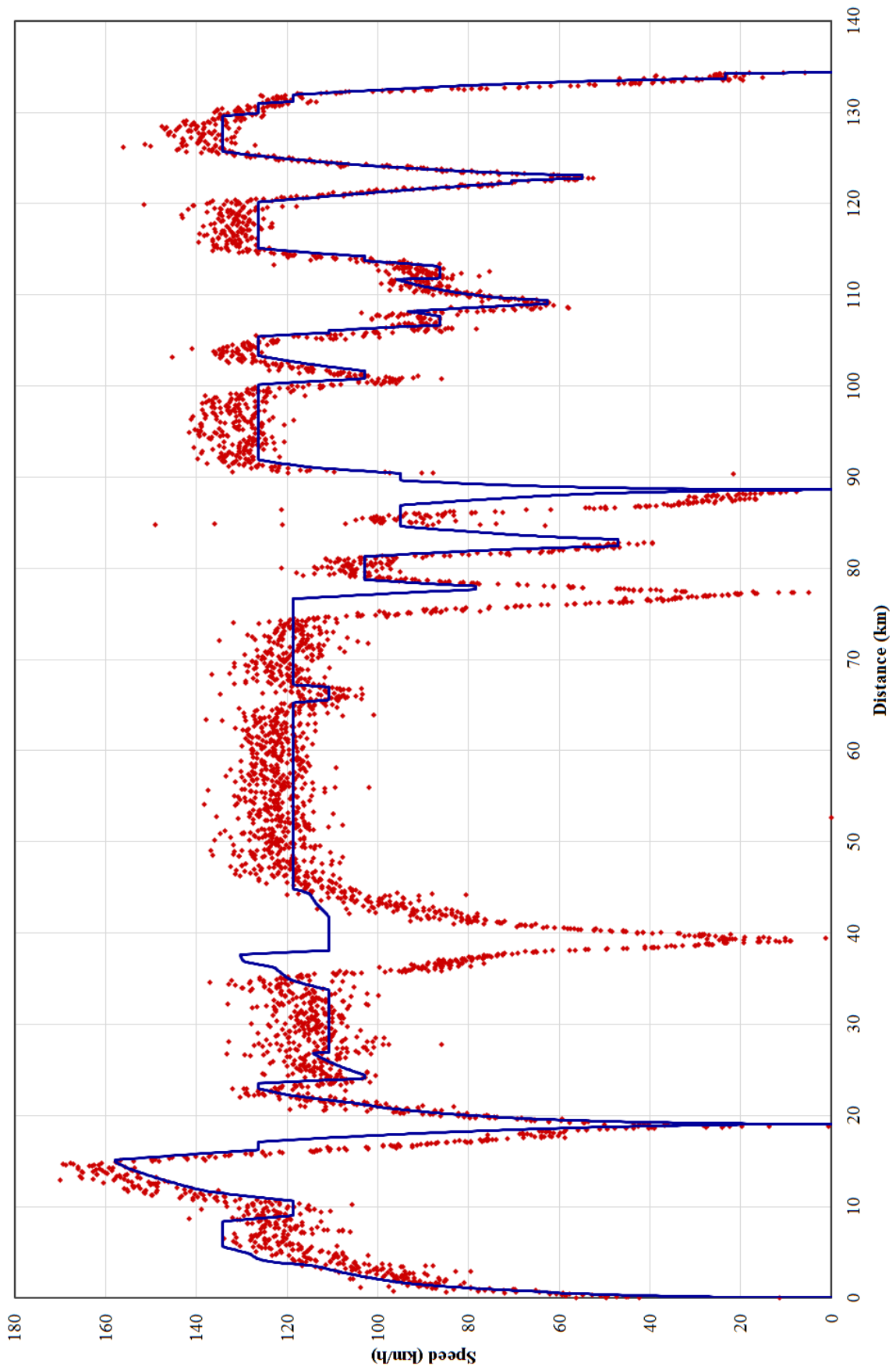
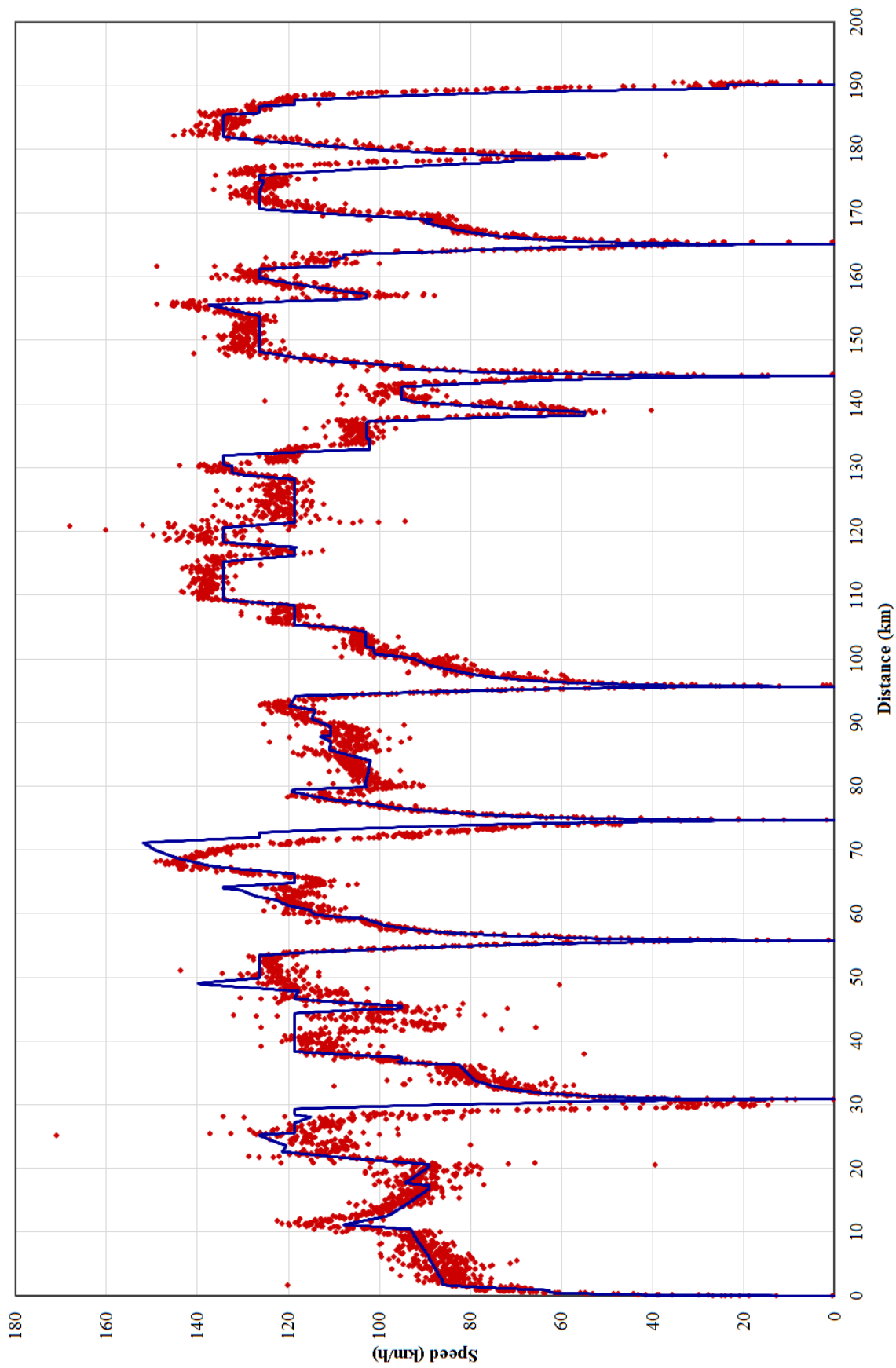


Figure 61: HST speed-distance profile (Aviemore-Perth)



**Figure 62:** Class 170 speed-distance profile (Inverness-Perth)



The correlation between the OpenTrack model results for the HST and GPS data in Figure 61 is generally very good during acceleration and braking. The Swindon HST data demonstrated that the speed profile while cruising is not expected to match the simulation exactly. There were some notable events in the actual journey that resulted in mismatch between the profiles. The train used the opposite platform at Kingussie to the model, and this required a reduced approach speed to the station. It was also stopped by signals at Dalwhinnie and Blair Atholl, and slowed on the approach to Pitlochry, due to following a slow-running rail head treatment train. Given the significant delays between Dalwhinnie and Pitlochry, which added around 15 minutes to the journey time, this section is not useful for validating the on-time run simulated by OpenTrack. The sections from Aviemore to Kingussie and Pitlochry to Perth could be used however, and the differences in journey times were 1.4% and 0.1% respectively. The published results from the iRFP FBS simulation software gave an energy consumption of 2380 kWh for an HST between Perth and Inverness. The corresponding result from the OpenTrack model was an energy consumption of 2286 kWh, a 3.9% difference. These figures are well within the required margin for successful validation.

The correlation between the Class 170 profiles in Figure 62 is also generally very good. The most notable difference is a considerably slower approach to Tomatin loop, where the train is scheduled to wait for six minutes to cross another service. There was also a brake application just north of Carrbridge, and a slower approach to Kingussie to use the opposite platform. The effect of the approach to Tomatin was to add around two minutes to the journey section time from Inverness, and it therefore does not match the OpenTrack results. The differences in journey time between the GPS data and OpenTrack results for the other sections are small, between 1.0% and 4.1%.

#### **5.7.5. Conclusions**

The variation in speed and energy consumption in the measured data reinforces the point made in Section 3.3.1: simulations generally aim to model an average day rather than try to replicate reality exactly. The OpenTrack results are a good match to the measured data, with the majority of the journey times and energy consumption results within the criteria detailed in Chapter 3. The differences are readily explained by observable factors, such as delays or weather. It can therefore be concluded that the models of the three case studies are reasonably representative of reality, and suitable for use in Chapter 6 for investigating the effects of linear motor technology. The suitability of multi-train simulation as the experimental method is considered further in Section 6.7.5, to complement the model validation in this chapter.

## CHAPTER 6. APPLICATIONS OF LINEAR MOTOR TECHNOLOGY

### 6.1. Introduction

This chapter considers the application of linear motor technology to the three case studies, to determine the effects on railway system capacity and energy consumption. The principal benefit of linear motor technology was highlighted previously in Chapter 2: increasing tractive and braking effort beyond what can be obtained with conventional rolling stock, which in turn can reduce journey times, delays and/or overall energy consumption. These benefits must be balanced against the additional cost and the energy consumed by the linear motor equipment. The results of the investigation into train movement and driving styles in Chapter 4 suggest that a suitable design target would be for drivers to consistently brake at the top end of the ranges of existing deceleration values measured, without increasing the adhesion demand above that of the measured average decelerations. This aims to provide the benefits alluded to above, while still respecting existing defensive driving requirements and limits for in-train forces.

The review in Chapter 2 also identified four potential implementations of linear induction motors using the running rails as the secondary, and these are described further in Section 6.2:

- DC eddy current brakes, currently in service on the ICE 3 trains in Germany
- The AC linear rail brake developed by RTRI in Japan
- The DC linear booster concept described in work by Darmstadt University/DB
- A linear induction motor (LIM) running at synchronous speed

This thesis also proposes a further concept as a fifth option, named LEMUR (Linear Electromagnetic Machine Using Rails). The initial concept outline was based on the findings of the literature review in Chapter 2, then developed and refined during the analysis of the other four options, with the aim of addressing the weaknesses identified when they were applied to the case studies. The background and development of the concept are described in Section 6.3.

The principal aim of the experiment described in this chapter is therefore to measure the effect of these five applications of linear motor technology on capacity and energy consumption in the three case studies, and hence test the hypothesis detailed in Chapter 3. The experimental method used is described in Section 6.4, and subsequent sections detail the results and analysis.

## **6.2. Existing Linear Motor Options**

### **6.2.1. DC eddy current brakes**

Although DC-fed linear eddy current brakes (ECBs) are not strictly linear motors, they use similar principles to provide adhesion independent braking forces (ECBs may be considered analogous to LIMs operated with DC injection braking only). The characteristics of the ECBs fitted to the ICE 3 trains were used for this experiment, providing a braking force of 20 kN per two-axle bogie above 100 km/h, ramping down to zero at 50 km/h. The maximum forces available are illustrated in Figure 9 in Section 2.2.3. The maximum power drawn is 86 kW, and the mass of the equipment on the bogie is 860 kg.

### **6.2.2. RTRI linear rail brake**

The RTRI linear rail brake (LRB) was developed as an alternative to ECBs, with reduced rail heating and no external power supply required. The characteristics were taken from the modified bogie used for on-track tests at RTRI (Sakamoto *et al.*, 2014), which can provide a braking force of 10 kN per two-axle bogie above 50 km/h.

The mass of the LRB in the test bogie was 610 kg, but further equipment would be required to mount it to a bogie in actual service (rather than the test bogie), so the mass is likely to be similar to an ECB. However, the inverter on the vehicle would be larger than the DC power supply for an ECB.

### **6.2.3. DB/Darmstadt linear booster**

The DC linear booster (DLB) designed by Darmstadt University is another option that is not strictly linear motor technology, but shares common ground with ECBs. It is intended to be fitted to locomotives to maximise tractive effort at low speeds in low adhesion conditions, by increasing the vertical force between wheel and rail, and the Darmstadt analysis considered the potential benefits (Werle, 2003).

The conclusions of Chapter 4 suggest that an alternative application may be to fit the equipment to bogies throughout the train, to increase the braking effort for a given coefficient of friction between wheel and rail. The variation of vertical attractive force (*Normalkraft*) and longitudinal braking force (*Tangentialkraft*) with speed (*Geschwindigkeit*) are illustrated in Figure 63. The power drawn is around 14-21 kW per bogie from 0-200 km/h, with the overall mass of equipment on the bogie likely to be similar to the LRB. The small longitudinal forces mean that rail heating per bogie is around 30 times lower than for ECBs.

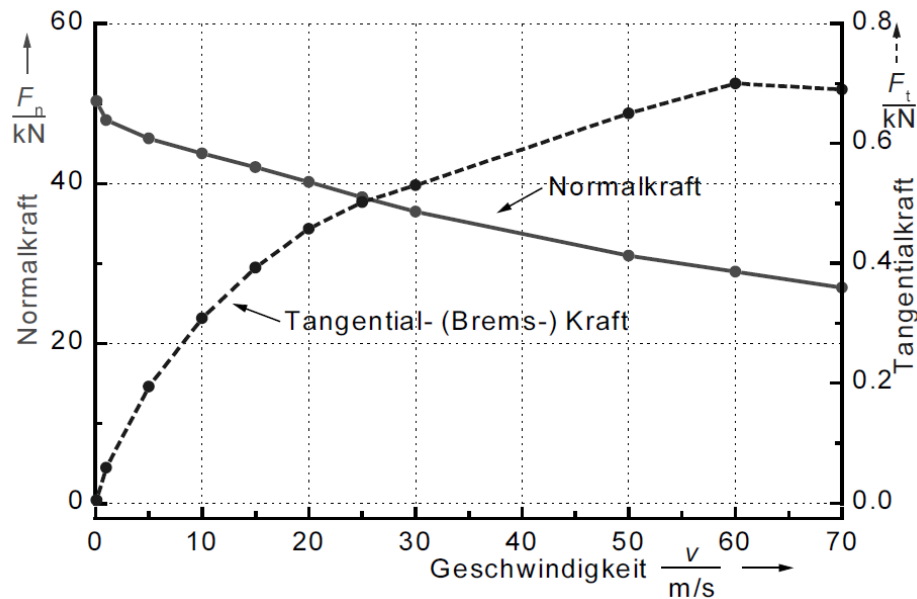


Figure 63: DLB force characteristics (Werle, *ibid.*)

#### 6.2.4. Zero slip linear induction motor

A German patent identified during the review in Chapter 2 described the use of a linear induction motor running at synchronous speed (zero electrical slip) to provide an extra attractive force between wheel and rail, principally to increase resistance to vehicle rollover in crosswinds (Konrad and Heidt, 2000). However, no research was found during the literature review for this thesis that analysed the potential development and application of this idea to traction and braking.

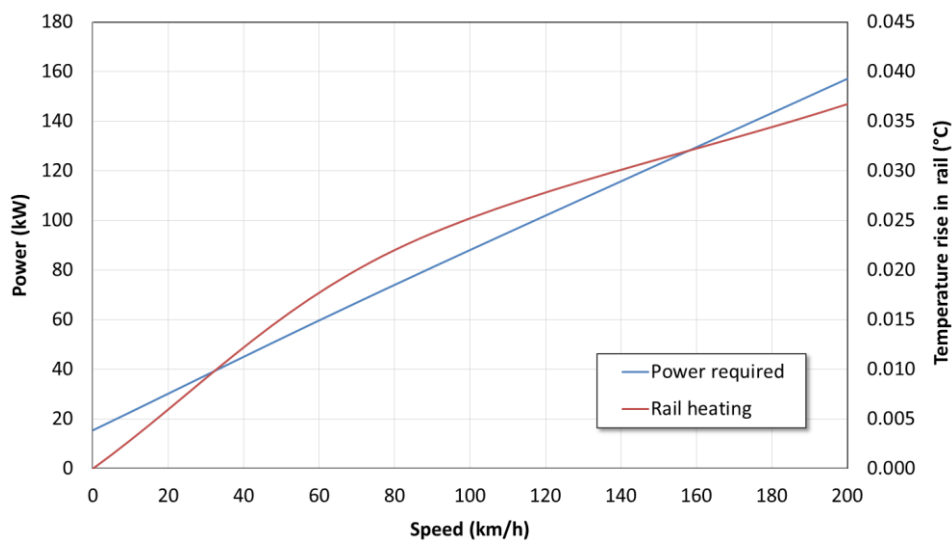
The zero slip linear induction motor (ZSL) concept is based on a hybrid rotary/linear traction system, with LIM primaries mounted between the axles of a bogie in the same way as the other options outlined above. The attractive vertical force from the LIM effectively increases the adhesive weight of the vehicle (in the same way as DLBs) to allow greater efforts to be transmitted by existing traction and braking equipment. A number of conclusions can be drawn about the concept from induction machine theory (Boldea and Nasar, 2010):

- The vertical attractive force produced by a LIM can be around an order of magnitude greater than the maximum longitudinal force, although the tractive effort available from a conventional rotary traction system is greater still.
- For a given longitudinal force, the energy efficiency of a conventional rotary traction system is significantly higher than that of a traction system using only a LIM with a narrow solid steel secondary.
- The vertical force is a maximum when operating a LIM at synchronous speed, although the longitudinal force is zero.

- The energy consumed by the LIM at synchronous speed is lower than the energy consumption when providing a longitudinal force.
- The secondary (rail) heating is also likely to be close to the minimum at synchronous speed.

These points imply that operating a LIM at synchronous speed will provide the greatest improvement in adhesion for the conventional rotary drive, with lower rail heating than if longitudinal forces are generated directly. Although designing a motor to operate with zero efficiency initially appears counterintuitive, the basis of the concept is that the LIM consumes a relatively small amount of energy but allows the conventional traction equipment to develop significantly higher tractive/braking effort, at a higher efficiency than would be possible if the LIM was providing the extra longitudinal force. This is a novel approach by comparison with previous research found in academic literature, where the focus was on the energy consumed and longitudinal forces provided by the LIM.

To accurately determine the performance of a LIM requires detailed 3D finite element modelling (Boldea and Nasar, *ibid.*, p. 611), and for the unusual case of a short primary motor with a narrow steel rail profile for the secondary component, the construction of a prototype to verify the modelling and validate the performance (Sakamoto *et al.*, 2012a). A test rig was constructed at Newcastle University that confirmed a vertical force of 40 kN could be provided for a two-axle bogie between 0 and 200 km/h (Martin *et al.*, 2016). The power drawn (per bogie) and rail heating is illustrated in Figure 64.



**Figure 64:** Modelled ZSL input power and rail heating characteristics (Martin *et al.*, 2016)

The estimated mass of the equipment is similar to LRBs, and the rail heating per bogie is around ten times lower than ECBs.

### **6.3. The LEMUR concept**

#### ***6.3.1. Background and development***

The most significant research projects (for this thesis) studying linear induction motors using the running rails as the secondary component were the on-track testing by MTE in France (Machefert-Tassin, 1971), the analysis carried out by Darmstadt University in Germany (Werle, 2003) and the RTRI linear rail brake in Japan (Sakamoto *et al.*, 2014). A number of observations were made about the results, from which the LEMUR concept was developed.

Firstly, the energy consumed is very high relative to the modest traction forces produced, which suggests that using a LIM to augment the traction system in low adhesion conditions cannot be justified in isolation. This is a likely reason why such a system has not been implemented in practice, despite the number of patents over the last few decades. It was concluded in Chapter 4 that low adhesion conditions provides a much greater constraint on braking forces than traction, which suggests that braking is a more promising application. In addition, the MTE and Darmstadt results both indicated that the braking effort that can be obtained is rather greater than the tractive effort. Operating the LIM as a generator to provide the braking forces also largely removes the problem of high energy consumption as regenerative braking is possible. This is the basis of the LRB developed by RTRI.

The second observation is that an important weakness of ECBs and LRBs is that they are only active above 50 km/h. For ECBs, this is due to the reductions in longitudinal force available and the very high vertical forces at low speed, and for LRBs the energy recovered from the kinetic energy of the train is also insufficient to feed the losses in the primary. At lower speeds, it also becomes more difficult to supply very low frequency AC. To overcome this problem, it is possible to include additional equipment that allows the LIM to be supplied with energy from the main traction or auxiliary supply, and allowing surplus regenerated brake energy to be recovered at higher speeds. An energy storage system could also be used in conjunction with the traction or auxiliary supply. At very low speeds, where the frequency required or the forces generated are too low, the LIM can be switched from generating to plugging operation. The vertical forces of a LIM operating away from synchronous speed are significant, and can be exploited to improve adhesive weight, but they are well below those of similarly sized ECBs at lower speeds.

Thirdly, Chapter 4 demonstrated that the conscious choice of defensive driving during braking is the main constraint on deceleration values achieved in day-to-day operation. This is a preventative approach intended to minimise potential risks in case low adhesion conditions

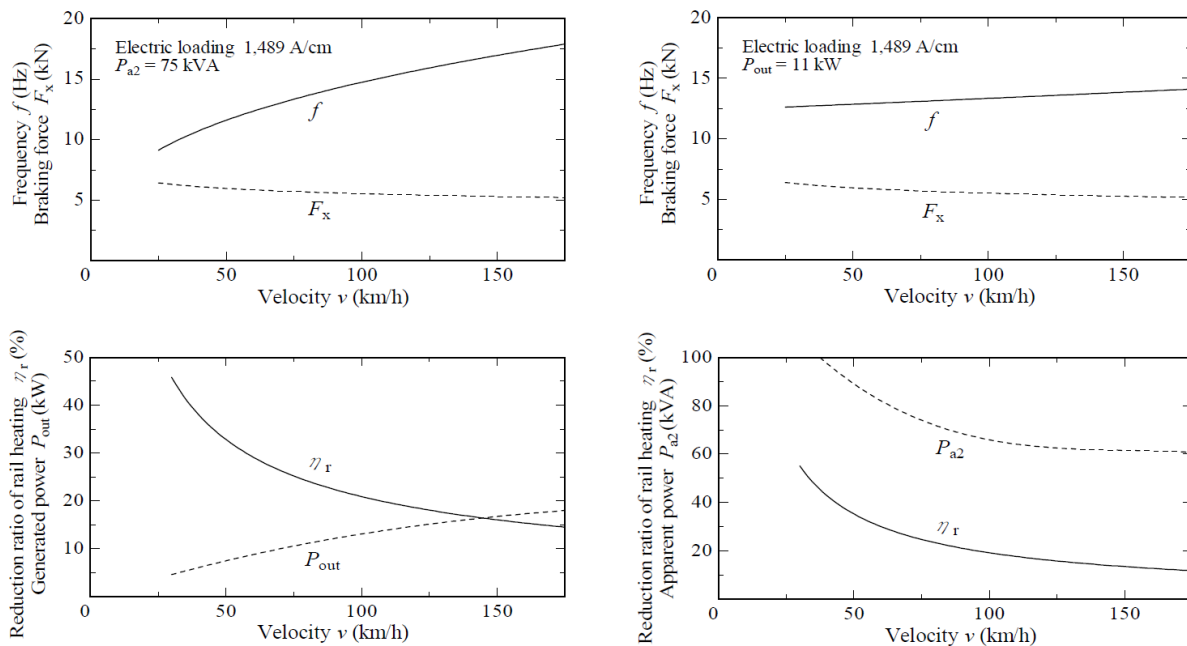
are present, rather than a reactionary approach that depends on the actual level of adhesion. With a LIM present, higher deceleration values could be used. The LIM would only operate in generating mode, to obtain the benefits of energy recovered through regenerative braking and reduced wear on friction brakes, with conventional brakes providing all of the deceleration at low speed. Operation in plugging mode then becomes part of the wheel slip protection (WSP) strategy, providing adhesion-independent braking forces as and when they are required, so that the overall risks associated with low adhesion conditions are no higher than if the more conservative deceleration values associated with current defensive driving and rolling stock are used. Plugging can consume a significant amount of energy, and potentially lead to rail heating similar to ECBs, so using it in case of low adhesion conditions only (rather than all brake applications) is beneficial. The higher deceleration values suggested from Chapter 4 are still below the values required by the signal spacing standards for emergency braking of existing rolling stock using conventional friction brakes only. This suggests that the LIM would not necessarily need to be considered safety-critical, although it does have the potential to improve railway safety if also used as part of the emergency braking system.

There are two further findings from Appendix A that are relevant. Adhesion tends to be lower at high speeds, especially during wet weather, which further reduces the likelihood that the use of plugging is required. Secondly, hot and sunny conditions (where increases in rail temperature are more of a concern) are not likely to be associated with low adhesion. Low adhesion is more likely in damp conditions, and moisture has the potential to assist cooling of the rails, although the magnitude of this effect is not known. This also suggests that the higher rail heating associated with plugging may be less important.

The LEMUR concept can therefore be described as a linear induction motor using the running rails as the secondary component, providing additional adhesion-independent braking forces to augment an existing braking system. At higher speeds, it is operated as a generator to provide energy recovery through regenerative braking, reduce rail heating and reduce wear of friction brakes. At lower speeds, the conventional braking system takes over, but it remains possible to operate the linear motor in plugging mode down to zero speed, in order to provide adhesion-independent braking forces if very low wheel/rail adhesion is encountered. The increased vertical forces that are generated will also increase adhesion for the existing braking system. Increasing the regenerative braking power will also reduce the heat input to the rails, but the increase in reactive power required means that the on-board equipment will be heavier and more expensive as a result. Optimising this trade-off requires specific consideration of the design and operation of the rolling stock in question.

### 6.3.2. Performance specification

A specification was developed using published figures from the LRB development, where on-track tests have demonstrated that a braking force of 10 kN per bogie is possible (Sakamoto *et al.*, 2014). Power generation characteristics were derived in an earlier RTRI paper from test rig figures (Sakamoto *et al.*, 2008), and these are illustrated in Figure 65 for operation with a constant apparent power of 75 kVA (left) and a constant power output of 11 kW (right).



**Figure 65:** RTRI LRB performance estimates (Sakamoto *et al.*, 2008)

As noted in Section 6.3.1, increasing the maximum acceptable reactive power would allow for a higher regenerative braking power. For this experiment, the published figures for a constant reactive power of 75 kVA were used.

It was also assumed that plugging would not be used in day-to-day operation, and so the energy consumed would be likely to remain small. However, a sensitivity test was carried out to examine how changes in regenerative braking power and the use of plugging would likely affect overall energy consumption. The intention was to investigate whether a higher regenerative braking power would be worthwhile, and also whether the assumption about plugging energy consumption being small was valid. Three cases were tested in total: regeneration only (in accordance with Figure 65), regeneration but no net power output (effectively operating in the same way as LRBs), and plugging only (at an assumed power consumption of 100kW per bogie below 40 km/h). The results and implications of this sensitivity study are considered further in Section 6.7.4.



## 6.4. Experimental Methods

### 6.4.1. Design specifications

This section details the translation of the characteristics of each of the five linear motor technology options into rolling stock performance specifications for the three case studies. The basic requirement for these specifications was to determine the number of bogies in each train that should be fitted with linear motor equipment in order to achieve the target decelerations required in each case.

The relationship between the additional vertical and longitudinal forces and the change in deceleration of a train can be derived from the equations of motion:

$$\sum F = m_e \cdot a \quad (2)$$

The translational motion of vehicles along the track and the rotational motion of the wheelsets and elements of the traction system are both considered, with the extra work done to change the kinetic energy of the rotating parts accounted for by using an effective mass  $m_e$ . This can be expressed in terms of a coefficient  $\lambda$ :

$$m_e = m \cdot \lambda \quad \text{where} \quad \frac{1}{2} \cdot m_e \cdot v^2 = \frac{1}{2} \cdot m \cdot v^2 + \sum_{i=1}^n \left( \frac{1}{2} \cdot I_i \cdot \omega_i^2 \right) \quad (3)$$

The expression for effective mass can be substituted into Equation 2, and the forces identified explicitly (tractive/braking effort, the train's resistance to motion, and the force due to gravity if running on a gradient):

$$a = \frac{(F_{TE} - F_{BE} - F_r - F_g)}{m \cdot \lambda} \quad (4)$$

The braking effort from conventional friction brakes (acting on all axles of a train) can be expressed as a function of the required coefficient of adhesion  $\mu$ :

$$F_{BE1} = \mu \cdot R = \mu \cdot m \cdot g \quad (5)$$

The longitudinal force  $F_L$  and vertical force  $F_V$  provided by linear motor equipment can be added into the above expression, with braking effort and attractive force defined as positive in this case. The (non-rotating) mass  $m_x$  of this extra equipment is also included, and the adhesion demand is assumed to remain unchanged:

$$F_{BE2} = F_L + \mu \cdot ((m + m_x) \cdot g + F_V) \quad (6)$$

These equations can be combined to determine the change in deceleration values during braking when the influence of the additional longitudinal and vertical forces is considered:

$$a_2 - a_1 = \frac{(-F_L - \mu \cdot ((m + m_x) \cdot g + F_V) - F_{r2} - F_{g2})}{m \cdot \lambda + m_x} - \frac{(-\mu \cdot m \cdot g - F_{r1} - F_{g1})}{m \cdot \lambda} \quad (7)$$

Section 6.2 suggests that the extra mass associated with linear motors is small when compared to the mass of the train as a whole:

$$m_x \ll m, m_e \Rightarrow \frac{m + m_x}{m \cdot \lambda + m_x} \approx \frac{m}{m \cdot \lambda} \quad (8)$$

The differences in the components of acceleration due to the resistance to motion and track gradients are also likely to be small when  $m_x \ll m, m_e$ . Applying these simplifications to Equation 7 results in the following approximation, which can be used to provide a reasonable estimate of the forces required from a linear motor to achieve a given increase in deceleration:

$$a_2 - a_1 \approx -\frac{F_L + \mu \cdot F_V}{m \cdot \lambda + m_x} \quad (9)$$

This approximation was applied to all of the possible rolling stock/linear motor combinations for the three case studies. This determined either the number of bogies to fit with linear motor equipment to achieve the target deceleration, or the deceleration possible if all bogies were fitted and the target remained unachievable. The extra mass (and the resulting effect on resistance to motion) was also estimated and applied to the simulation models, although this was somewhat constrained as OpenTrack has a resolution of one tonne for vehicle masses.

The revised rolling stock was then tested in single train simulation runs to determine the driving performance required to meet the timetables in the case studies, in the same way as described previously in Section 5.6.2. The full specifications are detailed in Section 6.5.

#### **6.4.2. Multi-train simulation**

The second stage was to analyse the changes in capacity and energy consumption when the different linear motor options were applied to each of the case studies. The method for analysing capacity outlined in Chapter 3 was applied: 100 individual simulation runs were carried out for each viable combination of rolling stock, signalling and linear motor technology. Each run represented a full 24-hour period, using OpenTrack's built in delay scenarios to define initial delays in accordance with the delay distributions defined in Section 5.6.3. The timetable stability was derived from the final delays measured, and the total energy consumption of the trains was recorded. The results are given in Section 6.6.

## 6.5. Rolling Stock Specifications

### 6.5.1. Tyne and Wear Metrocar

An initial assumption was made that all bogies on the same vehicle should be fitted with linear motor equipment, to prevent the vertical forces causing significant imbalances in axle load between different axles on the same vehicle. Further research may show this conservative precaution to be unnecessary, however detailed vehicle and suspension dynamics modelling is outside the scope of this thesis. Therefore, as each individual Metrocar is an articulated twin-section vehicle, it was assumed that all bogies should be fitted.

The maximum permitted axle load on some parts of the Tyne and Wear Metro system is 12.5 t. The crush-laden mass of a six-axle Metrocar is 62.5 t, and so the vertical attractive force generated by linear motor equipment was capped at around 20 kN per axle. This imposed a limit on the performance of DLBs. Other options (ECB, LRB and LEMUR) did not need to be limited, as the requirement for all bogies to be fitted meant that the equipment on each individual bogie would be operating well below its maximum rating to achieve the target deceleration for the train.

The Metrocar bogies are currently fitted with magnetic track brakes, which clamp onto the rail, rather than inducing currents in it. For the purposes of the case study, it is assumed that the linear motor equipment replaces the track brakes. If carried out in reality, this may affect signalling arrangements elsewhere in the Tyne and Wear Metro system, but the issue is specific to this rolling stock and not of importance for the experiment as a whole.

Table 4 summarises relevant data from the train specifications that result. The deceleration varies across the speed range for ECBs and LRBs as they are deactivated below 50 km/h, and for DLBs as the longitudinal force varies for a constant value of vertical force. The equipment utilisation is the proportion of the maximum rated vertical/longitudinal forces actually used.

	Linear motor technology option					
	(none)	ECB	LRB	DLB	ZSL	LEMUR
Number of bogies fitted	-	6 / 6	6 / 6	6 / 6	6 / 6	6 / 6
Deceleration (m/s <sup>2</sup> )	0.5	0.5-0.7	0.5-0.7	0.6-0.62	0.6	0.7
Train mass (t)	84	84	86	84	86	86
On-time performance (%)	94	≥94	≥94	91	91	89
Equipment utilisation (%)	-	14	26	40-50	100	26

**Table 4:** Linear motor technology options – Tyne and Wear Metrocar

In the case of ECBs and LRBs, the effect of the increased train mass more than offset the effect of the increased deceleration, requiring an increase in driving performance relative to the base case (with no linear motor equipment) to maintain the same journey times. As such, ECBs and LRBs are not viable options to increase timetable stability in this case.

### 6.5.2. Class 150 DMU

The individual vehicles in a Class 150 DMU are essentially self-contained units, and as such it was assumed that all bogies should be fitted (in the same way as the Tyne and Wear Metrocar). Class 150s are also able to take advantage of SP differential speed limits, and are around eight tonnes per vehicle lighter than the heaviest qualifying rolling stock (Class 171). Therefore, the 20 kN per axle vertical limit was also applied so that the SP differential speed limits could still apply. Table 5 summarises the resulting specifications:

	Linear motor technology option					
	(none)	ECB	LRB	DLB	ZSL	LEMUR
Number of bogies fitted	-	4 / 4	4 / 4	4 / 4	4 / 4	4 / 4
Deceleration (m/s <sup>2</sup> )	0.29	0.29-0.5	0.29-0.5	0.34-0.37	0.34	0.5
Train mass (t)	80	83	83	84	84	84
On-time performance (%)	95	≥95	≥95	94	94	93
Equipment utilisation (%)	-	22	43	40-60	100	43

**Table 5:** Linear motor technology options – Class 150 DMU

As for the Metrocar case, ECBs and LRBs do not provide benefits to timetable stability.

### 6.5.3. Class 156 DMU

The effects of the linear motor technology options on the Class 156 DMU are very similar to the Class 150, and are summarised in Table 6:

	Linear motor technology option					
	(none)	ECB	LRB	DLB	ZSL	LEMUR
Number of bogies fitted	-	4 / 4	4 / 4	4 / 4	4 / 4	4 / 4
Deceleration (m/s <sup>2</sup> )	0.29	0.29-0.5	0.29-0.5	0.34-0.37	0.34	0.5
Train mass (t)	76	79	79	80	80	80
On-time performance (%)	90	≥90	≥90	89	89	88
Equipment utilisation (%)	-	21	41	40-60	100	41

**Table 6:** Linear motor technology options – Class 156 DMU

#### 6.5.4. Class 170 DMU

The same reasoning for fitting all bogies of the Class 150 also applies to the Class 170. The vehicles are heavier however, which means that the additional vertical forces from linear motor equipment would prevent the Class 170 from being able to run at SP differential speed limits. The DLBs are however no longer limited to 20 kN of vertical force. At the deceleration levels considered, the reduction in vertical forces and increase in longitudinal forces with increasing speed (as illustrated in Figure 63) balanced to result in an approximately constant deceleration across the speed range. Table 7 summarises the overall specifications:

	Linear motor technology option					
	(none)	ECB	LRB	DLB	ZSL	LEMUR
Number of bogies fitted	-	6 / 6	6 / 6	6 / 6	6 / 6	6 / 6
Deceleration (m/s <sup>2</sup> )	0.31	0.31-0.5	0.31-0.5	0.43	0.36	0.5
Train mass (t)	147	150	153	150	153	153
On-time performance (%)	98	≥98	≥98	≥98	≥98	≥98
Equipment utilisation (%)	-	24	47	100	100	47

**Table 7:** Linear motor technology options – Class 170 DMU

None of the linear motor options are viable in this case.

#### 6.5.5. Class 43 (HST)

Unlike the multiple units already considered, HST sets consist of two power cars and a rake of trailer coaches. The power cars already have a high axle load, and limited space in their bogies for additional equipment, and as such the specification was developed on the basis of only fitting trailer bogies with linear motor equipment. There are different numbers of trailer coaches in each case study: Table 8 summarises the data for Tyne and Wear (six coaches), Table 9 for Swindon (eight coaches) and Table 10 for the Highland Main Line (nine coaches).

	Linear motor technology option					
	(none)	ECB	LRB	DLB	ZSL	LEMUR
Number of bogies fitted	-	4 / 16	8 / 16	12 / 16	12 / 16	8 / 16
Deceleration (m/s <sup>2</sup> )	0.31	0.31-0.5	0.31-0.5	0.4	0.35	0.5
Train mass (t)	357	361	365	366	369	365
On-time performance (%)	90	≥90	≥90	88	89	87
Equipment utilisation (%)	-	83	81	100	100	81

**Table 8:** Linear motor technology options – HST (six coaches)

As with the Class 156 and Metrocar that also feature in the Tyne and Wear case study, ECBs and LRBs are not viable options.

	Linear motor technology option					
	(none)	ECB	LRB	DLB	ZSL	LEMUR
Number of bogies fitted	-	6 / 20	10 / 20	16 / 20	16 / 20	10 / 20
Deceleration (m/s <sup>2</sup> )	0.31	0.31-0.5	0.31-0.5	0.4	0.35	0.5
Train mass (t)	446	451	456	458	462	456
On-time performance (%)	91	89	90	90	90	88
Equipment utilisation (%)	-	69	81	100	100	81

**Table 9:** Linear motor technology options – HST (eight coaches)

All of the linear motor options are viable for the HSTs in the Swindon case study.

	Linear motor technology option					
	(none)	ECB	LRB	DLB	ZSL	LEMUR
Number of bogies fitted	-	6 / 22	10 / 22	18 / 22	18 / 22	10 / 22
Deceleration (m/s <sup>2</sup> )	0.31	0.31-0.5	0.31-0.5	0.4	0.35	0.5
Train mass (t)	484	489	494	497	502	494
On-time performance (%)	98	97	97	97	≥98	96
Equipment utilisation (%)	-	75	88	100	100	88

**Table 10:** Linear motor technology options – HST (nine coaches)

ZSLs are the only option that is not viable in the Highland Main Line case study.

### 6.5.6. Class 66 locomotive

Class 66 locomotives have three-axle bogies, with less distance between the axles and therefore less space for linear motor equipment compared to Class 43 bogies, and so again only trailing vehicle bogies were considered. However, the axle load for fully loaded freight wagons can be up to the absolute maximum limit for the infrastructure (25.4 t). The additional vertical forces associated with linear motor equipment would therefore reduce the maximum allowable mass of cargo per wagon. Therefore, to carry the same amount of cargo per train without a radical wagon redesign, additional wagons would have to be added to the train to carry this cargo, adding further mass and length to the train. An iterative process was used to establish the number of additional wagons and the number of wagons to fit with linear motor equipment to move towards the target deceleration of 0.2 m/s<sup>2</sup> established in Chapter 4.

Table 11 and Table 12 summarise the specifications for trains of HYA hopper wagons and FKA container wagons respectively, for the fully loaded case.

	Linear motor technology option					
	(none)	ECB	LRB	DLB	ZSL	LEMUR
Additional wagons	-	1	1	6	3	1
Number of bogies fitted	-	6 / 44	12 / 44	52 / 54	46 / 48	12 / 44
Deceleration (m/s <sup>2</sup> )	0.15	0.15-0.2	0.15-0.2	0.18-0.19	0.16	0.2
Train mass (t)	2170	2199	2209	2373	2298	2209
On-time performance (%)	90	≥90	≥90	≥90	≥90	≥90
Equipment utilisation (%)	-	89	88	100	100	88

**Table 11:** Linear motor technology options – Class 66, twenty HYA hopper wagons

	Linear motor technology option					
	(none)	ECB	LRB	DLB	ZSL	LEMUR
Additional wagons	-	1	1	3	1	1
Number of bogies fitted	-	6 / 35	9 / 35	39 / 41	33 / 35	9 / 35
Deceleration (m/s <sup>2</sup> )	0.15	0.15-0.2	0.15-0.2	0.18-0.2	0.16	0.2
Train mass (t)	1490	1542	1547	1663	1571	1547
On-time performance (%)	90	≥90	≥90	≥90	≥90	≥90
Equipment utilisation (%)	-	64	85	100	100	85

**Table 12:** Linear motor technology options – Class 66, ten FKA container wagons

In all cases considered here, the linear motor options were not viable.

Table 13 summarises the specifications for the Night Riviera sleeper train in the Swindon case study, which were calculated in the same way as the HST.

	Linear motor technology option					
	(none)	ECB	LRB	DLB	ZSL	LEMUR
Number of bogies fitted	-	6 / 18	10 / 18	16 / 18	16 / 18	10 / 18
Deceleration (m/s <sup>2</sup> )	0.31	0.31-0.5	0.31-0.5	0.4	0.35	0.5
Train mass (t)	473	477	483	485	489	483
On-time performance (%)	96	≥96	≥96	≥96	≥96	95
Equipment utilisation (%)	-	73	86	100	100	86

**Table 13:** Linear motor technology options – Night Riviera

### 6.5.7. Class 68 locomotive

The Class 68 specifications were also calculated based on only trailing vehicles being fitted with linear motor equipment, and the Caledonian Sleeper specifications are summarised in Table 14:

	Linear motor technology option					
	(none)	ECB	LRB	DLB	ZSL	LEMUR
Number of bogies fitted	-	6 / 18	10 / 18	16 / 18	16 / 18	10 / 18
Deceleration (m/s <sup>2</sup> )	0.31	0.31-0.5	0.31-0.5	0.4	0.35	0.5
Train mass (t)	429	433	439	441	445	439
On-time performance (%)	98	97	97	97	≥98	95
Equipment utilisation (%)	-	66	78	100	100	78

**Table 14:** Linear motor technology options – Caledonian Sleeper

As with the HSTs in this case study, ZSLs are the only option not viable.

The container train in the Highland Main Line case study is carrying supermarket goods, and the lower cargo density means that no additional wagons would be required to stay within axle load limits for the loaded train. Table 15 summarises the specifications.

	Linear motor technology option					
	(none)	ECB	LRB	DLB	ZSL	LEMUR
Number of bogies fitted	-	3 / 32	6 / 32	30 / 32	30 / 32	6 / 32
Deceleration (m/s <sup>2</sup> )	0.15	0.15-0.2	0.15-0.2	0.19-0.2	0.16	0.2
Train mass (t)	966	969	972	989	996	972
On-time performance (%)	90	≥90	≥90	≥90	≥90	89
Equipment utilisation (%)	-	82	81	85-100	100	81

**Table 15:** Linear motor technology options – Class 68, ten FKA container wagons

Unlike all of the freight services considered previously, the LEMUR concept is a viable option in the Highland Main Line case study.



## 6.6. Multi-Train Simulation Results

### 6.6.1. Outputs

A total of 2500 simulation runs were carried out, totalling nearly half a million individual train journeys. A script was written in Matlab to extract the relevant information from the OpenTrack output files created by each individual simulation run:

- OT\_TimetableStatistics.txt – this file contains the planned and actual arrival/departure of each train at each station defined on its journey.
- OT\_Physic.tsvP – this file contains movement information for every train, including: distance travelled, speed, acceleration, forces, power and total energy consumed. These data are sampled at one-second intervals within the simulation.

The Matlab script then calculated the timetable stability for each simulation run, by dividing the cumulative delays to trains departing their first station by the cumulative delays to trains arriving at their final station. The time at which the case study boundaries were passed was included as the first or last station where required. The total energy consumed was calculated by adding together the energy consumption of each train and the additional energy consumed or recovered by the linear motor equipment at every time step where the train in question was braking, using the power consumption characteristics and equipment rating defined previously. All three options considered in Section 6.3.2 for the energy consumption of the LEMUR concept were included in the calculation.

The results for timetable stability and total energy consumption of all 100 simulation runs for each combination of linear motor/signalling technology are presented in Figure 66 to Figure 71 as standard Tukey box plots. The ends of the whiskers represent the last datum point within 1.5 times the interquartile range. Outliers beyond the whiskers are marked with a circle ('o'), and the mean with a diagonal cross ('x').

It was demonstrated in Section 6.5 that some combinations of rolling stock and linear motor technology were not viable, as the increases in train performance required to remain on time (due to extra mass) more than offset the reductions from improved deceleration. Where this was the case for all of the rolling stock for a particular case study and linear motor option, the simulations were not run and do not appear in the results.

In the Highland Main Line case study, train movements and timetable design are constrained by the large sections of single track and location of passing loops, and moving block signalling technology has no influence as a result. These simulations were therefore not run.

6.6.2. Tyne and Wear

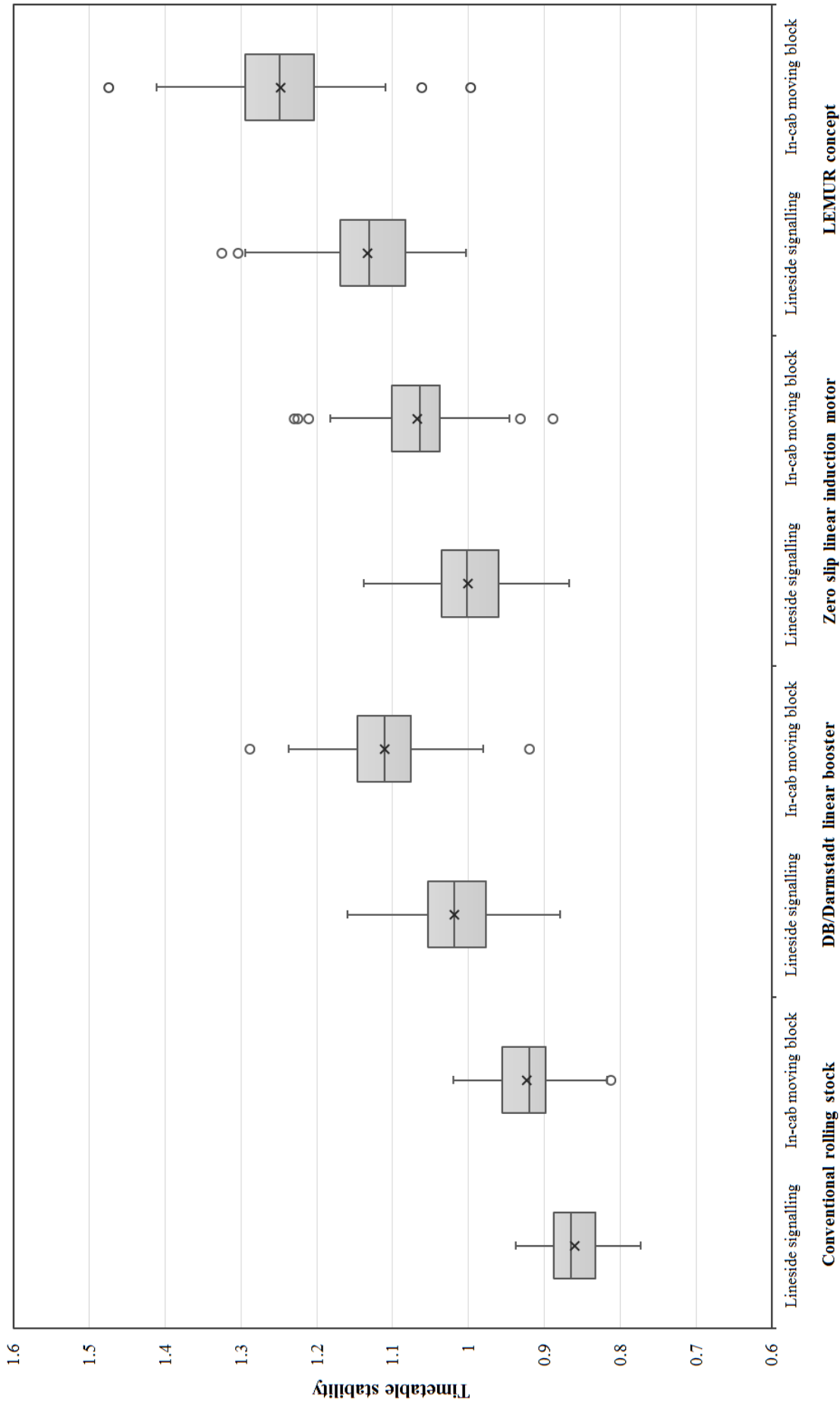
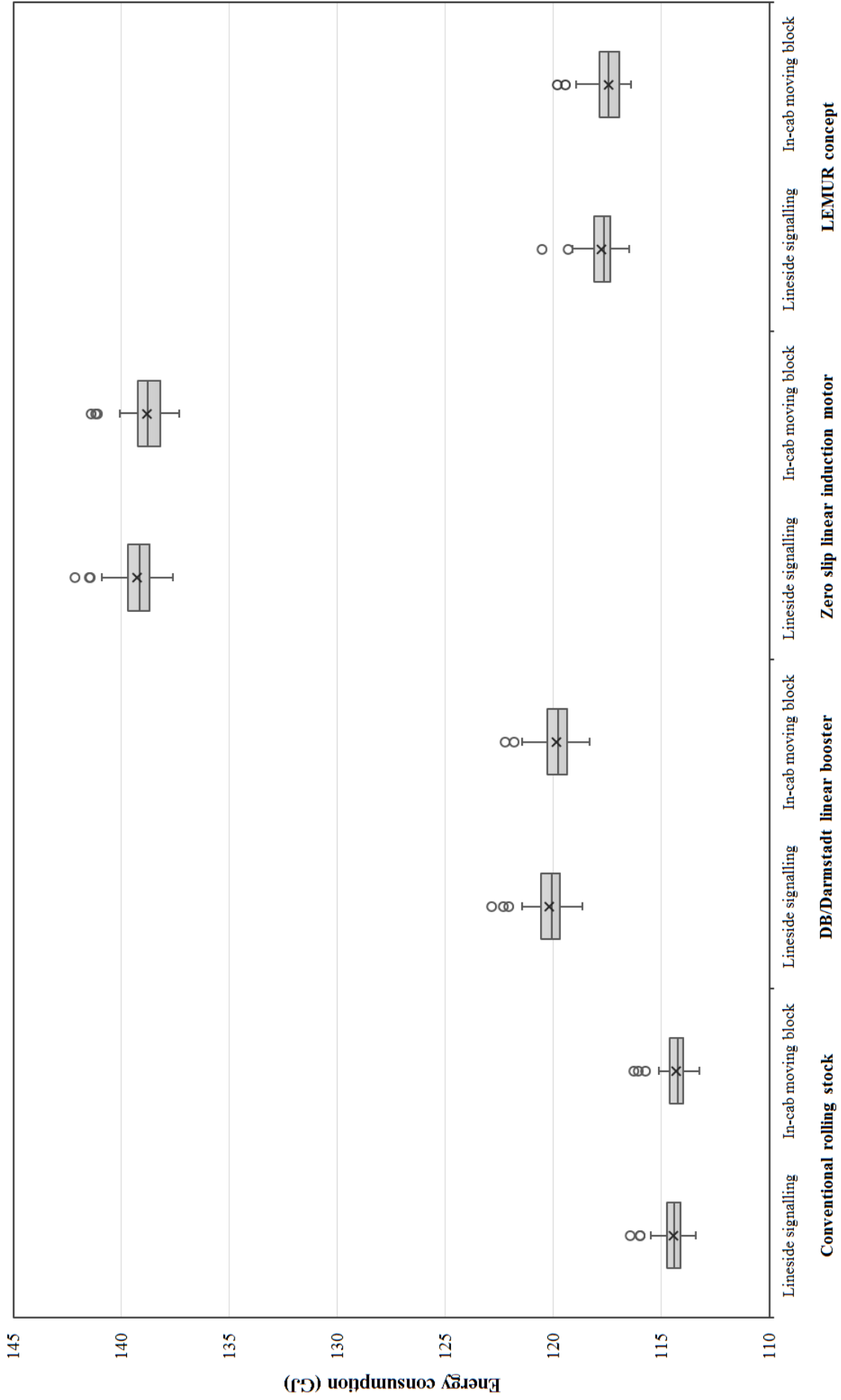


Figure 66: Tyne and Wear - timetable stability



**Figure 67:** Tyne and Wear - energy consumption

6.6.3. Swindon

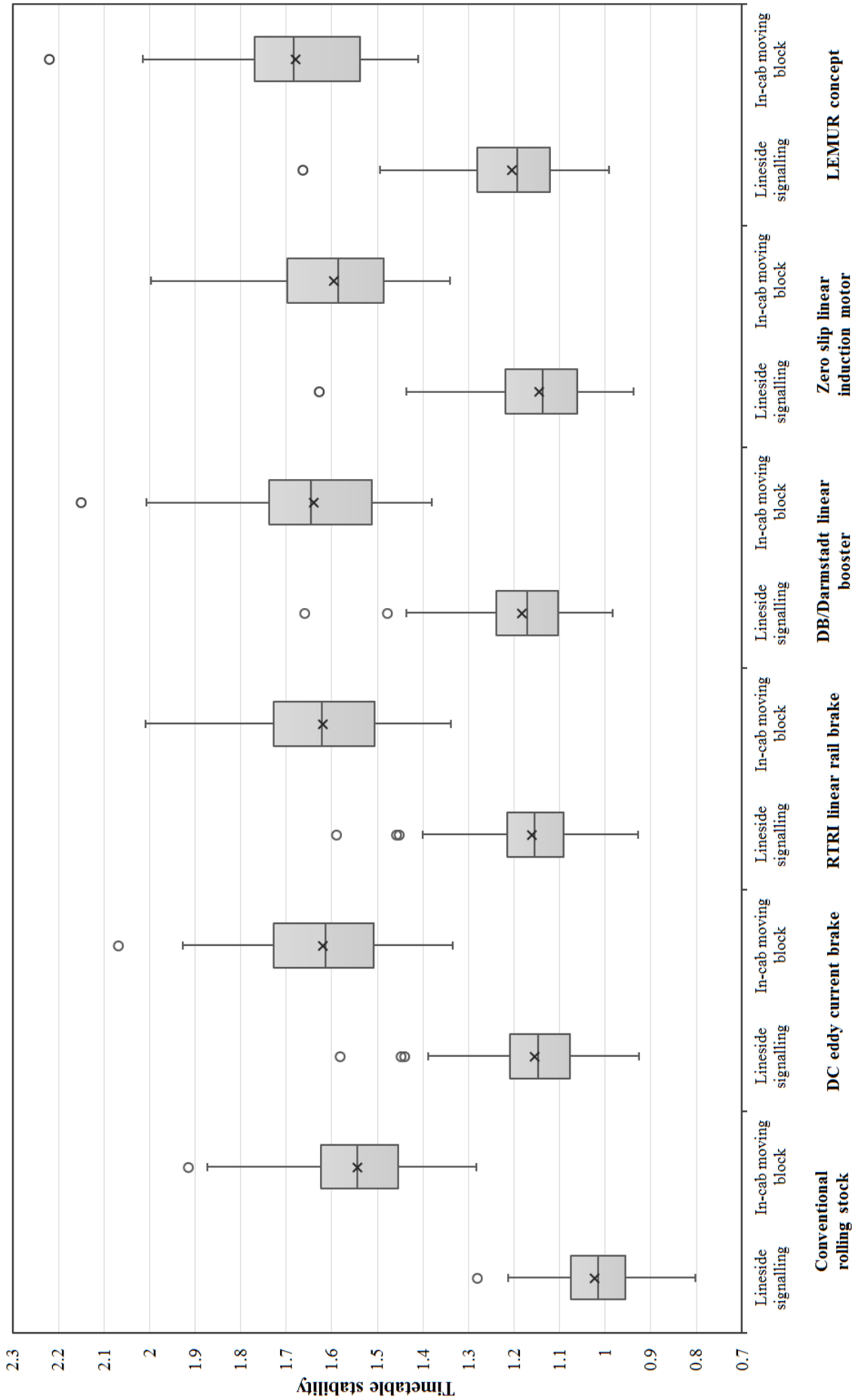


Figure 68: Swindon - timetable stability

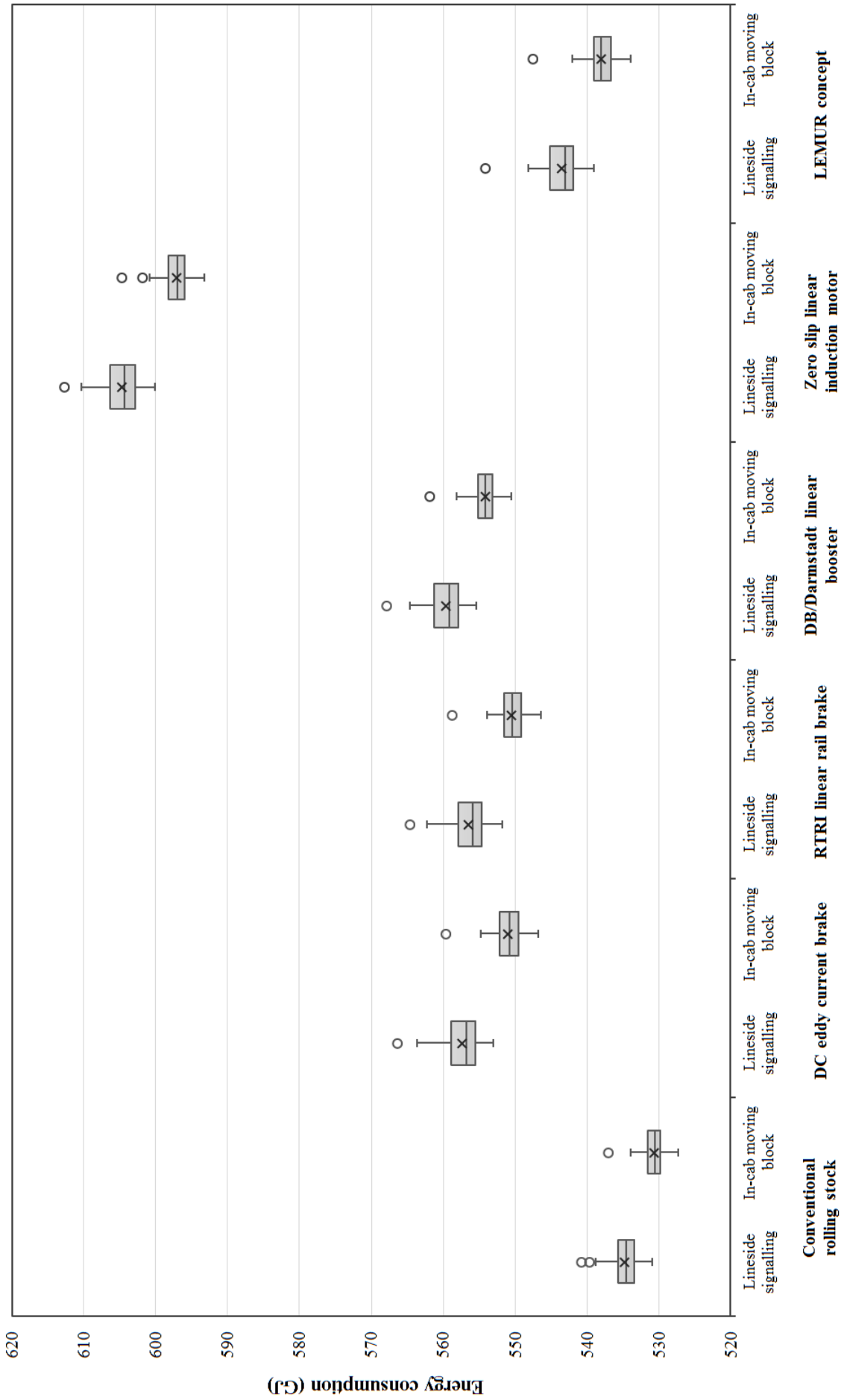


Figure 69: Swindon - energy consumption

6.6.4. Highland Main Line

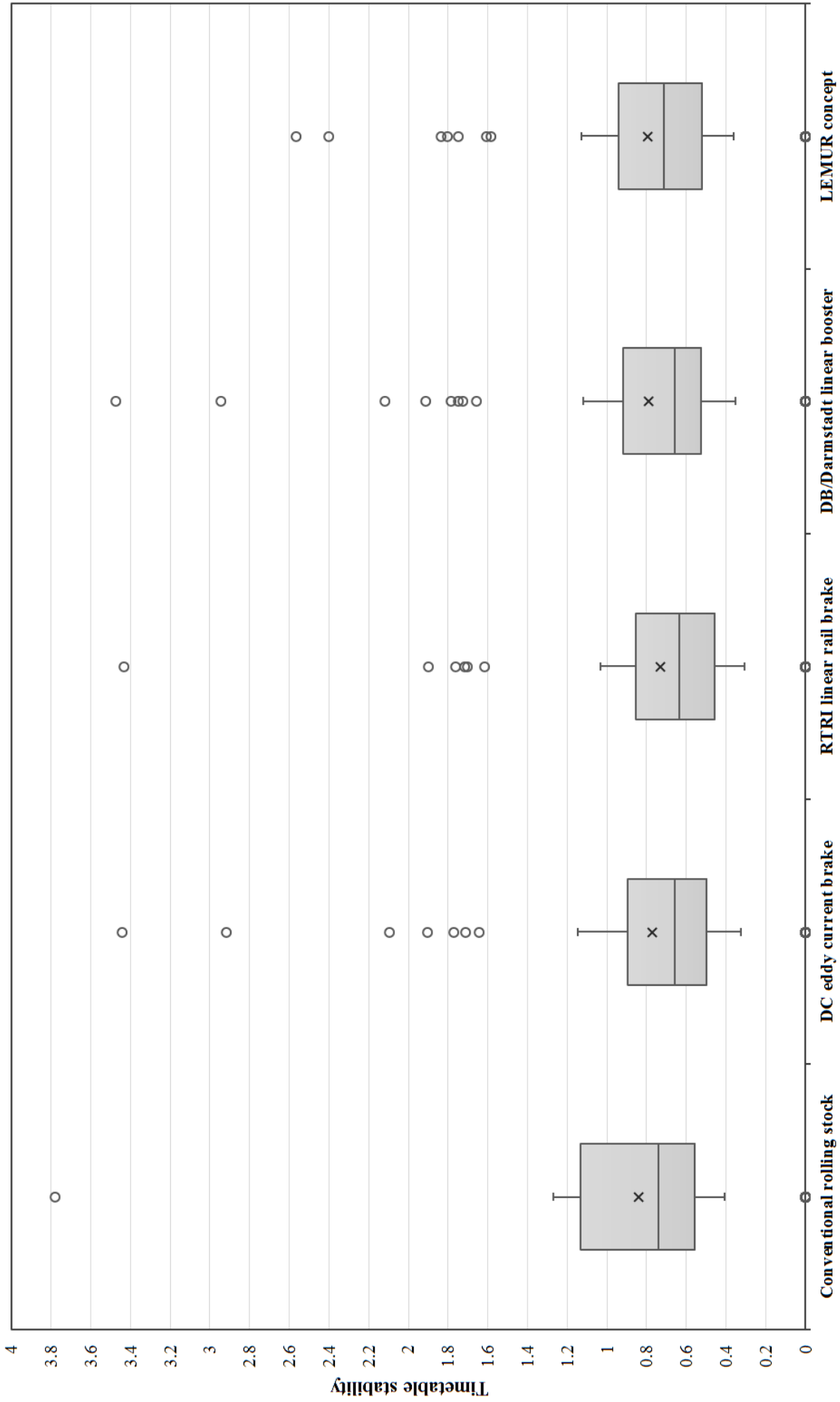
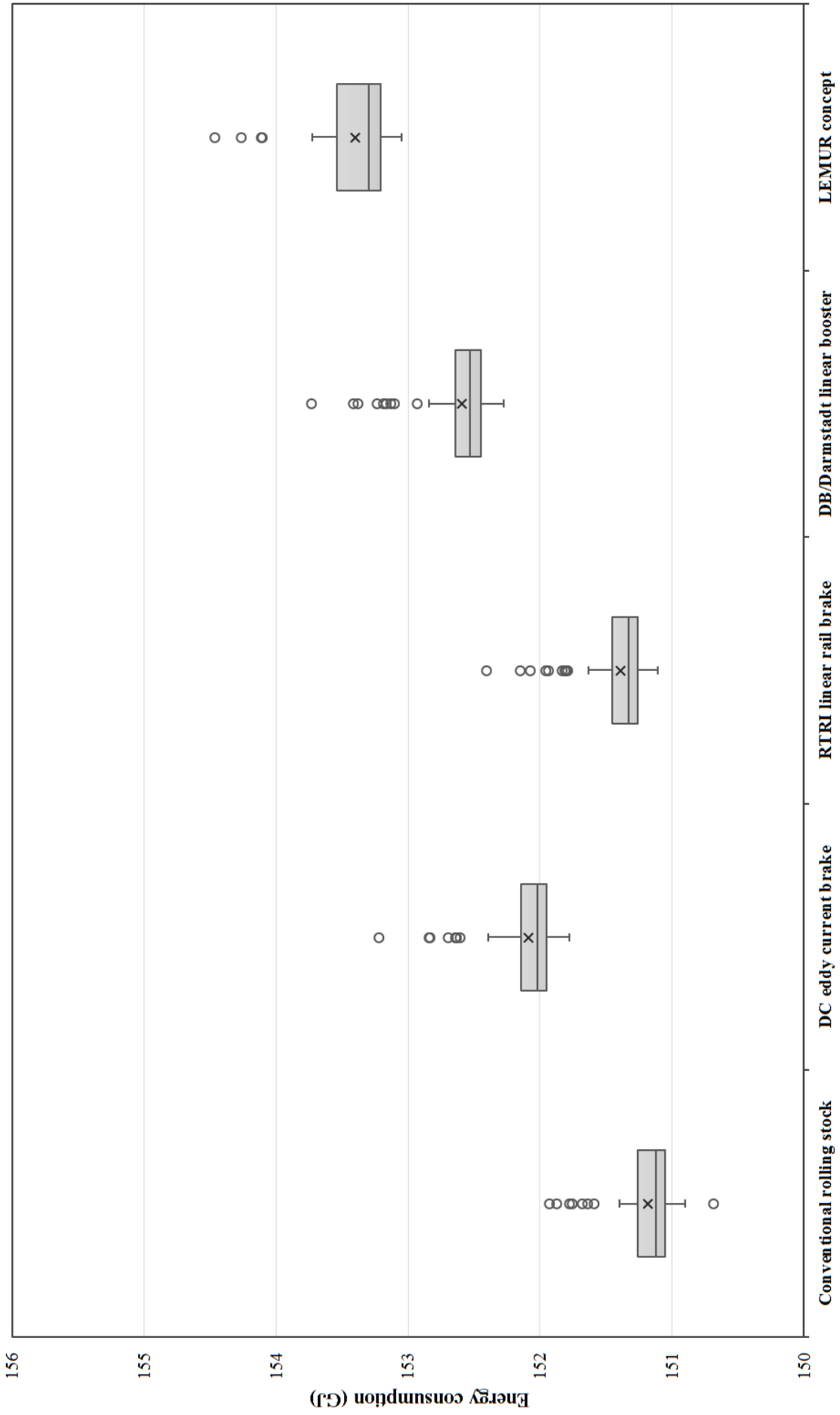


Figure 70: Highland Main Line - timetable stability



**Figure 71:** Highland Main Line - energy consumption

### 6.6.5. Analysis

For normally distributed data, the 95% confidence interval of the median  $m$  can be approximated from the interquartile range  $IQR$  and sample size  $n$ .

$$95\% \text{ CI} = m \pm \frac{1.58 \times IQR}{\sqrt{n}} \quad (10)$$

The difference in the medians of the results of two different sets of simulations are judged to differ significantly if the 95% confidence intervals do not overlap, although some overlap does not necessarily rule out a statistically significant difference. The results for many of the simulation sets are not normally distributed, however the sample sizes of  $n = 100$  are sufficiently large for this approximation to be reasonably accurate for other distributions (Krzywinski and Altman, 2014).

Table 16 summarises the 95% confidence intervals of the medians for each of the Tyne and Wear data sets illustrated in Figure 66 and Figure 67. Visual inspection of the box plots suggests that all of the data sets are relatively close to normally distributed. The mean and median of each individual data set are also very close to each other.

Linear motor technology	Signalling	Timetable stability		Energy consumption (GJ)	
		Lower	Upper	Lower	Upper
(none)	Lineside	0.86	0.87	114.3	114.5
	Moving block	0.91	0.93	114.1	114.3
DLB	Lineside	1.01	1.03	119.9	120.2
	Moving block	1.10	1.12	119.6	119.9
ZSL	Lineside	0.99	1.01	139.0	139.3
	Moving block	1.05	1.07	138.6	138.9
LEMUR	Lineside	1.12	1.14	117.6	117.8
	Moving block	1.23	1.26	117.3	117.6

**Table 16:** 95% confidence intervals of the median (Tyne and Wear results)

There is no overlap between any of the intervals, and so it is reasonable to conclude that there is a statistically significant difference between all of the data sets. All of the linear motor options offer an improvement in timetable stability, which is greater than the improvement for conventional rolling stock from moving block signalling. The LEMUR concept offers the greatest increase in timetable stability over other options, with DLBs outperforming ZSLs.



Table 17 summarises the 95% confidence intervals of the medians for each of the Swindon data sets illustrated in Figure 68 and Figure 69. The data sets appear reasonably close to being normally distributed, although with a little more skew than the Tyne and Wear case. The mean and median of each data set also remain close.

Linear motor technology	Signalling	Timetable stability		Energy consumption (GJ)	
		Lower	Upper	Lower	Upper
(none)	Lineside	1.00	1.03	534.2	534.8
	Moving block	1.52	1.57	530.3	530.8
ECB	Lineside	1.13	1.17	556.3	557.3
	Moving block	1.58	1.65	550.3	551.1
LRB	Lineside	1.13	1.17	555.4	556.4
	Moving block	1.59	1.66	550.0	550.8
DLB	Lineside	1.15	1.19	558.6	559.7
	Moving block	1.61	1.68	553.8	554.5
ZSL	Lineside	1.11	1.16	603.8	604.9
	Moving block	1.55	1.62	596.7	597.4
LEMUR	Lineside	1.17	1.22	542.5	543.5
	Moving block	1.65	1.72	537.6	538.4

**Table 17:** 95% confidence intervals of the median (Swindon results)

It is clear that moving block signalling offers a greater improvement in timetable stability than linear motor technology in this case, but the differences between linear motor options are less clear. It is reasonable to conclude that the LEMUR concept still offers the greatest improvement in timetable stability, despite the small amount of overlap in the confidence intervals at the lower bound. Of the four other options, DLBs appear slightly better and ZSLs slightly worse, although it cannot be confirmed with certainty whether this is an accurate reflection of the underlying pattern. Likewise, it appears that LRBs consumed slightly less energy than ECBs, but the difference is not statistically significant.

Table 18 summarises the 95% confidence intervals of the medians for each of the Highland Main Line data sets illustrated in Figure 70 and Figure 71. The box plots for both timetable stability and energy consumption show a much greater positive skew than the previous case studies, with outliers at a much greater distance. The mean and median of each individual set are also further from each other than in the other case studies.

Linear motor technology	Signalling	Timetable stability		Energy consumption (GJ)	
		Lower	Upper	Lower	Upper
(none)	Lineside	0.65	0.83	151.1	151.2
ECB		0.60	0.72	152.0	152.0
LRB		0.57	0.70	151.3	151.4
DLB		0.60	0.72	152.5	152.6
LEMUR		0.65	0.78	153.2	153.4

**Table 18:** 95% confidence intervals of the median (Highland Main Line results)

All of the confidence intervals for timetable stability show a large amount of overlap, and it therefore cannot be said that the differences are statistically significant. The intervals for energy consumption do not overlap however, so the differences appear to be representative.

### 6.6.6. Summary

Table 19 illustrates the potential reductions in OpenTrack driving performance during on-time running. Each cell contains the difference when compared to the driving performance values given in Table 2 in Section 5.6.2. The cells are shaded red where there is no change in individual train performance, yellow where performance changes but overall timetable stability was not affected, and green where timetable stability was increased.

Case study	Rolling stock	Linear motor technology option				
		ECB	LRB	DLB	ZSL	LEMUR
Tyne and Wear	Tyne and Wear Metrocar	-	-	-3	-3	-5
	Class 156	-	-	-1	-1	-2
	HST (six coaches)	-	-	-2	-1	-3
	Class 66, twenty HYA wagons	-	-	-	-	-
Swindon	Class 150	-	-	-1	-1	-2
	HST (eight coaches)	-2	-1	-1	-1	-3
	Night Riviera	-	-	-	-	-1
	Class 66, twenty HYA wagons	-	-	-	-	-
	Class 66, ten FKA wagons	-	-	-	-	-
Highland Main Line	Class 170	-	-	-	-	-
	HST (nine coaches)	-1	-1	-1	-	-2
	Caledonian Sleeper	-1	-1	-1	-	-3
	Class 68, ten FKA wagons	-	-	-	-	-1

**Table 19:** Changes in driving style performance (original values in Table 2)

Table 20 summarises the absolute and percentage increases in median timetable stability and energy consumption due to the application of each of the linear motor options. It covers the simulations with lineside signalling, for the Tyne and Wear and Swindon case studies.

Case study	Linear motor technology	Timetable stability		Energy consumption (GJ)	
		Value	Increase	Value	Increase
Tyne and Wear	(none)	0.86	-	114.4	-
	DLB	1.02	0.15 (18%)	120.1	5.7 (5.0%)
	ZSL	1.00	0.14 (16%)	139.2	24.8 (22%)
	LEMUR	1.13	0.27 (31%)	117.7	3.3 (2.9%)
Swindon	(none)	1.02	-	534.5	-
	ECB	1.15	0.13 (13%)	556.8	22.3 (4.2%)
	LRB	1.15	0.14 (14%)	555.9	21.4 (4.0%)
	DLB	1.17	0.15 (15%)	559.2	24.7 (4.6%)
	ZSL	1.14	0.12 (12%)	604.3	69.8 (13%)
	LEMUR	1.19	0.18 (17%)	543.0	8.5 (1.6%)

**Table 20:** Median timetable stability and energy consumption (lineside signalling)

Likewise, Table 21 illustrates the increases for simulations with moving block signalling.

Case study	Linear motor technology	Timetable stability		Energy consumption (GJ)	
		Value	Increase	Value	Increase
Tyne and Wear	(none)	0.92	-	114.2	-
	DLB	1.11	0.19 (21%)	119.8	5.5 (4.9%)
	ZSL	1.06	0.14 (16%)	138.8	24.5 (22%)
	LEMUR	1.25	0.33 (36%)	117.4	3.2 (2.8%)
Swindon	(none)	1.54	-	530.6	-
	ECB	1.61	0.07 (4.6%)	550.7	20.2 (3.8%)
	LRB	1.62	0.08 (5.0%)	550.4	19.9 (3.7%)
	DLB	1.65	0.10 (6.6%)	554.1	23.6 (4.4%)
	ZSL	1.59	0.04 (2.7%)	597.0	66.5 (13%)
	LEMUR	1.68	0.14 (9.1%)	538.0	7.4 (1.4%)

**Table 21:** Median timetable stability and energy consumption (in-cab moving block signalling)

Note that in some cases, rounding the raw data for display causes small discrepancies between the actual values and the absolute increases.

Table 20 directly illustrates the capacity benefits of linear motor technology that are derived from reducing the journey times of delayed trains (through greater deceleration). This figure applies for the existing lineside signalling in the case studies.

It is more complex to determine the capacity benefits derived from reduced headway however. The capacity benefits of linear motor technology and moving block signalling illustrated in Table 21 are from a combination of reduced headway and reduced journey times. The contribution of reduced journey time to capacity in this case is not the same as in Table 20 however, as the changes to the signalling system mean that the frequency, location and train speed for brake applications associated with adverse signals are likely to be different between the lineside signalling and moving block signalling cases. Furthermore, reductions in headway will also be constrained by other fixed infrastructure features such as stations and junctions. Nonetheless, a tentative conclusion for these two specific case studies is that capacity benefits from increased recovery margins appear to be greater than the benefits of reduced headway.

Finally, Table 22 contains the absolute and relative differences between the median results for conventional lineside signalling and in-cab moving block signalling data from Table 20 and Table 21 respectively, illustrating directly the effect of changes in signalling technology for each of the linear motor options in the two case studies.

Case study	Linear motor technology	Changes due to in-cab moving block signalling	
		Timetable stability	Energy consumption (GJ)
Tyne and Wear	(none)	+0.06 (6.4%)	-0.2 (-0.1%)
	DLB	+0.09 (9.0%)	-0.3 (-0.2%)
	ZSL	+0.06 (6.1%)	-0.4 (-0.3%)
	LEMUR	+0.12 (10%)	-0.2 (-0.2%)
Swindon	(none)	+0.53 (52%)	-3.9 (-0.7%)
	ECB	+0.47 (41%)	-6.1 (-1.1%)
	LRB	+0.47 (40%)	-5.5 (-1.0%)
	DLB	+0.47 (41%)	-5.0 (-0.9%)
	ZSL	+0.45 (39%)	-7.3 (-1.2%)
	LEMUR	+0.49 (41%)	-5.0 (-0.9%)

**Table 22:** Comparison of lineside and in-cab moving block signalling

## **6.7. Discussion**

### ***6.7.1. Comparison of linear motor technology and moving block signalling***

It is clear from the overall results that the linear motor technologies outlined in this chapter provide a greater increase in timetable stability than moving block signalling for the Tyne and Wear case study, but vice-versa for the Swindon case study. The influence on the Highland Main Line case study was not significant.

The Swindon case study represents one of most heterogeneous cases of a mixed-traffic railway on the network in Great Britain, with heavy freight trains running at a maximum of 45 mph (72 km/h) sharing tracks with intercity passenger trains running at 125 mph (201 km/h). The signal sections are relatively long to accommodate the higher speeds, and the combination of sub-optimal block layout and high service heterogeneity mean that moving block signalling has significant potential to improve capacity. The speed differences between services in the Tyne and Wear case study are smaller, and as a result the signalling block lengths are closer to the optimum for most trains, reducing the potential improvements achievable from moving block signalling. There are also significantly more station stops, and so a greater proportion of journeys are spent braking, which also favours the applications of the linear motor technologies described.

In the Swindon case study, the relative and absolute increases in timetable stability due to linear motor technology (compared to conventional rolling stock) were both reduced when in-cab moving block signalling was also present. In the Tyne and Wear case study, the increases in Table 20 and Table 21 are relatively similar. The combination of the significant differences in speed between trains, longer signalling block sections and fewer station stops in the Swindon case study make it more likely for trains to stop outright at signals when there are delays. With moving block signalling, fewer trains will stop and the proportion of the journey spent braking will be reduced, which in turn reduces the relative effect of linear motor technology on timetable stability. The lower speed differences in the Tyne and Wear case study, with signalling block lengths closer to the optimum for all trains, result in fewer stops for signals. The proportion of journeys spent braking is therefore dominated by stations or speed restrictions for both lineside and in-cab moving block signalling, and the relative effect of linear motor technology is likely to be similar.

The effect of linear motor technology on energy consumption was also relatively similar for lineside and moving block signalling in both of the case studies. This leads to another finding from the results in Table 22: the reductions in delays from moving block signalling make only

a very small difference to overall energy consumption for both case studies. It is possible, but rather counterintuitive, that stopping and starting at signals only has a small effect on overall energy consumption. A more likely explanation is the way in which driving style is simulated for heterogeneous train types running under moving block signalling. Where a faster train is following a slower train with different acceleration and braking characteristics, the simulation may switch rapidly back and forth between acceleration and braking for this faster train, consuming extra energy compared to a smoother profile. The uncertainty around how trains would be driven in such circumstances suggests that driving style and choice of deceleration level for in-cab moving block signalling on mixed-traffic railways may be a subject for future research.

Moving block signalling is less applicable to the Highland Main Line, as the single track sections and limited passing places constrain the movement of trains, and the timetable is not designed to accommodate two trains following each other closely. Such moves are generally an exception rather than normal operation, for example the rail head treatment train referred to in Section 5.7.4. These infrastructure constraints are a likely reason why no significant differences were found in the timetable stability of the linear motor options, despite the increase in the available running time margins for recovering delays. The small number of trains running in the 24-hour time window analysed may have also contributed to the larger spread in results.

The final comparison to be made is the likely costs of the various options. In a study of this nature, it is very difficult to get accurate costs compared to a project investigating the detailed design of specific options in a specific location. Nevertheless, order of magnitude estimates can be made from previous research, but should be treated as such rather than as detailed and accurate cost data. The recent resignalling contracts for London Underground provide a reference point for the costs of fitting a particular network with a moving block signalling system. The Northern Line (Kessel, 2015) and Sub-Surface Lines (Hewitt, 2015) both averaged around £3-4 million per train (in 2015 prices). This can be compared with estimates for linear motor equipment. A requirement from Section 2.1.3 is that the linear motor options under consideration should be able to interwork with existing infrastructure and rolling stock. This means that train fitment can be done incrementally, whereas resignalling must be done for a complete section of railway in a short space of time to minimise the costly and inefficient transition period, especially if the signalling technology is being changed. The following sections deal with each of the five linear motor options.

### **6.7.2. DC eddy current brake and RTRI linear rail brake**

ECBs and LRBs only had a measurable effect on timetable stability in the Swindon case study, when fitted to HSTs. While they could also provide measurable benefits to recovery margins for HSTs and the Caledonian Sleeper in the Highland Main Line case study, the effect on timetable stability was negligible, most likely due to the infrastructure constraints. The recovery margin benefits from increased deceleration for the Class 170s on the Highland Main Line were more than offset by the axle load increases that would prevent them from running at higher SP differential speeds. All of the other rolling stock across the case studies (including HSTs in the Tyne and Wear case study) spent a greater proportion of their journeys at speeds below 50 km/h, where ECBs and LRBs are not active. As a result, potential increases in recovery margin from increased deceleration were more than offset by the reduced acceleration and lower speeds on uphill gradients, due to the extra mass of the equipment.

The increases in timetable stability over conventional rolling stock in Figure 68 are very similar for both ECBs and LRBs. The energy consumption of LRBs was lower (marginally for Swindon, and significantly for the Highland Main Line), showing that the regenerated energy recovered by LRBs for excitation of its primary component can be greater than the extra energy consumption that results from the higher mass of equipment (compared to ECBs). A further advantage of LRBs is the reduction in rail heating, which was the original driver behind their development (Sakamoto *et al.*, 2012b).

A disadvantage of AC systems like LRBs is that the relatively low power factor means the power supply must be significantly higher rated than for a DC system providing similar performance. In this case, the DC supply rating for ECBs would be of the order of tens of kilowatts, compared to hundreds of kilovolt-amperes for LRBs. The relative costs can be estimated from the data provided by Werle (2003), converted to 2015 UK prices. The capital costs of DC equipment work out at approximately £35,000 per bogie, and AC equipment approximately £75,000 per bogie. The number of bogies to be fitted also varies depending on the linear motor option chosen. For the HST in the Swindon case study, the total cost of ECBs would be around £200,000, and LRBs around £750,000. For comparison, the total cost of the train is likely to be in the region of £10-20 million.

### **6.7.3. DB/Darmstadt linear booster and zero slip linear induction motor**

DLBs potentially show a slightly greater improvement in timetable stability than ECBs and LRBs in the Swindon case study, despite the maximum deceleration achievable being lower for the HSTs fitted with DLBs when compared to ECBs and LRBs. This is principally because DLBs allow extra braking effort right down to zero speed. As a result, DLBs bring measureable recovery margin benefits to most of the passenger rolling stock across the three case studies. However, any benefits for freight trains are more than offset by the mass of extra wagons, which are required to carry a given cargo without exceeding the maximum axle load once the additional vertical forces from DLBs are taken into account. The energy consumption of DLBs is higher than ECBs in both the Swindon and Highland Main Line case studies.

The effect on the Highland Main Line case study of DLBs is similar to ECBs and LRBs: recovery margin improvements are possible for HSTs and the Caledonian Sleeper, but timetable stability is likely constrained by the infrastructure. The constraints imposed by axle load mean that Class 170s and freight trains do not see any journey time benefit. In the Tyne and Wear case study, DLBs also provide an increase in timetable stability compared to conventional rolling stock, and this increase is proportionally larger than in the Swindon case study. The greater proportion of time the train services spend braking in the Tyne and Wear case study has already been mentioned as a likely factor. Two more potential factors can be derived from Equation 9: the mass of the Metrocars relative to the vertical force provided by the DLBs is lower than for the HSTs in the Swindon case, and the adhesion demanded (for the higher deceleration level) is higher.

The effect of ZSLs on timetable stability in all three cases is generally similar to DLBs, but the increases appear to be smaller. In the Tyne and Wear case study, both DLBs and ZSLs are limited to a maximum of 20 kN vertical force per primary, but for Swindon there are no constraints on vertical load and DLBs are able to provide larger vertical forces. This results in a greater relative increase in timetable stability for DLBs in the Swindon case study. ZSLs also have the disadvantages of higher rated and more costly AC power supplies compared to the low power DC supply for DLBs, as well as greater rail heating. DLB costs can be taken directly from the Darmstadt research (Werle, *ibid.*). For the HST in the Swindon case study, DLB costs are around £550,000, and can be estimated at £1,200,000 for ZSLs. As such, it can be concluded that DLBs are a better solution than ZSLs for the provision of vertical forces.



#### 6.7.4. LEMUR concept

The results indicate that the LEMUR concept consistently provides the highest increases in recovery margin/timetable stability and the lowest increases in energy consumption by comparison with conventional rolling stock. The increase in timetable stability is greater in the Tyne and Wear case study, again likely due to the greater proportion of journeys spent braking and lower mass of the trains. The LEMUR concept was also the only one of the five options that made a measurable difference in freight train recovery margins, for the intermodal train carrying low-density cargo in the Highland Main Line case study. As with other trains in this case study however, there was no measurable increase in timetable stability.

The increase in energy consumption is proportionally lower in the Swindon case study compared to Tyne and Wear, as there is greater opportunity to recover energy from regenerative braking at higher speeds. In the Highland Main Line case, the energy consumption was higher as the LEMUR concept was also fitted to the freight trains in this case, rather than just the HST and Caledonian Sleeper. These energy consumption figures used the case where regeneration was possible and plugging was not used. The results for all three of the sensitivity study cases defined in Section 6.3.2 are summarised in Table 23.

Case study	Signalling	Regenerative braking only	Zero overall power flow	Plugging braking only
Tyne and Wear	Lineside	117.7	118.7	125.8
	Moving block	117.4	118.5	125.5
Swindon	Lineside	543.0	548.7	553.8
	Moving block	538.0	543.5	548.5
Highland	Lineside	153.3	154.5	155.1

**Table 23:** Sensitivity study results for median LEMUR energy consumption (GJ)

It can be seen that regeneration has a relatively small effect of around one percent on overall energy consumption. Although plugging appears to show a significant increase in energy consumption, comparison of the required adhesion level against Figure 1 (5-7%) suggests it would be used very infrequently, in exceptionally low adhesion conditions only. The likely actual increase in energy consumption over a full year would therefore be negligible.

The disadvantage of the concept is the complexity of the power supply equipment and control strategy. However, if a viable design can be developed, the costs of implementation are likely to be relatively similar to the LRB option. Assuming an extra power converter would be required for regenerated energy gives an estimate of £850,000 for the Swindon HST example.

### ***6.7.5. Limitations of experiment and methods***

One of the difficulties with multi-train simulation highlighted in Chapter 3 is that the lack of a human signaller or traffic management system overseeing the running of trains in the simulation, with such decisions controlled by relatively basic internal logic within OpenTrack. The effects of this became apparent in the simulations, especially when trains were delayed and not running according to timetable, resulting in more incidences of junction conflicts or fast trains being routed behind slower trains. Although this was the case for all of the 25 sets of simulations, the same conflicts would not necessarily occur when rolling stock performance or signalling characteristics were changed, and one reason for carrying out 100 individual simulation runs in each set is to help mitigate these effects.

The energy consumption of the LEMUR concept was an important unknown factor, as it could have a significant effect on the results. This was the principal reason for carrying out the additional sensitivity study, which demonstrated that the differences to overall energy consumption were small where plugging was used or where regenerative braking power was increased.

In each of the case studies, the majority of the services are run with a particular type of rolling stock: the Metrocars for Tyne and Wear, HSTs for Swindon and Class 170 DMUs for the Highland Main Line. These will tend to dominate the results for timetable stability and energy consumption. The rolling stock chosen does represent a reasonable spread of different types, but does make it more difficult to determine the exact causes driving the individual level of improvements in timetable stability and energy consumption. Further case studies or specifically constructed scenarios would be required to isolate the precise drivers of improvements, for example whether lower mass or more frequent stops is a more important factor. Nonetheless, the general conclusions about the potential benefits offered by the various linear motor technologies remain valid. Although freight rolling stock is less represented, the effect of linear motor technology on recovery margins was shown to be minimal for freight.

A potential source of inaccuracy was the limited resolution of train mass and driving performance in OpenTrack. It is difficult to relate small changes in mass or driving performance to timetable stability, but it is possible to get see the likely order of magnitude of the influence by comparing the results for ECBs and LRBs in Figure 68, as the values of mass and driving performance are relatively close for both. The similarity of the results suggests that the effect of this coarse resolution in input data is not enough to affect the overall conclusions drawn from the results.

The driving performance measure in OpenTrack applies a blanket percentage reduction in tractive effort, cruising speed and deceleration, whereas in reality it is likely that drivers may choose to maintain their maximum chosen tractive and braking effort, and coast or cruise at a lower speed to meet a longer journey time. The effect on energy consumption would likely be similar in all 25 sets of simulations, and the changes to train times at intermediate points between stations of the order of a few seconds only.

A further point about driving style is that the improvements in deceleration were based on increasing the deceleration from the average values measured during Chapter 4 towards the maximum values measured, without increasing the average adhesion demand. The deceleration however remains a matter of choice by the driver (or ATO system), and if the dependence of braking forces on adhesion was reduced, the interpretation of defensive driving policies and choice of deceleration strategy may well be different.

One of the reasons for the development of LRBs was to provide an independent emergency brake that could be taken into account for calculating safe signalling distances. If the linear motor technologies are proven sufficiently reliable to be used in this way, capacity for fixed block systems may be improved through higher speeds (without changing block lengths) in areas where the signalling block lengths are the constraint on maximum line speed. This possibility was not explicitly considered in the experiment in this chapter, as it could be considered to go against the principle established in Chapter 2 of little to no infrastructure changes to accommodate linear motor technology, but moving block achieves similar benefits in a different way by reducing headways for a given train speed.

Ultimately, the limitations of the experiment that are described in this section suggest that there are likely to be some uncertainties remaining in the precise values of energy consumption and timetable stability, given the complexity of the relationship between the simulation input data and the results. It can be observed that the limitations of the study are generally consistent across all of the 25 sets of results however, especially given the number of simulation runs. Where it was possible to estimate, the effect of these limitations was generally smaller than the differences between the 95% confidence intervals of the medians of results in most of the Tyne and Wear and Swindon cases. Therefore, it is reasonable to conclude that the limitations of the study do introduce a little more uncertainty into the values of timetable stability and energy consumption obtained, but they do not change the overall trends and conclusions drawn.

## **6.8. Conclusions**

### ***6.8.1. Overall results***

The aim of the experiment described in this chapter can be summarised as answering the following questions:

- Can linear induction motors using the running rails as their secondary component provide an increase in railway system capacity?
- Is this increase likely to be worthwhile?
- What are the characteristics of railway systems for which linear motor technology is likely to be more suitable?
- Which of the possible options for application of linear motor technology are likely to be more effective?

The results demonstrate that the linear motor applications tested in this chapter were able to provide an increase in timetable stability in two of the three case studies, effectively an increase in railway system capacity in accordance with the standard UIC Code 406 definition. There are limitations to the study, and as a result some uncertainty remains about the exact values of capacity obtained, but the research is considered sufficiently robust to confirm that measurable increases are indeed possible.

If results of all three case studies were to be generalised, the increases in timetable stability may be considered broadly equivalent to those provided by moving block signalling, which is considered to provide a worthwhile increase in capacity in its own right. The more effective option for a given railway system will depend on the infrastructure and train service characteristics. Costs are very difficult to estimate accurately without a detailed design study, but it is reasonable to suggest at this stage that adoption of linear motor technology is cheaper (per train) than resignalling a section of railway, and less disruptive. Maintenance costs for linear motors are relatively small, and experience with ECBs suggests that these costs can be more than offset by savings in wear to friction brake components.

### ***6.8.2. Application to railway systems***

Several characteristics of suitable railway systems for the application of linear motor technology considered can be suggested from the work in this chapter. To provide the greatest increase in timetable stability, a high proportion of trains' journeys should be spent braking for speed restrictions or station stops. The vehicles should be relatively light, to maximise the effect of the additional forces available and minimise the potential for excessive axle loads.

Running at higher speeds can increase the opportunity for energy recovery through regenerative braking. Electrified infrastructure would be preferable in this respect, but is not essential. Likewise, rolling stock where the conventional traction drive is electric would also be more suitable, but fitting vehicles that have other types of traction systems is certainly possible.

Providing additional recovery margins in running time is likely to have greater benefit on busy networks, where there are more opportunities for delays to propagate between trains. Although linear motor technology can provide additional benefits when a significant proportion of journeys are spent braking for adverse signals, later application of new signalling or traffic management systems would then reduce these benefits.

While it can be stated that greater service heterogeneity increased the benefits from moving block signalling in the case studies considered, the influence of heterogeneity on the possible benefits of linear motor technology are not clear without further parametric studies or experiments in specific scenarios. However, the applications of linear motor technology considered here are inherently suitable for mixed-traffic railway networks with a large number of different services and routes, as they were developed from the principle that trains fitted should be able to work alongside unfitted trains on existing infrastructure.

Overall, busy suburban lines that are part of wider mixed-traffic railway networks are likely to be the most promising application of the linear motor technologies considered for this thesis, with greater benefits and lower costs than the application of moving block signalling. Metro systems would also be a good application, but there are other potential technologies available for dedicated lines isolated from the wider railway network, such as LIMs with a separate reaction rail. Speeds on metro systems are also generally lower. Another potential application that has seen some real-world application (ECBs) is to augment braking systems at very high speeds. Application to freight is less likely, although high performance freight trains with lower maximum axle loads and similar acceleration, deceleration and maximum speeds to passenger trains may be a suitable area for future research.

### ***6.8.3. Linear motor technology options***

The results demonstrated that ECBs and LRBs are only effective for trains where a large proportion of their braking is from high speeds (160 km/h or more). This finding is reflected by reality, with the existing application of ECBs to ICE 3 trains for speeds of around 300 km/h, as well as previously proposed applications for TGV and Shinkansen trains. Given the similarity in timetable stability offered by ECBs and LRBs, the choice between them would

be dictated by whether the slightly lower energy consumption and reduced rail heating of the LRB offsets the higher cost of the power supply equipment.

The generation of vertical attractive forces to increase the adhesive weight of a train and allow greater traction and braking forces is a viable alternative. The effect of DLBs on timetable stability is similar to ECBs and LRBs. DLBs also work down to zero speed, meaning they have the potential for much wider application. A disadvantage is that all of the bogies in the train likely need to be fitted, meaning the cost is higher than ECBs, but DLBs are DC-fed so the capital costs are lower than LRBs. There would also be an increase in maintenance costs, but these are relatively low for linear motor technology. The energy consumption is also higher than ECBs, but the rail heating is significantly lower than other options, despite the increased number of bogies fitted. DLBs outperform ZSLs in all aspects, providing greater timetable stability, as well as lower energy consumption, cost and rail heating. As such, DLBs are a better solution for the provision of vertical forces.

Although traction was not specifically investigated in this experiment, it appears from the specification work in this chapter that DLBs would be the best solution for increasing tractive effort, due to their low power requirement. The adhesion demanded for traction is generally greater than braking, especially at low speed where tractive effort is adhesion limited and there is surplus power available). Equation 9 suggests that the benefits of providing additional vertical force are proportionally greater when the adhesion demand is greater. This matches the reasoning behind the original development of DLBs – to improve tractive effort for relatively light but high-power locomotives, where adhesion demands are very high, and adding more motored axles within the train is not necessarily possible. Depending on traction equipment design and rating, the addition of DLBs may allow more energy to be recovered during regenerative braking if higher braking efforts by the locomotive can be supported.

The LEMUR concept developed as part of this thesis consistently provided the greatest increase in timetable stability, with lower overall energy consumption than other options. Although the cost is higher than DC equipment such as ECBs, the increase is reasonably small compared to the total cost of the trains. It can therefore be concluded from this chapter that the LEMUR concept is the most promising application of linear motor technology for improving capacity in conventional railway systems. The comparisons with the costs and capacity benefits of moving block signalling also suggest that the capacity improvements would be worthwhile. This supports the hypothesis proposed in Chapter 3, and indicates further development of the LEMUR concept towards application can be justified.

## CHAPTER 7. CONCLUSIONS

### 7.1. Thesis

Wheel/rail adhesion represents an important constraint on the design and operation of existing railways. The basis of the research question for this thesis was to examine whether linear motor technology can improve the performance of conventional railway systems by reducing the dependence of tractive and braking effort on the available wheel/rail adhesion.

It has been more than a century since the use of linear motors for railways was proposed, and prototypes using short primary linear induction motors with a separate aluminium reaction rail were first built around fifty years ago. The technology has since been applied to a number of urban rail systems across the world. Long and short primary linear synchronous and linear induction motors are also used for unconventional guided transport systems. However, the capital and maintenance costs of additional equipment that must be fitted to the track have prevented more widespread adoption to existing main-line railway networks.

An alternative to additional equipment in the track is to use the existing steel running rails as the secondary component of a linear induction motor, requiring few (if any) changes to the infrastructure. The feasibility has been demonstrated by previous research, but the achievable tractive effort, energy efficiency and power factor are significantly lower than existing rotary traction motors or other designs of linear motor. As a result, the advantages of the concept are not sufficient for it to be competitive with conventional designs. Nonetheless, it does show potential when used to augment conventional traction and braking systems, rather than replace them. The attractive force between the motor primaries and the running rails can be used to increase the effective adhesive weight of the train, and useful additional braking efforts can be generated independently of wheel/rail adhesion using regenerated energy.

There have been a number of studies into the potential for this concept, but so far adoption into commercial service has been limited to DC eddy current brakes. Although not strictly linear induction motors, similar principles are exploited to provide adhesion-independent braking forces. The studies into linear motor technology have generally been focused on the design of motors and the influence on individual train performance; although some referred to the potential to increase the capacity of the wider railway network, no studies were found in the literature that investigated capacity increases in detail. The argument set out in this thesis is that these capacity benefits can justify adoption of linear motor technology.

The LEMUR concept developed in this thesis was designed to maximise the potential increases in railway system capacity, based on a critical analysis of previous research and new investigations into the design and operation of existing railway systems. These investigations suggested that adhesion is much more critical to braking than traction, and capacity benefits could be derived from increasing the deceleration achieved by trains. Further capacity benefits could also be obtained if improved braking allowed signalling headways to be reduced.

Multi-train simulation of three different railways networks was used to investigate the capacity benefits and energy consumption of the LEMUR concept, along with four other existing or proposed implementations of linear motor technology: DC eddy current brakes, an AC linear rail brake developed by RTRI in Japan, a DC linear booster proposed by Darmstadt University/DB, and a linear induction motor running at synchronous speed.

Railway capacity is qualitatively defined by UIC Code 406 as a trade-off between the number of trains, average speed, heterogeneity and timetable stability. The first three of these parameters are defined explicitly by the timetable, and so the effects of the linear motor technology options on the stability of a given timetable were used as a proxy to quantitatively measure changes in railway capacity, using Monte Carlo simulation with pseudorandom distributions of initial delays to trains. To provide a point of comparison, the potential effects of implementing moving block signalling were also examined. A comparison of the capacity benefits provided by linear motor technology against those from moving block signalling (in isolation) gives an indication of whether the increased deceleration offered by linear motor technology can offer a worthwhile improvement in capacity. The capacity benefits when both are applied together gives an indication of the full potential of linear motor technology to improve capacity by also reducing the headway between trains.

The results of the experiments indicated that a linear induction motor using the running rail as its secondary component can provide a measurable increase in railway system capacity. In the Tyne and Wear case study of urban rail services running in a mixed-traffic network, the measured capacity increase was greater (and the estimated costs lower) than moving block signalling. Although the limitations of the study do introduce some uncertainty into the precise values of timetable stability and energy consumption obtained, the experiments are sufficiently robust that the overall trends and conclusions are considered valid. The results of the experiments therefore support the hypothesis proposed in this thesis. The LEMUR concept shows considerable promise for further development and application to improve the performance of conventional railway systems.



## **7.2. Further Work**

### ***7.2.1. Further development of the LEMUR concept***

The most significant area for further work highlighted by the research undertaken for this thesis is further development of the LEMUR concept. The design and integration of a prototype within a train would allow the predicted performance to be validated and the uncertainties in this research to be reduced, especially the estimated costs. It would also allow further testing to ensure compatibility with infrastructure in areas highlighted by Chapter 2 as potentially problematic, such as electromagnetic compatibility and the acceptable levels of rail heating. A prototype could also be used to examine the trade-off between reactive power and reductions in rail heating/energy consumption identified in Section 6.3.1.

The results derived from the prototype could then be used to apply the LEMUR concept to specific railway projects. The design process can be seen as a multidisciplinary system design optimisation problem, with trade-offs between the achievable forces, minimum speed for regenerative braking, reactive power, energy consumption, number of bogies to fit, equipment mass, number of trains in the timetable, journey times, service pattern and timetable stability to ultimately optimise the costs and benefits of the concept for a particular application.

The characteristics that made the Tyne and Wear case study particularly suitable were a high density of passenger services with relatively light vehicles and frequent brake applications, running in a wider mixed-traffic network. Electrification of the infrastructure is an advantage, but not a prerequisite. There are many railways that are a good fit to these characteristics, suggesting the LEMUR concept has wide potential for application.

### ***7.2.2. New freight vehicle designs***

One of the findings of Chapter 4 was that the average deceleration values measured for freight trains were very low compared to passenger trains, due principally to the long brake application and release times and the need to manage in-train forces. The greater weight of individual vehicles, the findings of Chapter 4 and Equation 9 in Section 6.4.1 all suggest that the application of linear motor technology is less suitable for freight. However, electrically controlled pneumatic brakes and shorter, lighter trains could allow performance to match that of existing passenger trains. This has been proposed to allow railways to compete more effectively with road transport for low-volume high-value cargo, where the requirements are rather different to the railway's traditional strengths in the haulage of bulk cargo (Zunder *et al.*, 2014). Linear motor technology would be more beneficial for such designs compared to current freight trains.

### ***7.2.3. Simulation of freight timetables***

Chapter 5 noted that freight train formations, loads and running time (or even if the train runs at all) can change significantly day-to-day, and the driving style of individual trains can vary significantly as a result (Imrie, 2015). There is much less variation in passenger train operations by comparison. Therefore, further investigations of existing freight train operations would allow the accuracy of freight train simulations to be improved.

### ***7.2.4. In-cab moving block signalling driving style***

The majority of moving block signalling systems have been applied to metro systems that also include some degree of automatic train operation. Section 6.7.1 illustrated a potential difficulty when simulating moving block signalling in main-line mixed-traffic railways: higher performance trains may switch rapidly between traction and braking when following a train with a lower acceleration or top speed. This has been raised previously as a possible issue for the design of ATO systems if moving block signalling is applied to main-line railways (Gill, 1998). In addition, if trains are manually controlled, the driving style for in-cab signalling has been shown to be different to that for lineside signalling (Naweed *et al.*, 2009; Buksh *et al.*, 2013; Kecklund and Nordlöf, 2015). This suggests that there is scope for further research into how moving block signalling instructions are presented to individual trains in a mixed-traffic railway, and the speed profiles that will result under manual driving and ATO.

### ***7.2.5. Life cycle energy use***

The overall system energy consumption for the linear motor options considered shows an increase over the existing railway. If the life cycle energy use of the entire railway system is considered, traction energy accounts for approximately half of the total energy use. A significant proportion of the remaining energy is accounted for by infrastructure, including both energy consumed during operation and also energy embodied in its construction (Powell *et al.*, 2015). It is therefore possible that if the increases in capacity possible with linear motor technology are translated into an increase in the number of trains running on the same infrastructure, together with a growth in traffic to maintain load factors, the overall life cycle energy use per passenger or per tonne of freight may in fact decrease. A higher frequency service also has potential to encourage modal shift from other transport modes that are less energy efficient. Investigating this potential would require more detailed study of a specific project (as outlined in Section 7.2.1), but the results could further strengthen the case for adoption of the LEMUR concept.

## APPENDIX A. WHEEL/RAIL ADHESION

The coefficient of adhesion  $\mu$  is strictly defined as the ratio of the longitudinal traction or braking force transmitted at the wheel/rail interface to the nominal vertical load, as stated in Chapter 1:

$$F = \mu \cdot R \quad (1)$$

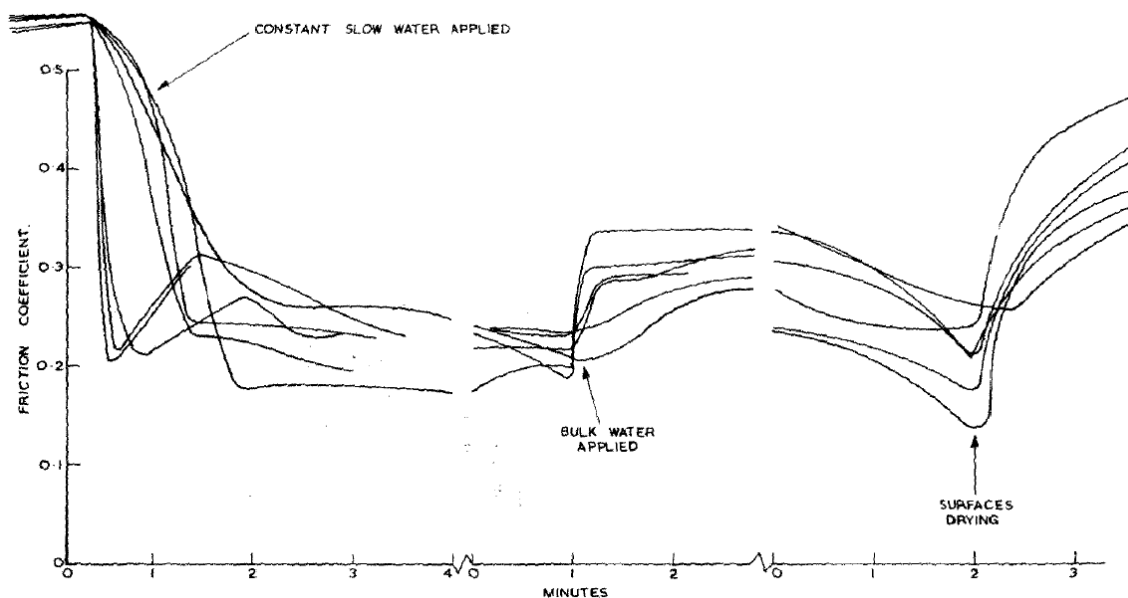
The vertical force  $R$  is based on the weight supported by driven or braked axles (for acceleration and braking respectively), also termed the adhesive weight. Therefore, the maximum acceleration or deceleration that can be achieved depends on the ratio of the adhesive weight to the total weight of the train. Almost all train formations have brakes acting on every axle, so that the adhesive weight for braking is equal to the total weight of the train. However, it is common for only some of the axles to be powered, so that the adhesive weight for traction may be significantly less, depending on the individual weights of vehicles with powered axles and the weight distribution within vehicles.

The instantaneous dynamic load on any given axle will vary, principally due to weight transfer during traction/braking and irregularities in the track alignment, and the influence on adhesion is significant (Marta and Mels, 1969). Track alignment irregularities can result in dynamic wheel unloading, and hence fluctuations in the apparent adhesion coefficient. This effect becomes more marked as the speed of the train increases. There may also be additional quasi-static lateral/longitudinal steering forces on the wheelset, principally while running on curved track, due to dynamic effects associated with the coned shape of the wheels. These are distinct from the traction or braking forces, but can be of a similar order of magnitude. Therefore, the resultant force in the horizontal plane that must be transmitted at the wheel/rail interface can be significantly higher for a given traction or braking force (Polach, 2001). These two effects can give rise to significant changes in the observed adhesion level for a constant coefficient of friction between wheel and rail. Nonetheless, it is the coefficient of friction that has the greatest influence on adhesion.

The wheel/rail interface is open to the elements, and therefore the tribology of the contact is dominated by the effects of contaminants. British Rail Research carried out a series of studies into the contaminants that change the coefficient of friction when compared to a clean steel-steel rolling contact. The most important was found to be water and its interaction with oil and solid debris, in particular rust from the rails, brake block dust and leaves (Beagley and Pritchard, 1975).

Heavy rain typically reduces the coefficient of friction from around 0.3 for a dry rail to 0.2 (Broster *et al.*, 1974). A far greater reduction in the coefficient of friction is observed where rails are damp, such as from light rain or condensation on the rails, essentially when the humidity is high relative to rail temperature. The water mixes with solid metallic debris to form a paste, with the quantity of water determining the viscosity. Below a critical value, the mixture is viscous enough not to be removed by the passage of a train, and forms a low shear strength layer between the wheel and rail that significantly reduces the coefficient of friction (Beagley and Pritchard, *op. cit.*).

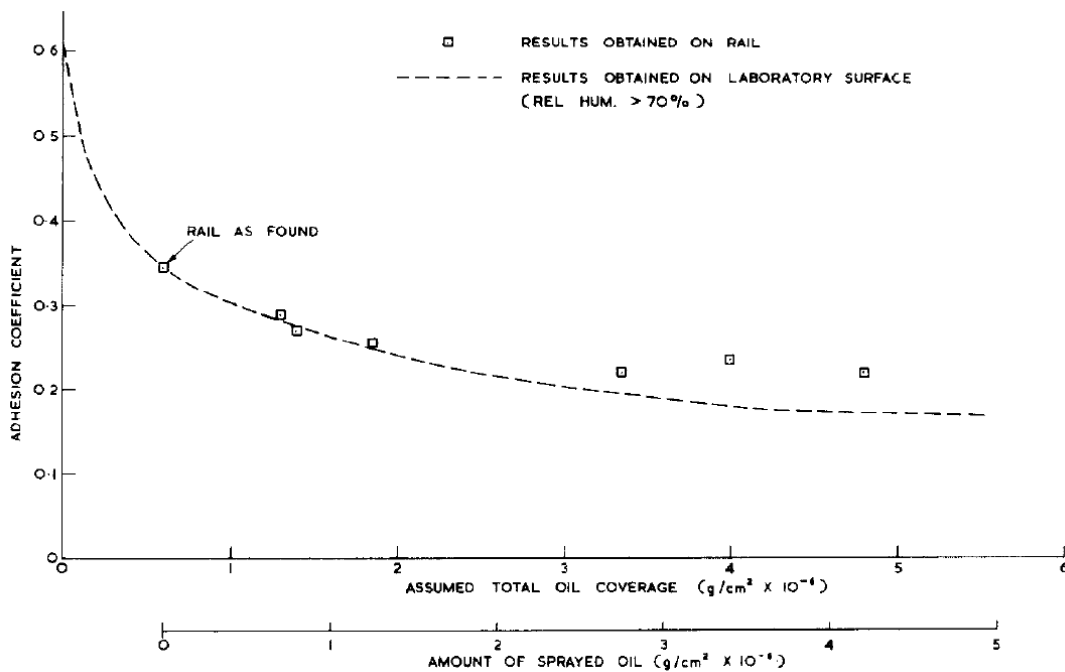
Figure 72 illustrates the results of a series of laboratory experiments to model these effects, with the constant slow water representing light rain and showing the significant reduction in the coefficient of friction for a steel/steel rolling contact. The application of bulk water represents heavier rain, with a higher coefficient of friction than the light rain case (although still lower than dry rails). Finally, as the surfaces dry the coefficient of friction will increase again, although after heavy rain it passes through a brief period while drying where the rails are damp rather than wet, hence another local minimum of the coefficient of friction at this point.



**Figure 72:** The effect of water on the coefficient of friction (Beagley and Pritchard, 1975)

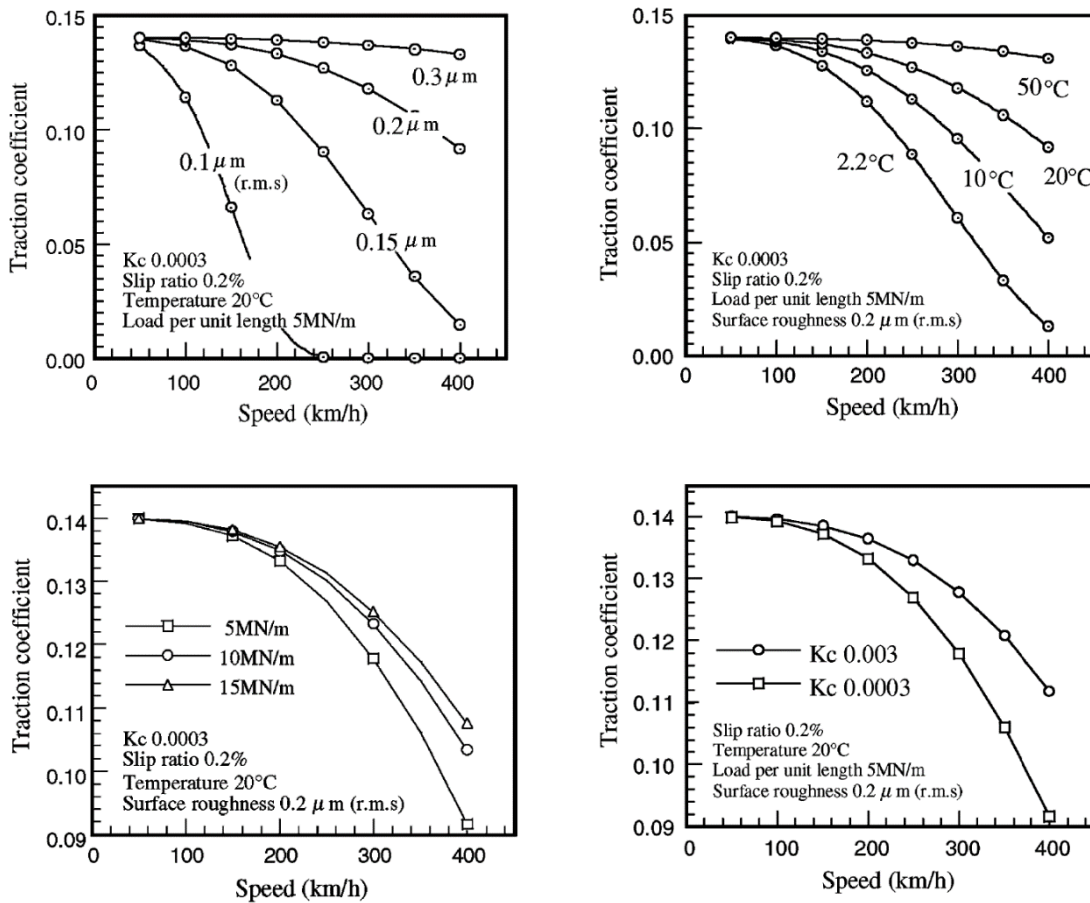
The worst case however is where leaves are picked up by the airflow of passing trains and crushed between wheel and rail, mixing with the metallic debris and water to form a hard layer with a very low coefficient of friction, especially in the presence of small amounts of water (Beagley, 1976). The most significant difficulties with wheel/rail adhesion typically occur in autumn as a result, although the severity depends on the local climate. The presence

of oil (generally originating from either trains or trackside lubricators) also has some effect, reducing the coefficient of friction of dry rails within a similar range to heavier rain (Beagley *et al.*, 1975a), as shown in Figure 73. When rails are wet, oil will reduce the coefficient further but it is the effects of water that dominate (Broster *et al.*, 1974), as the quantities of oil on the rails are generally very small by comparison with the amount of water. On dry rails, the effect of solid debris is to adsorb excess oil, and lessen the effect on the coefficient of friction (Beagley *et al.*, 1975b). In certain places other contaminants may be present and provide similar effects to either oil or rust and wear debris; these may include coal dust, china clay slurry, sawdust, salt from sea spray or mud from road vehicle tyres at level crossings (Broster *et al.*, *op. cit.*; Nagase, 1989).



**Figure 73:** The effect of oil on rails (Broster *et al.*, 1974)

Further studies in Japan examined second order effects on the coefficient of friction that emerge under the influence of water on the wheel/rail contact. The level of adhesion did not change much with increasing speed in dry conditions, but showed a significant decrease in wet conditions (Nagase, *ibid.*). The contact load is shared by asperities on the surface through a film of water, resulting in a decrease of actual contact area between the wheel and rail as a proportion of the load is supported by the water, which has significantly lower shear strength than steel. As the speed increases, the thickness of the water film also increases, resulting in the reduction of available adhesion (Ohyama, 1991). This mechanism means that several other factors can also influence the adhesion level; the result of investigations into four such factors are summarised in Figure 74.



**Figure 74:** Second order effects on wet rails (Chen *et al.*, 2002)

The two most significant factors are the surface roughness and temperature of the water. With a smoother surface, more of the contact load will be taken by the water film for a given film thickness; likewise the viscosity of the water will also be increased at lower temperatures, increasing the share of the contact load. The surface roughness will vary with wear of the wheel and rail; the temperature of water will vary with ambient environmental conditions, although it is likely to be heated by the pressure within the contact. The wheel load and shape of surface asperities (parameter of roughness  $K_c$ ) also have a slight effect at higher speeds on the adhesion level (Chen *et al.*, 2002). Rails contaminated with oil behave in a similar manner to dry rails and do not show a reduction in adhesion with increasing speed: oil weakens the interfacial bonding between asperities but does not share the contact load (Ohshima, *op. cit.*).

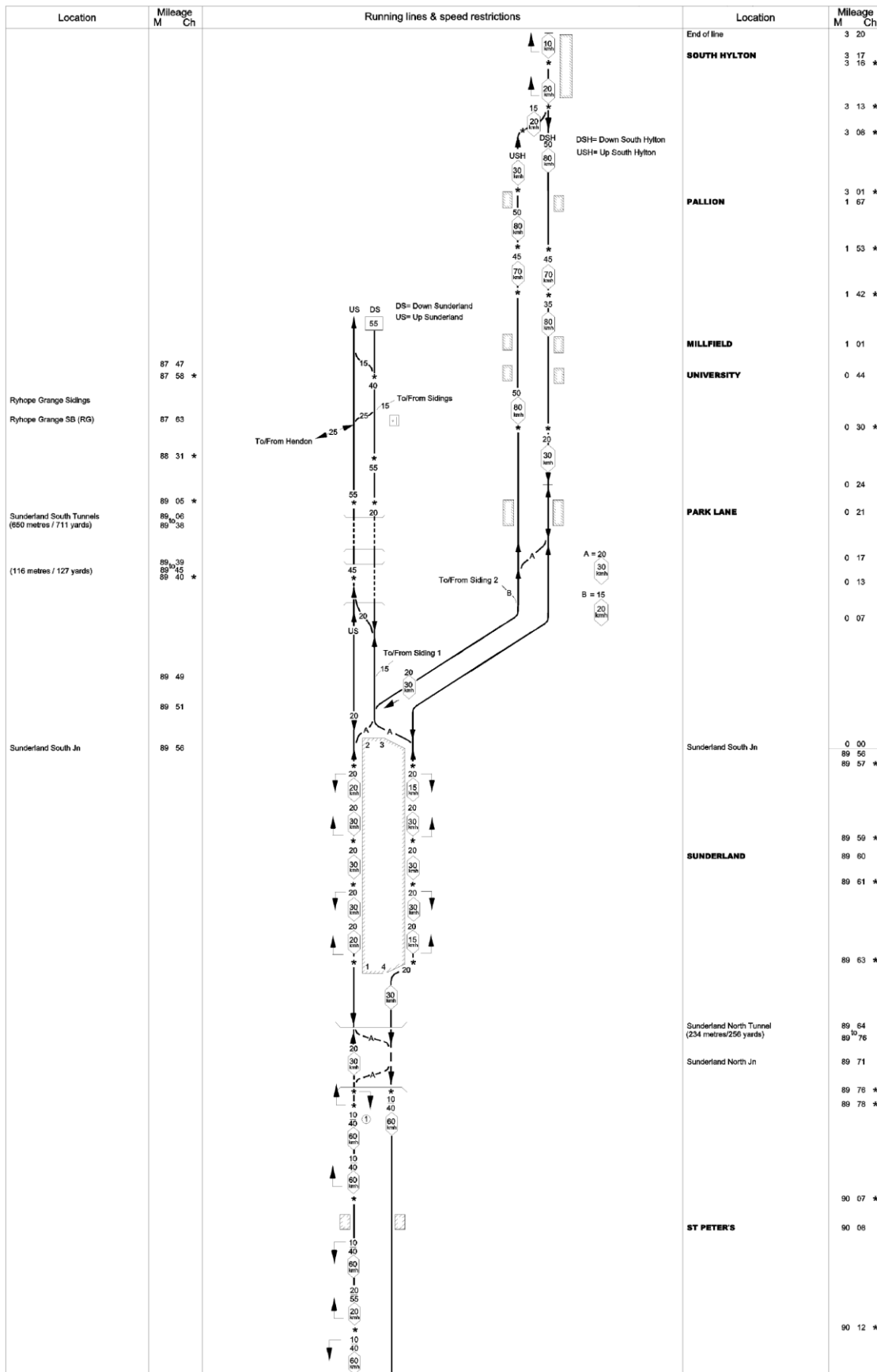
The coefficient of friction can change significantly in a short distance, depending on local conditions. For example, reductions from a coefficient of around 0.2 to less than 0.05 can be observed within tens of metres (Nagase, *op. cit.*). Likewise, the effect of light rain on a section of railway can be almost immediate, as shown by the rate of change of the coefficient of friction in Figure 72. Although heavy rain initially lowers the coefficient of friction of dry rails, it also tends to clean any contamination, leading to an overall improvement once the

rails have dried afterwards. Heavy rain also prevents leaves being picked up and deposited on the track by aerodynamic effects when a train passes, and helps to break up leaf films once formed on the rail. The passage of trains also tends to clean the rails of contaminants (Broster *et al.*, 1974), especially when operating close to the limiting value of adhesion (Logston and Itami, 1980). In dry conditions however, the passage of trains can also re-establish a leaf film on the track relatively quickly. The first train of the day, or trains on lightly used sections of the network, often suffer a disproportionate amount of low adhesion problems due to the build-up of frost, dew or light rust (Beagley and Pritchard, *op. cit.*).

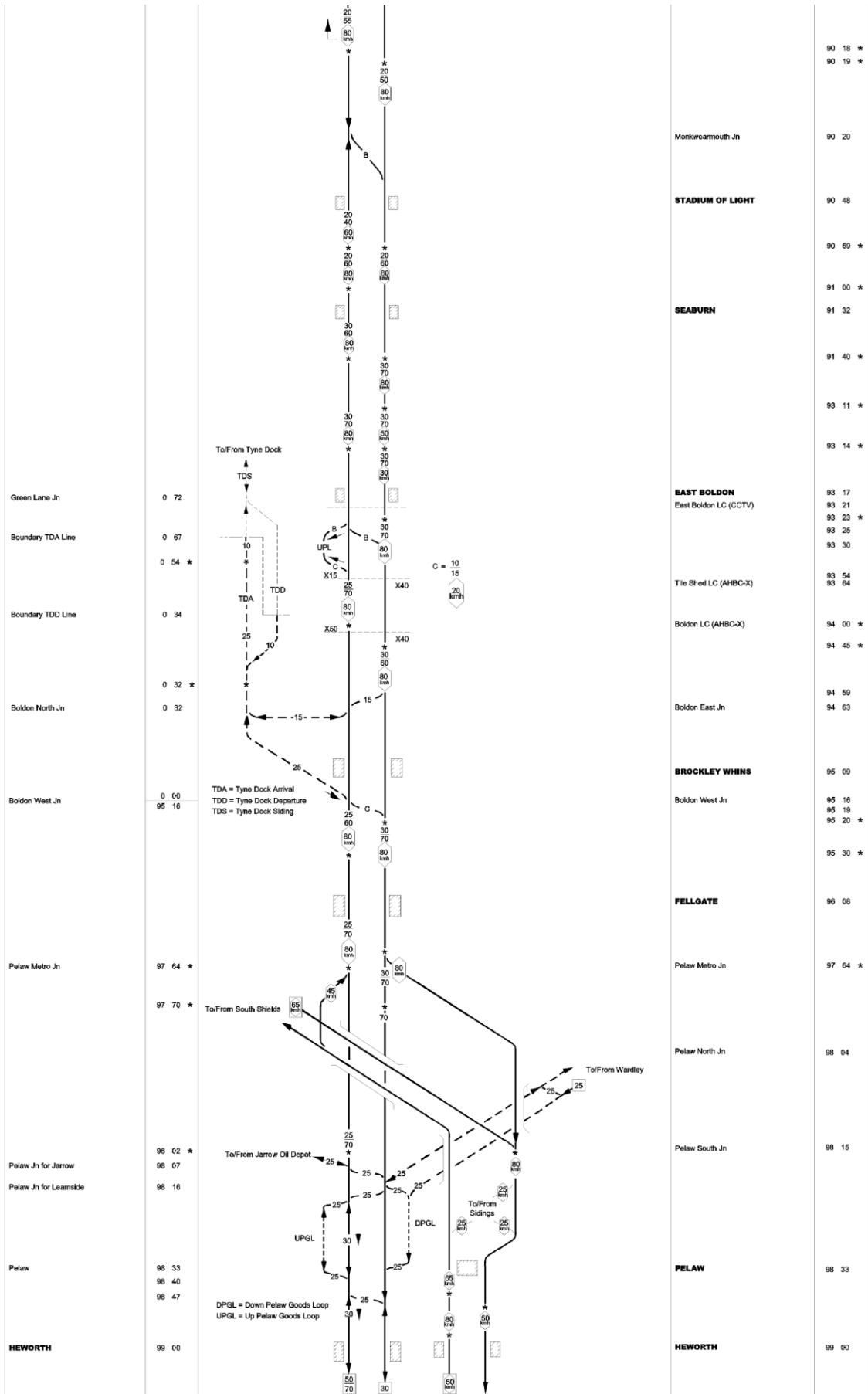
It can be concluded from this review that actual wheel/rail adhesion values show considerable variation over short distances and timescales. Although some mitigation is possible, the level of control over wheel/rail adhesion in an open environment is generally rather limited. It has already been noted in Section 1.1.2 that this variation, and the difficulty of controlling it, is a principal part of the motivation for this thesis.

# APPENDIX B. TRACK LAYOUTS

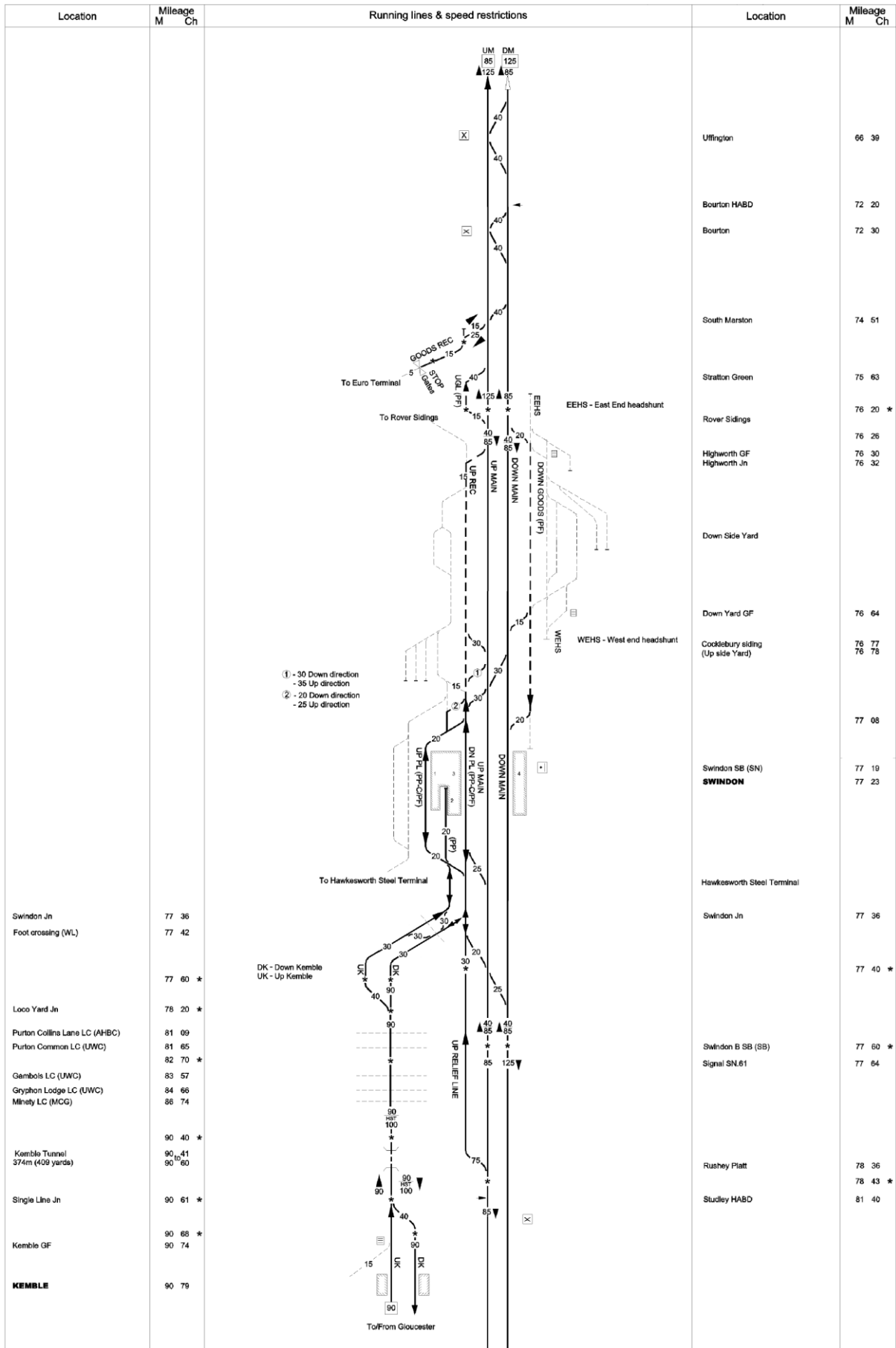
## B.1. Tyne and Wear

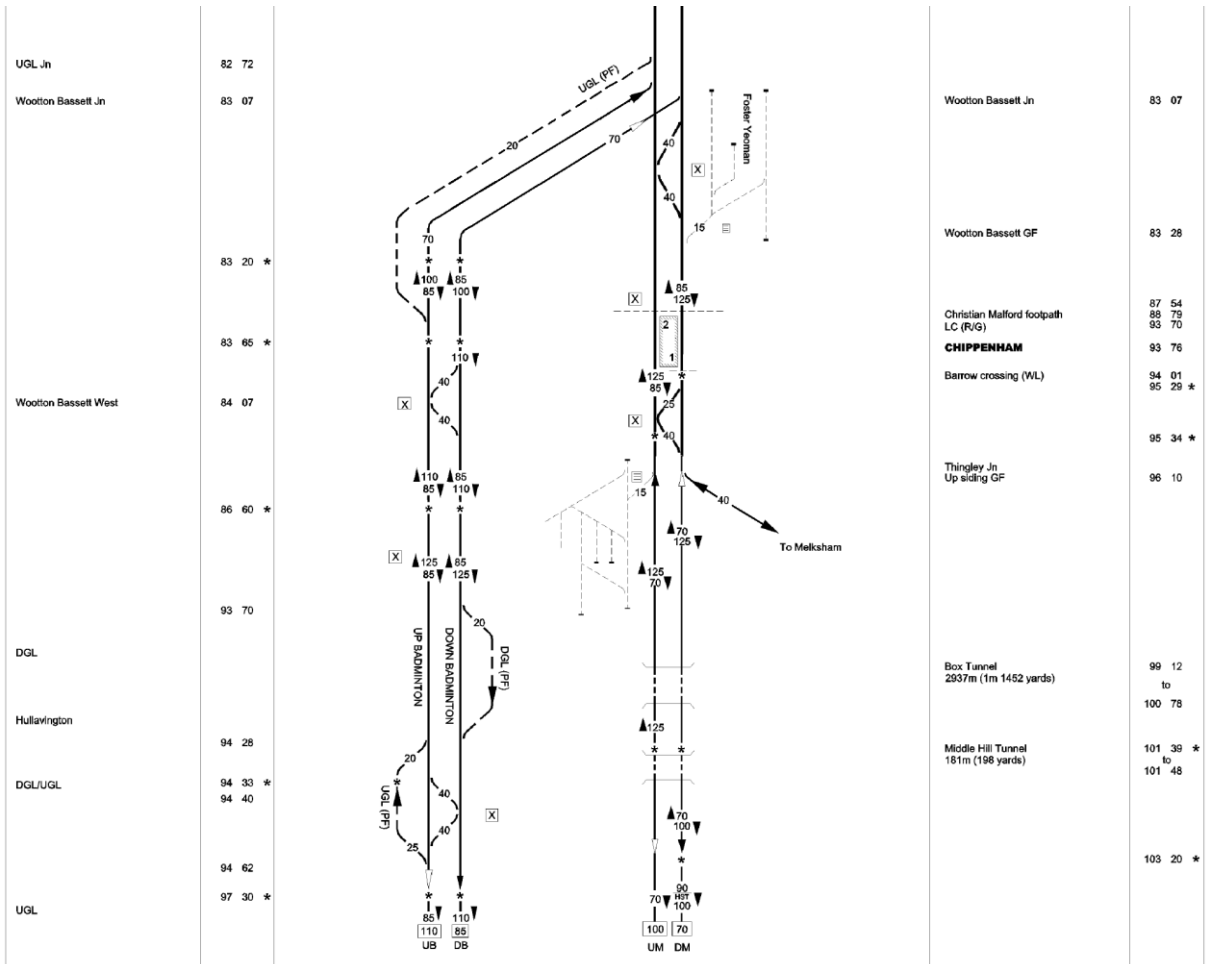




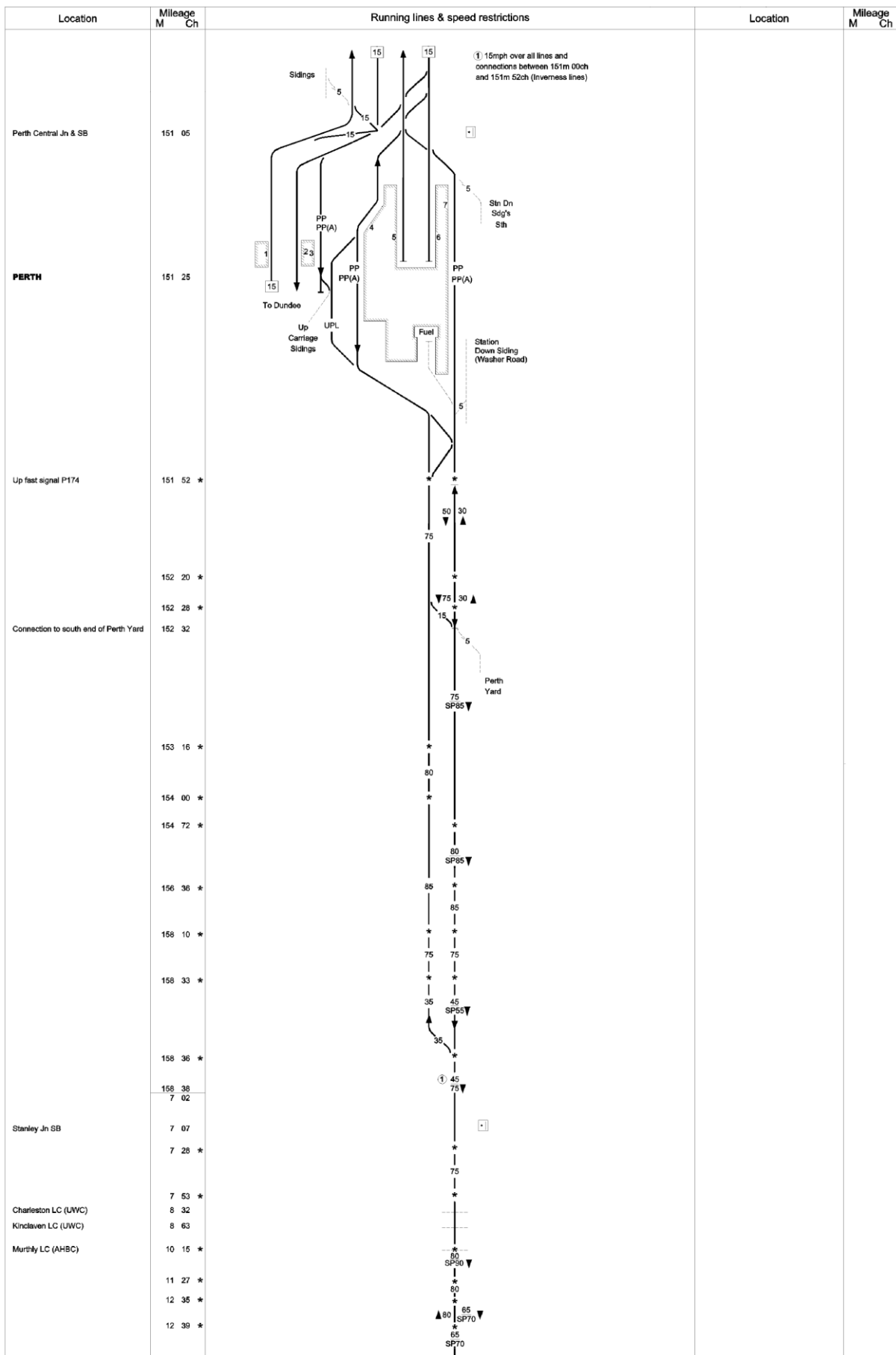


# B.2.Swindon

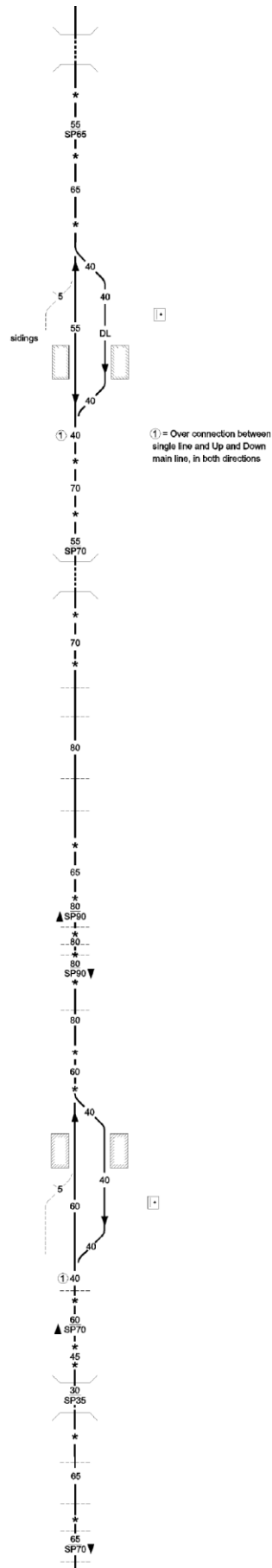




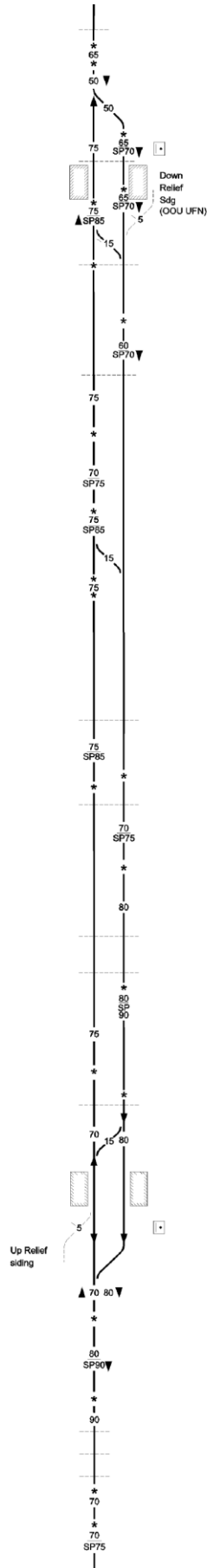
### B.3. Highland Main Line



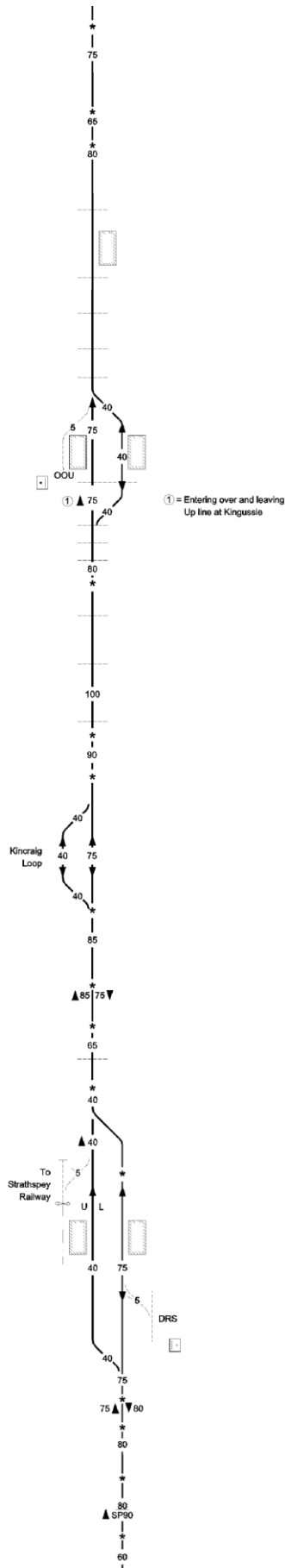
Kingwood Tunnel (330 yards)	12 78 to 13 13
	13 20 *
	13 63 *
	14 74 *
Dunkeld SB	15 25
<b>DUNKELD and BIRNAM</b>	15 31
	15 45 *
	16 45 *
Inver Tunnel 370 yards	16 55 to 16 72
	17 00 *
	17 42 *
Inchmagranachan No.2 LC (UWC)	18 36
Inchmagranachan No.3 LC (UWC)	18 57
	80
Easter Dalguise No.1 LC (UWC)	19 76
Easter Dalguise No.2 LC (UWC)	20 14
	20 23 *
	20 52 *
Guay LC (UWC)	21 23 *
Haugh of Kilmorich LC	22 35
Haugh of Tullymet LC (R/G)	22 67 *
	24 41 *
Moulineam LC (R/G)	25 33
	27 21 *
	28 16 *
<b>PITLOCHRY</b>	28 21
Pitlochry SB	28 31
	28 65
Moulin LC (UWC)	30 41 *
	30 00
	31 57 *
	31 62 *
Killiecrankie Tunnel (240 yards)	31 66 to 31 77
	32 06 *
Urrard No.1 LC (UWC)	32 15
	65
Urrard No 2 LC (UWC)	32 41
Aldcune No 3 LC (UWC)	33 19 *
	33 27
Kings Island LC (UWC)	34 02



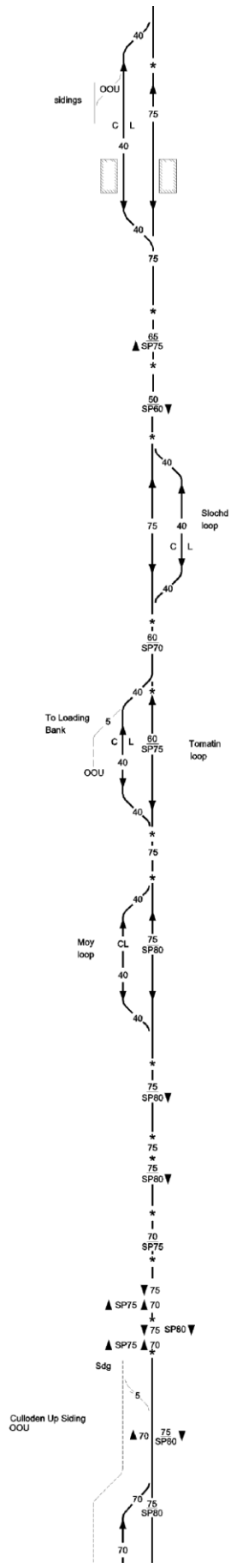
Ballentoul LC (UWC)	34 36
	34 72 *
	34 77 *
	35 02 *
Blair Atholl SB and LC (MCB)	35 05
<b>BLAIR ATHOLL</b>	35 09
	35 44 *
	36 58 *
	37 00
Pitgowan LC (UWC)	38 30 *
	39 17 *
Cuness LC (UWC)	41 25
	41 68 *
	42 40
	42 44 *
Dalnecardoch GF	44 76
	45 20 *
	45 61 *
Red Van LC (UWC)	49 03
	49 69 *
	50 53 *
Dalnesspidal LC (UWC)	50 60
	53 00 *
Whitebridge LC (UWC)	54 14
Balsporran LC (UWC)	54 65
	54 72 *
	57 40 *
Ben Alder LC (UWC)	58 29 *
	58 30 *
<b>DALWHINNIE</b>	58 47
Dalwhinnie SB	58 53
	59 50 *
Cualch LC (UWC)	60 41
Creag Ruadh LC	61 45
Inchlee LC (UWC)	62 38
	62 40 *
	63 29 *
	64 76



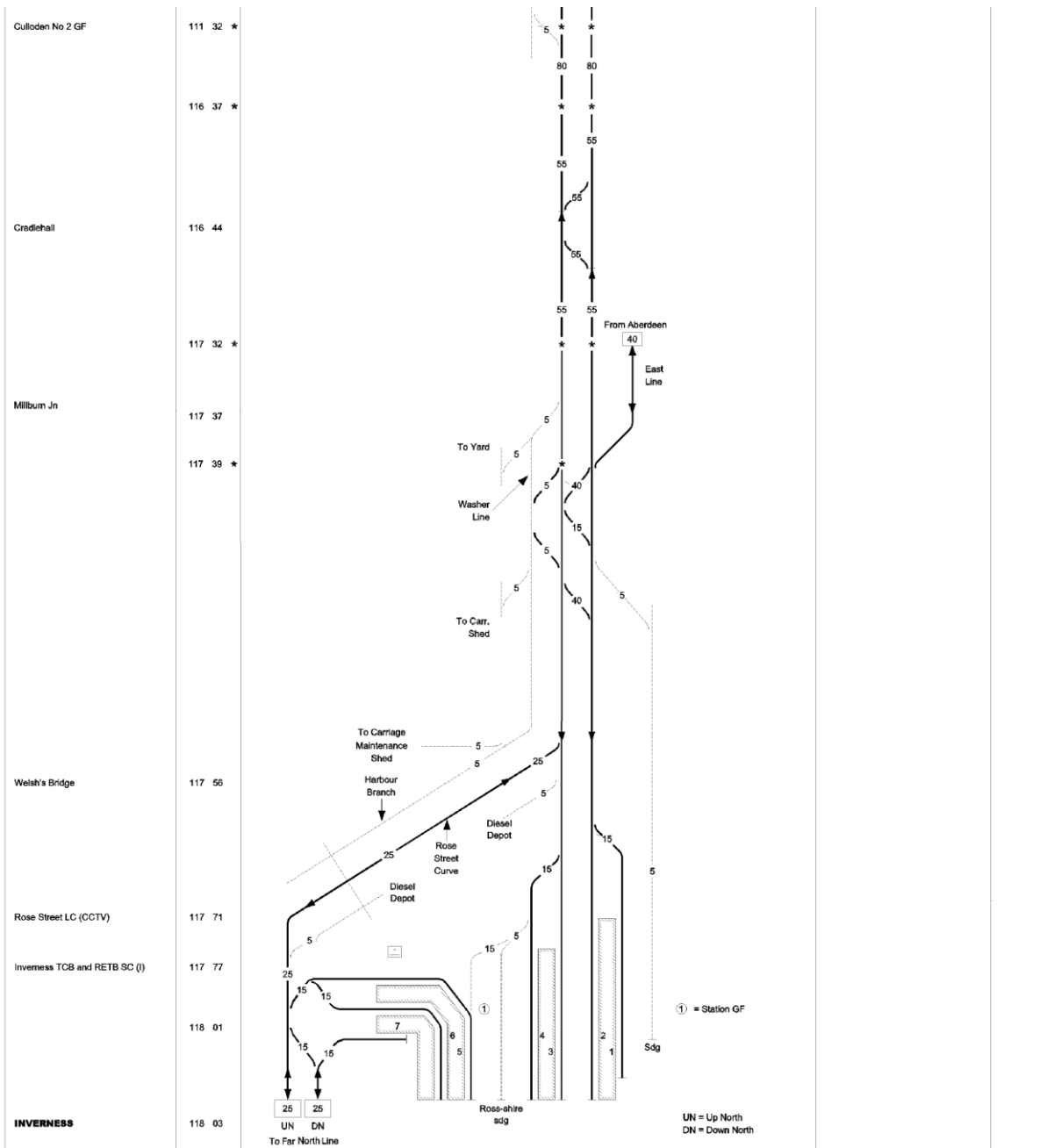
	66 46 *
	68 22 *
	68 28 *
Newtonmore Station LC	68 53
<b>NEWTONMORE</b>	68 62
Altlaire LC (UWC)	69 74
Ballachroan LC (UWC)	70 32
Pitmain No 1 LC (UWC)	70 56
Pitmain No 2 LC (UWC)	70 71
<b>KINGUSSIE</b>	71 43
Kingussie SB and LC (MCB)	71 50
Macraes LC (UWC)	72 39
Cemetery LC	72 65
Lynchat LC (UWC)	73 11
	73 17 *
Balavil Burn LC (UWC)	73 72
Balavil Gates LC (UWC)	74 05
	74 77
Croftersnoch No 2 LC (UWC)	76 20 *
	76 70 *
South Pts	77 23
	77 55 *
North Pts	82 09 *
	82 29 *
Lynwily No 1 LC (UWC)	82 31
	83 05 *
	83 15 *
GF	83 31
<b>AVIEMORE</b>	83 51
Aviemore	83 63 *
	83 70 *
	86 78 *
	89 59 *



South Pts	89 65
	89 73 *
<b>CARRBRIDGE</b>	90 00
North Pts	90 15
	93 40 *
	94 60 *
South Pts	95 13 *
	95 14
North Pts	95 46 *
	97 14 *
South Pts	98 60 *
	98 46 *
North Pts	99 11 *
South Pts	102 06 *
	102 70
North Pts	103 23
	105 00 *
	108 06 *
	108 47 *
	110 58 *
	110 73 *
	111 07 *
	111 14 *
Culloden No 1 GF	111 17
Culloden	111 30



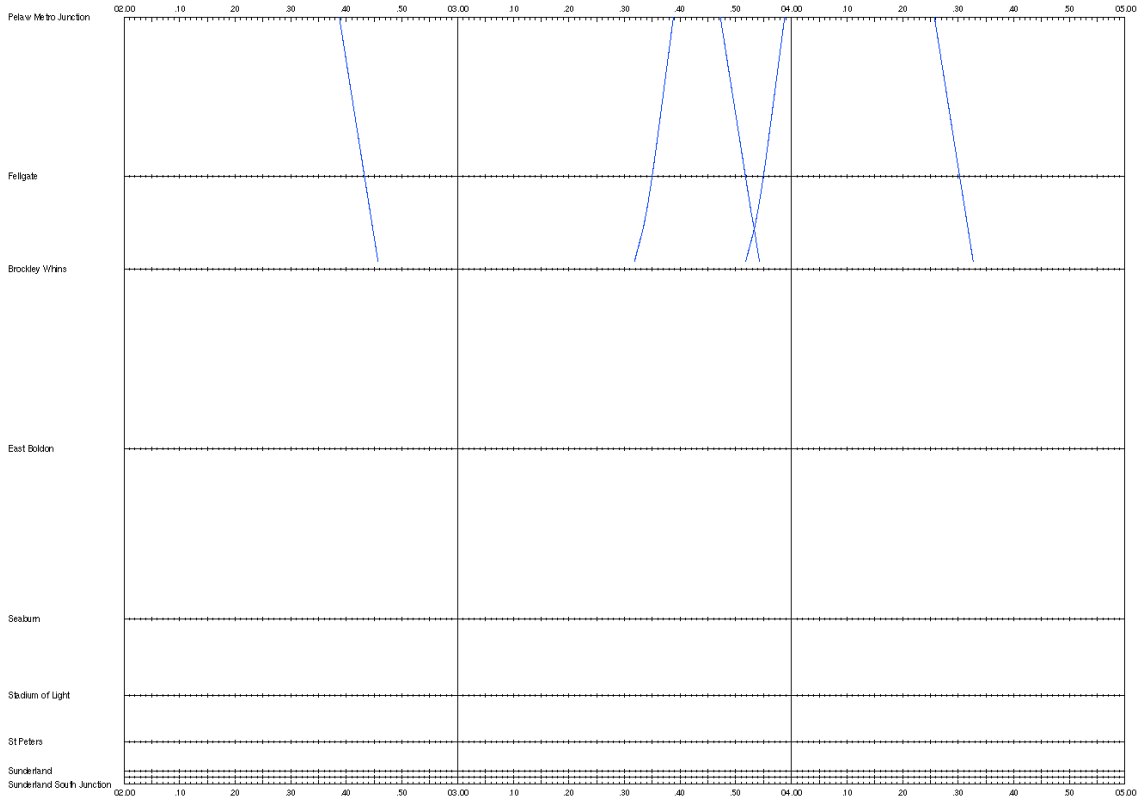




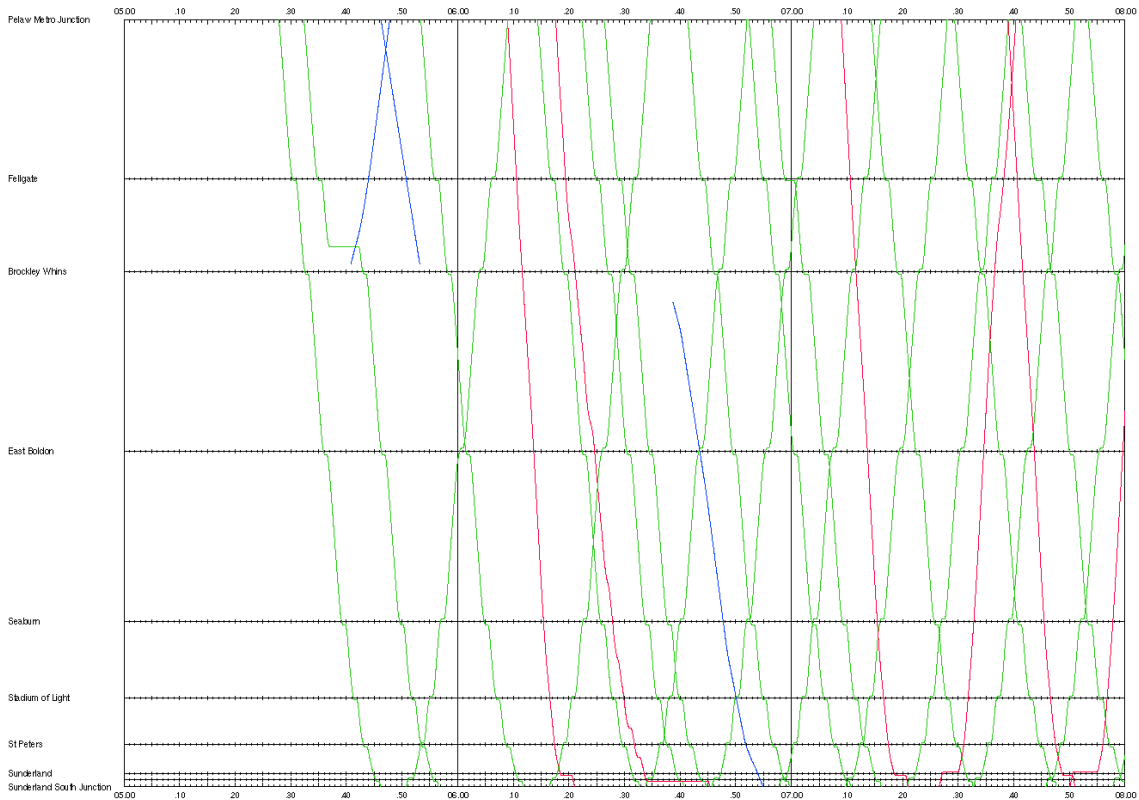
# APPENDIX C. TRAIN GRAPHS

## C.1. Tyne and Wear

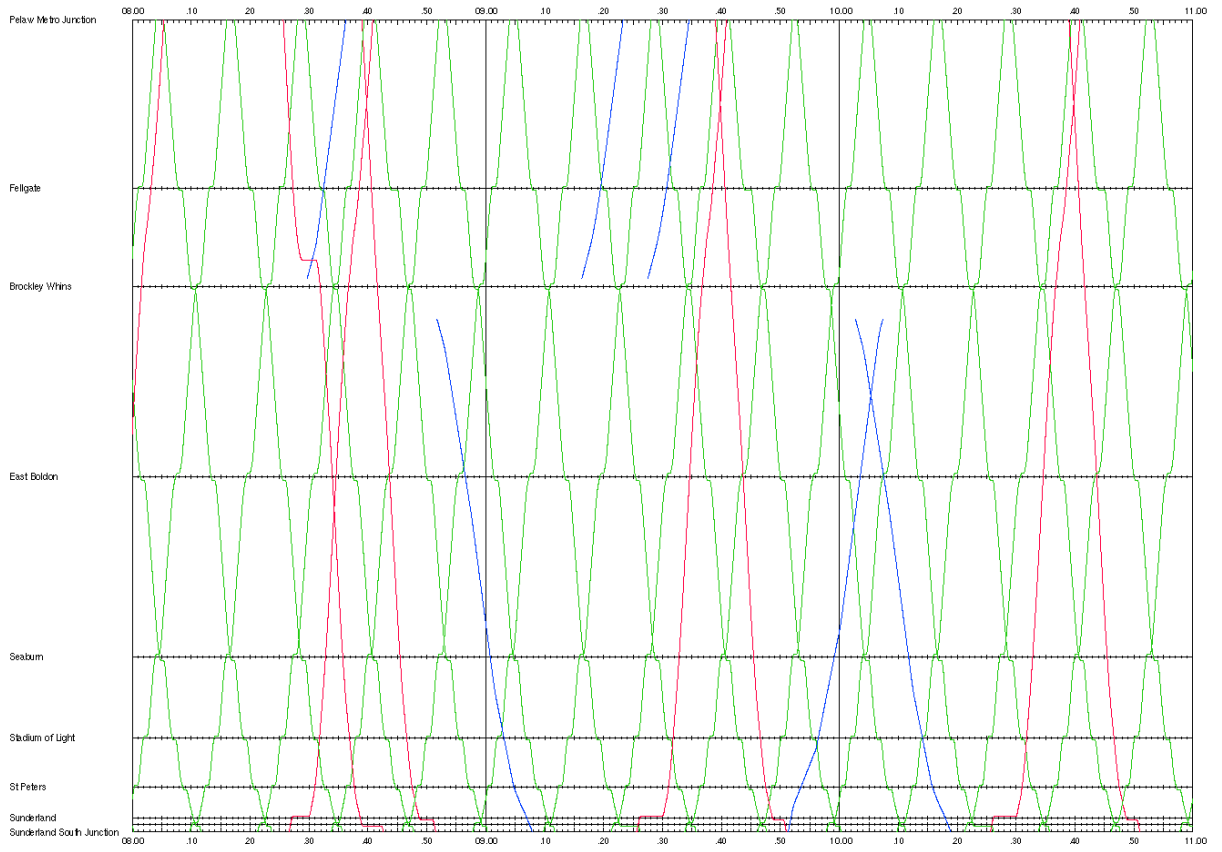
Pelaw Metro Junction - Sunderland South Junction



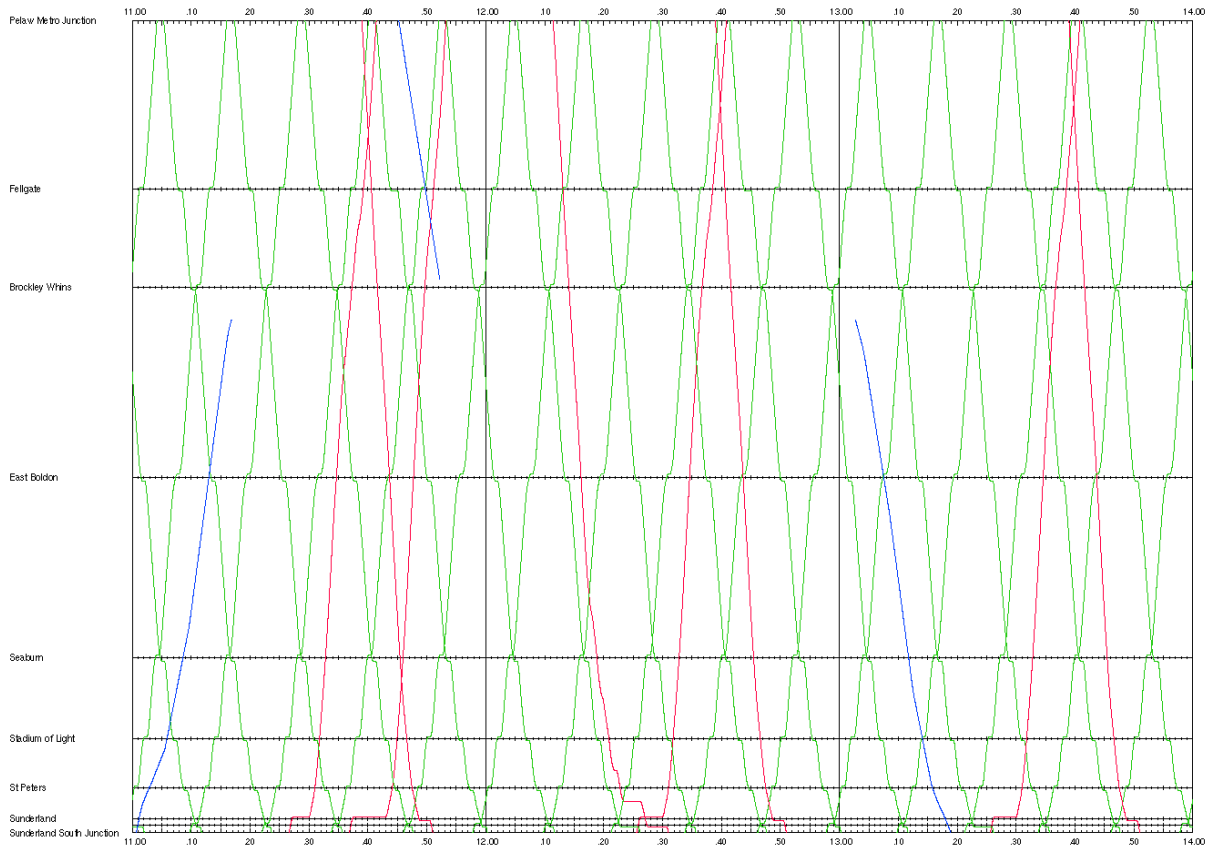
Pelaw Metro Junction - Sunderland South Junction



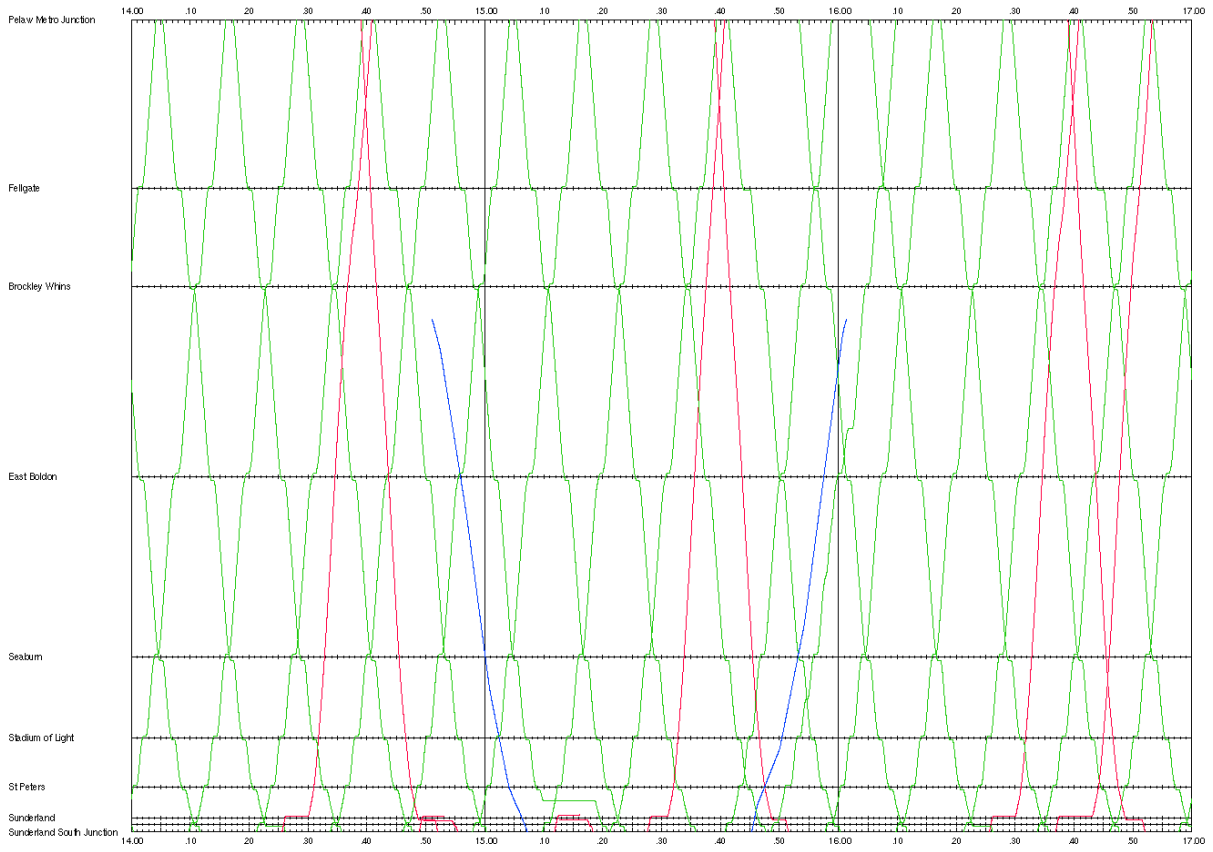
Pelaw Metro Junction - Sunderland South Junction



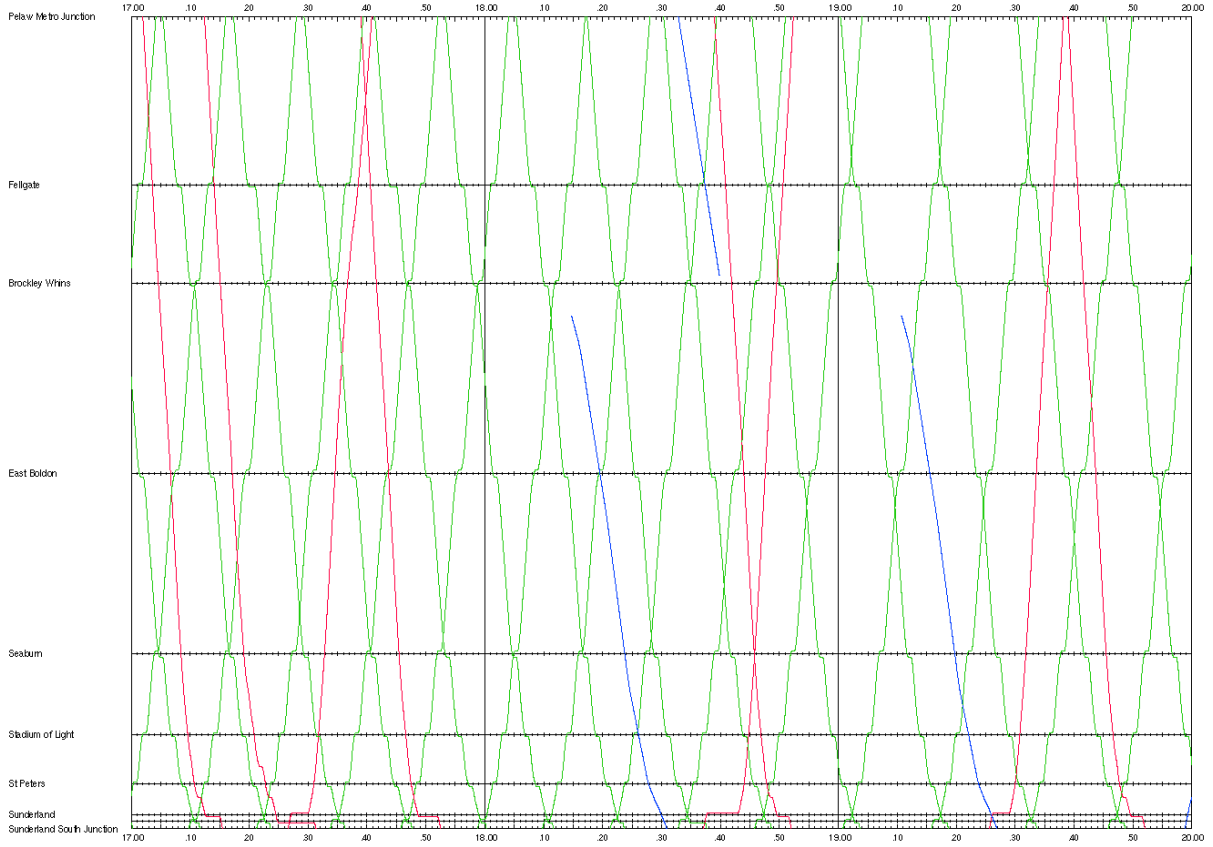
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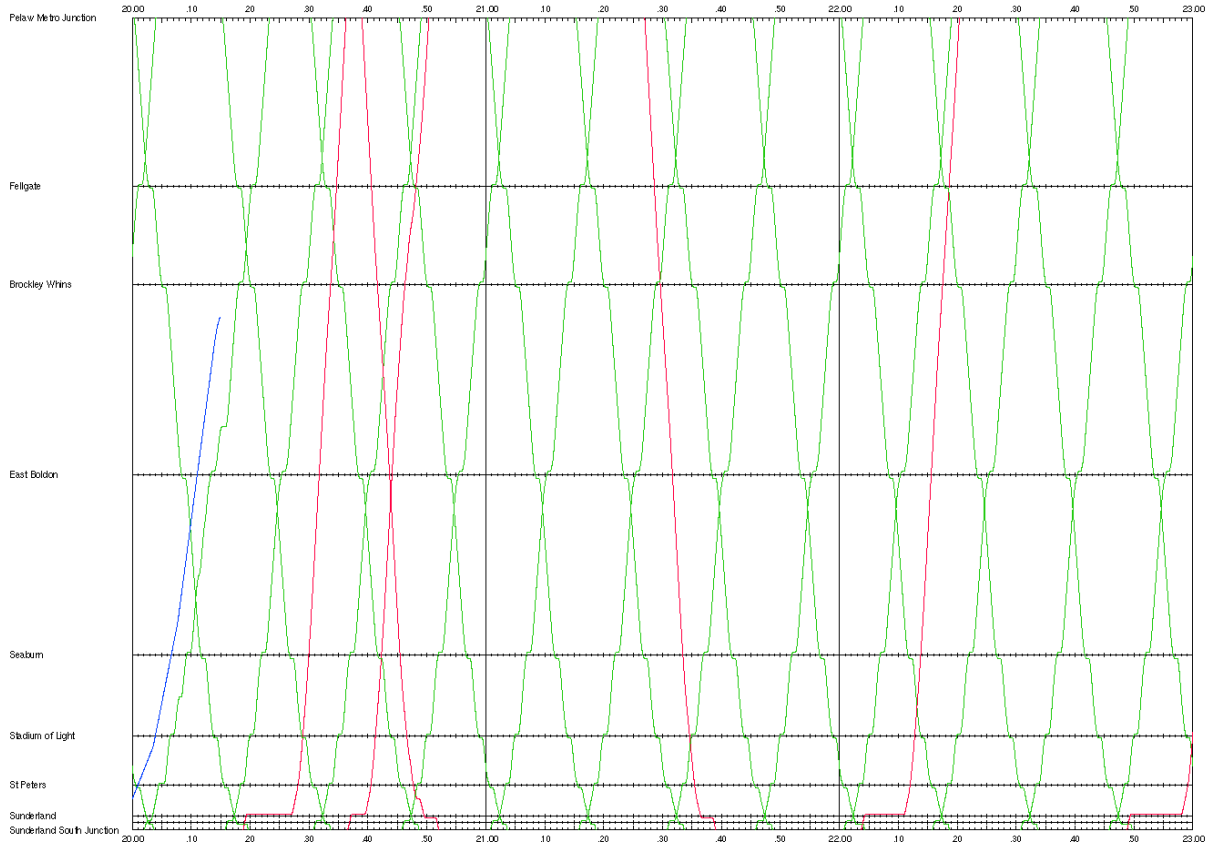
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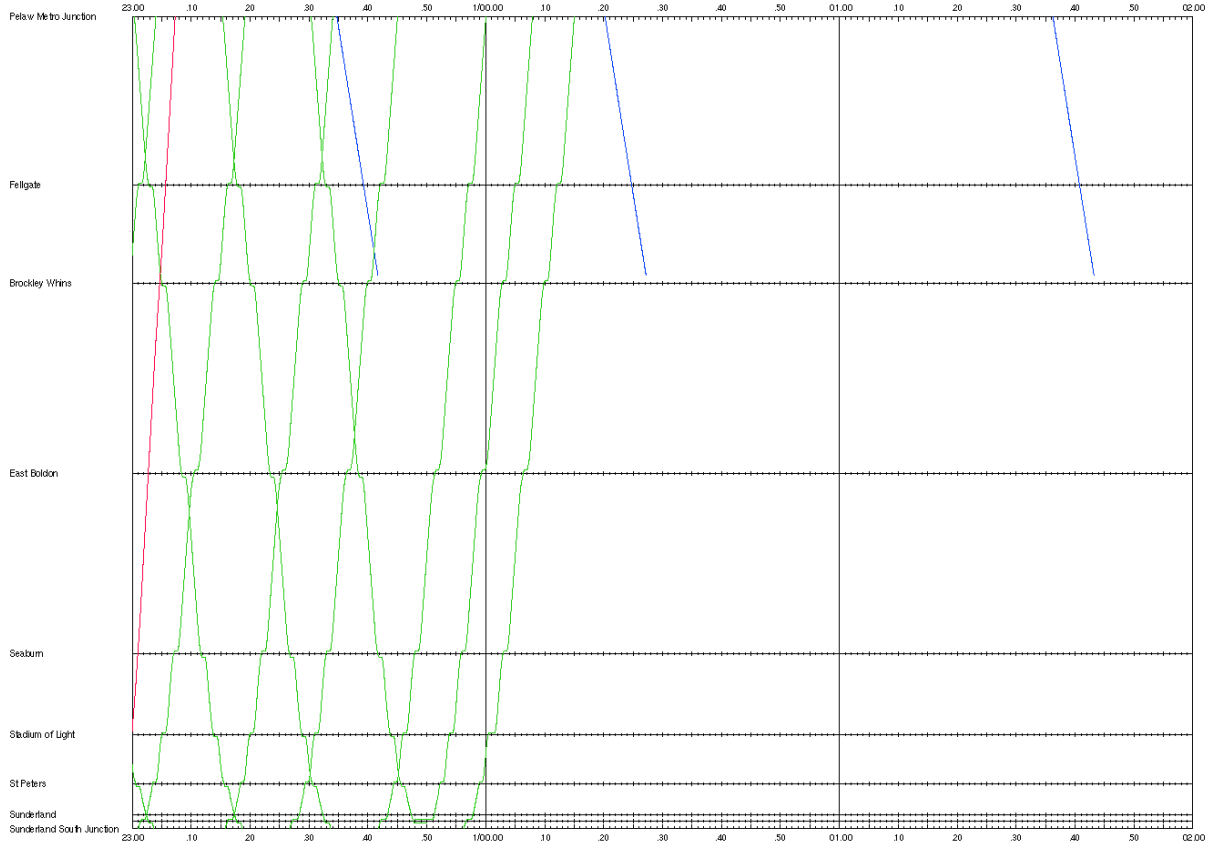
Pelaw Metro Junction - Sunderland South Junction



Pelaw Metro Junction - Sunderland South Junction

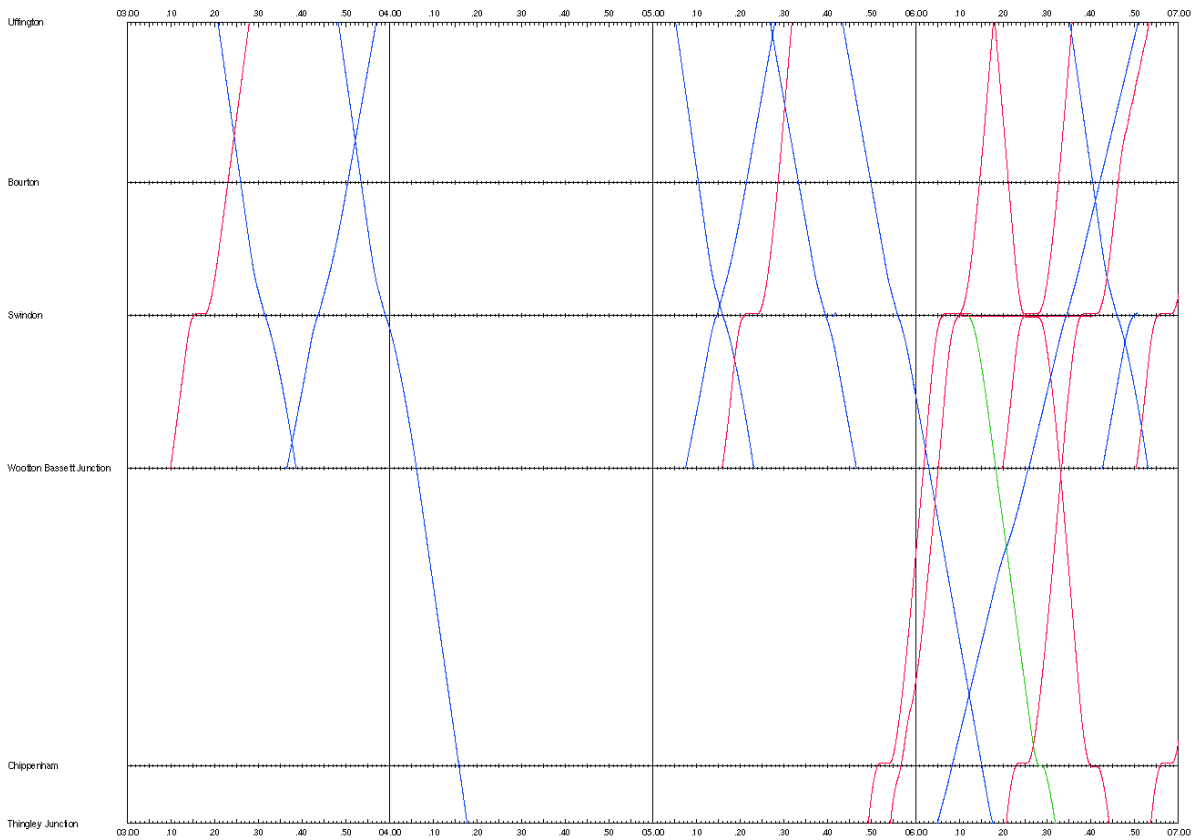


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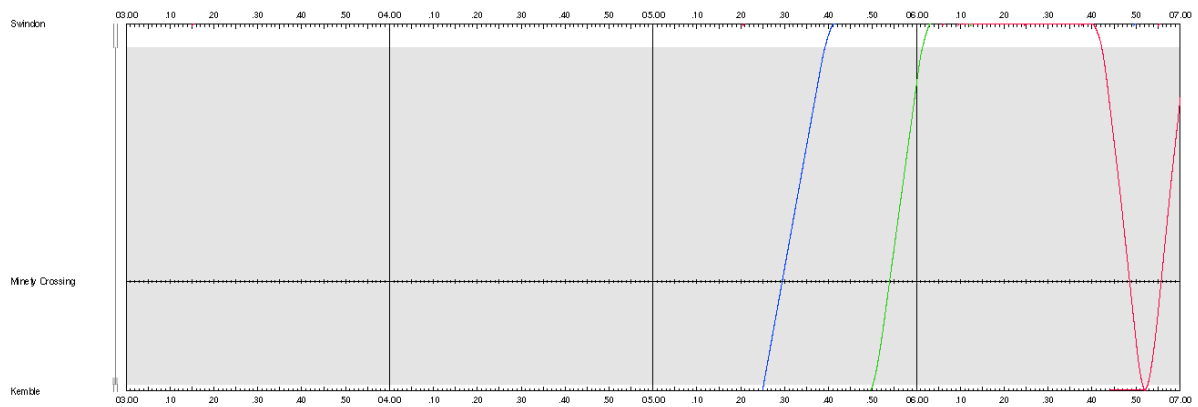


## C.2.Swindon

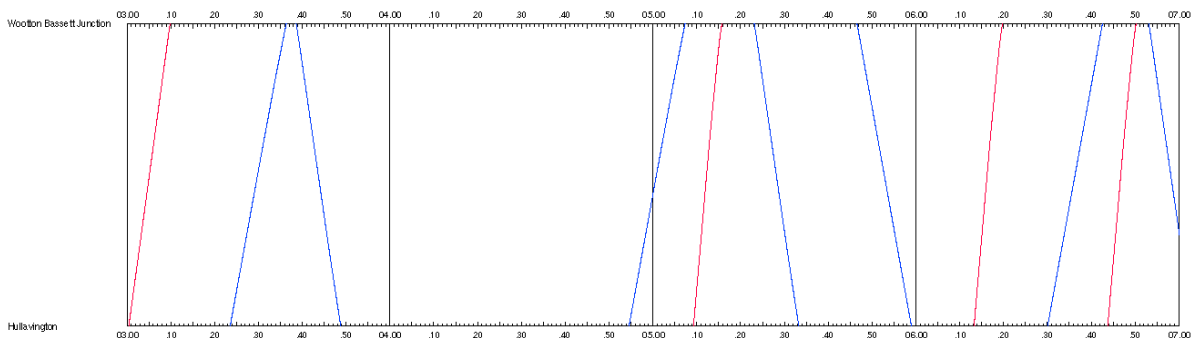
### Uffington - Thingley Junction



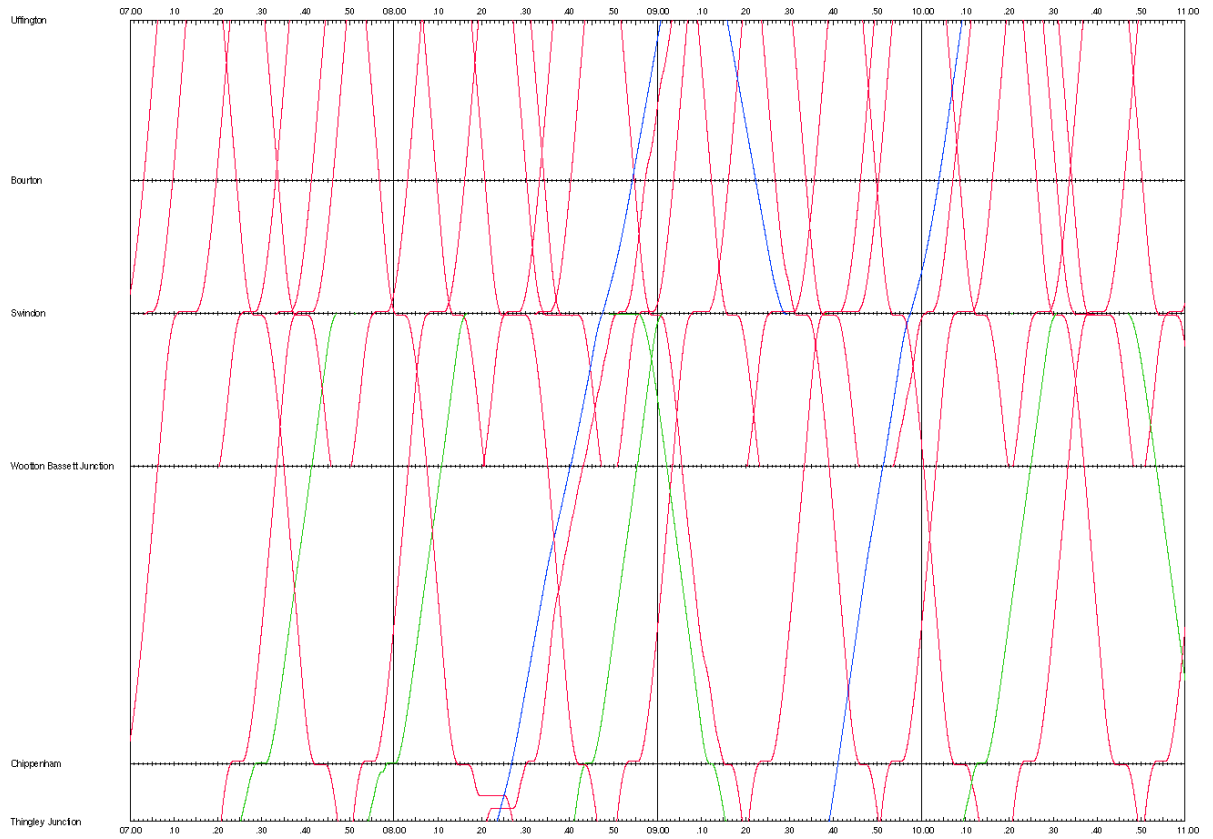
### Swindon - Kemble



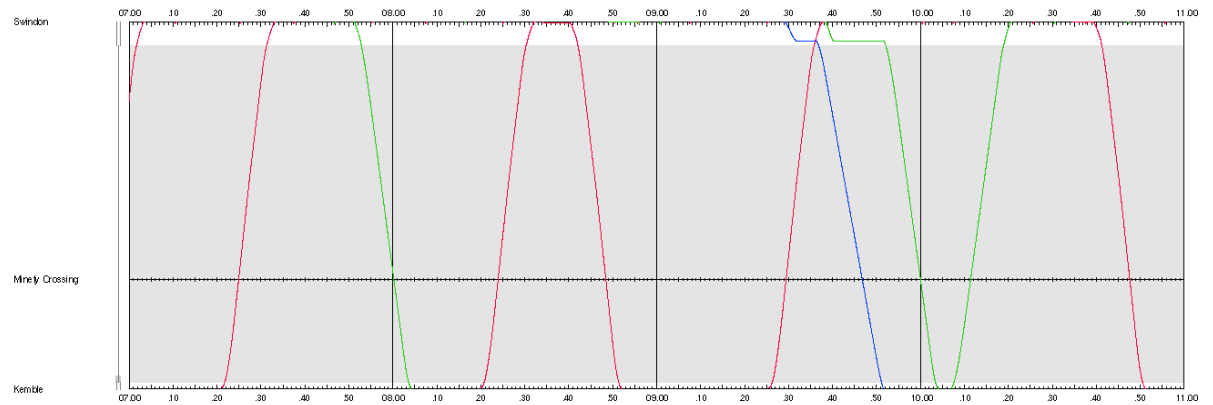
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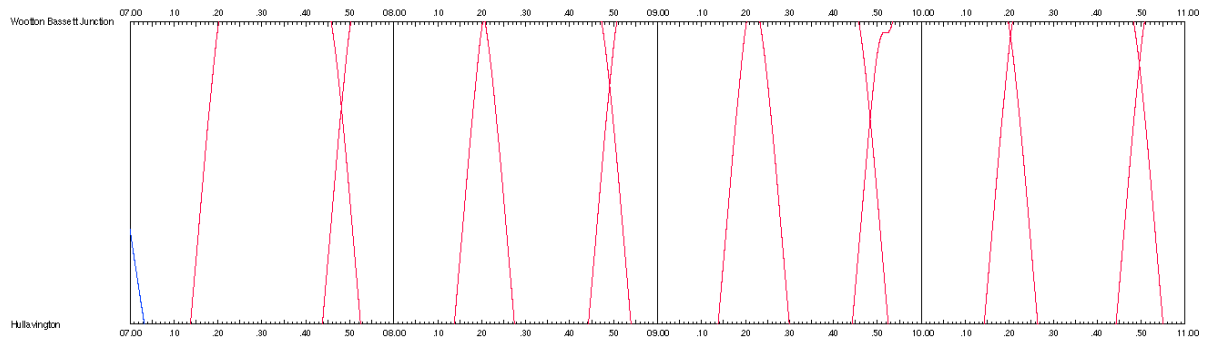
Uffington - Thingley Junction



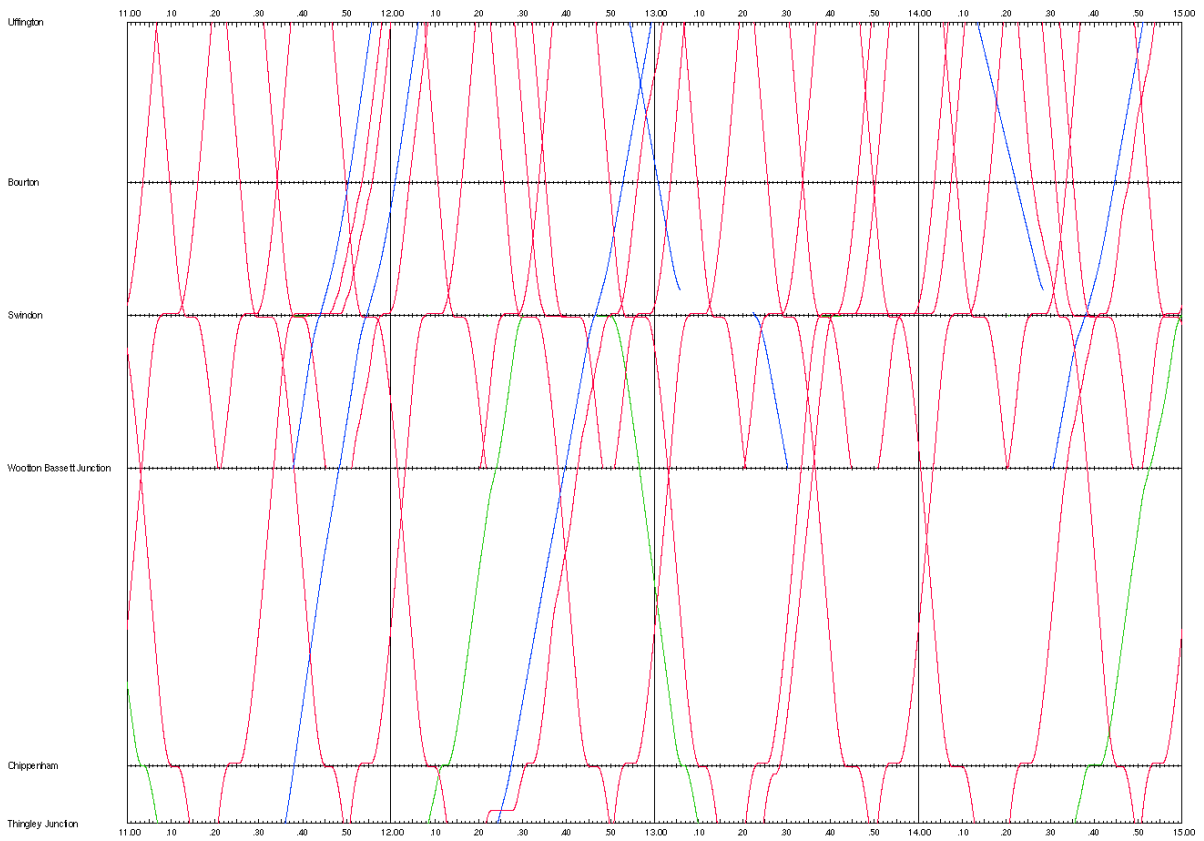
Swindon - Kemble



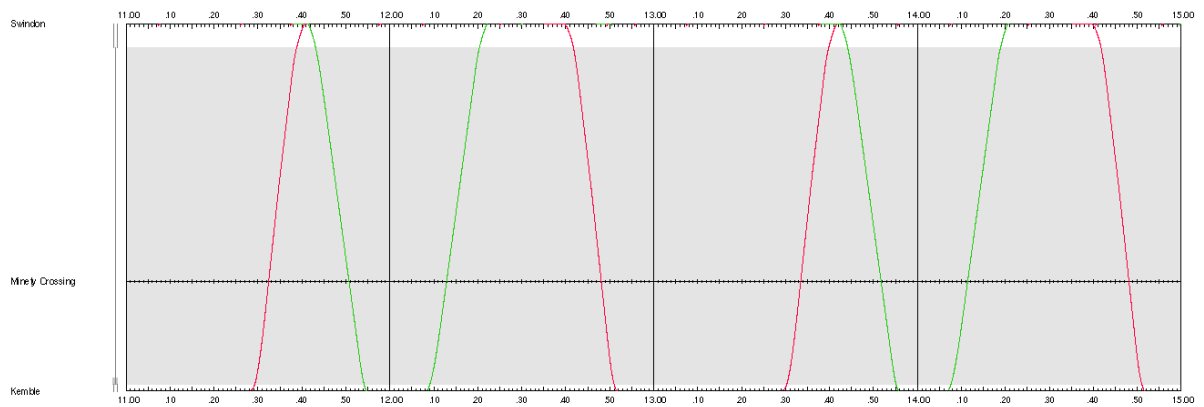
Woolton Bassett Junction - Hullavington



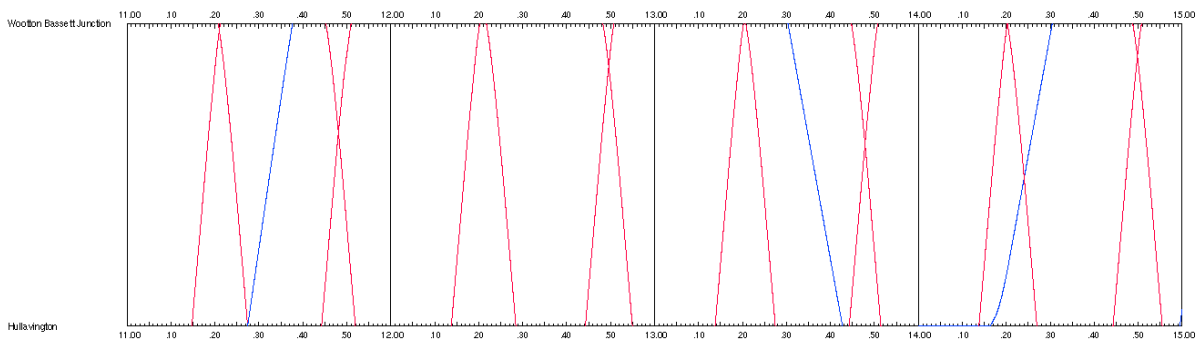
Uffington - Thingley Junction



Swindon - Kemble

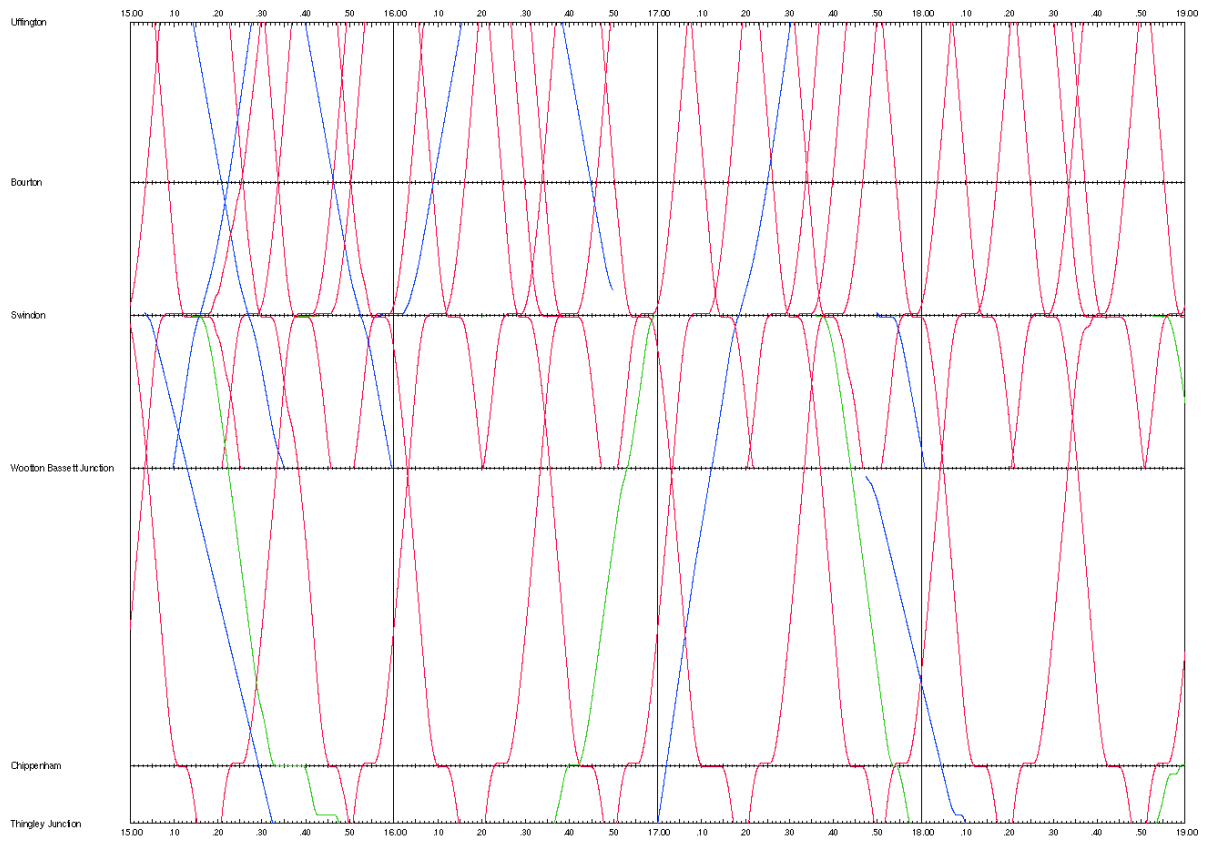


Wootton Bassett Junction - Hullavington

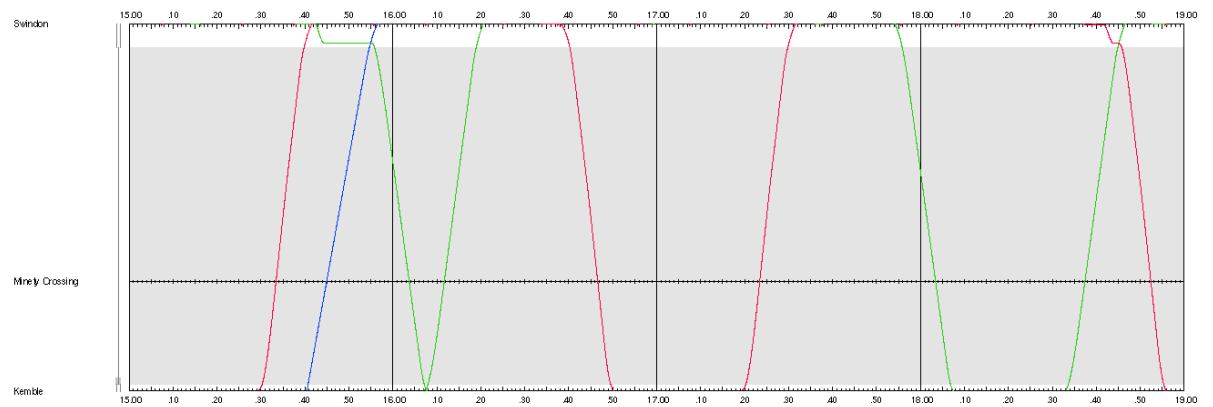




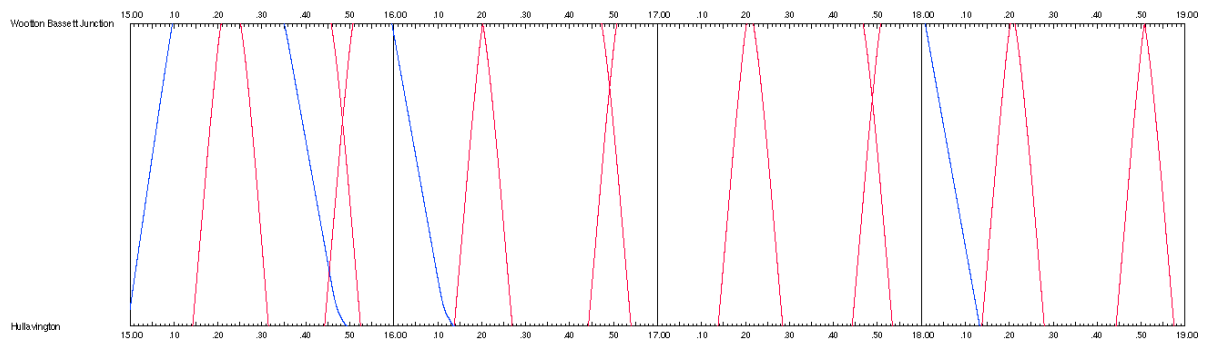
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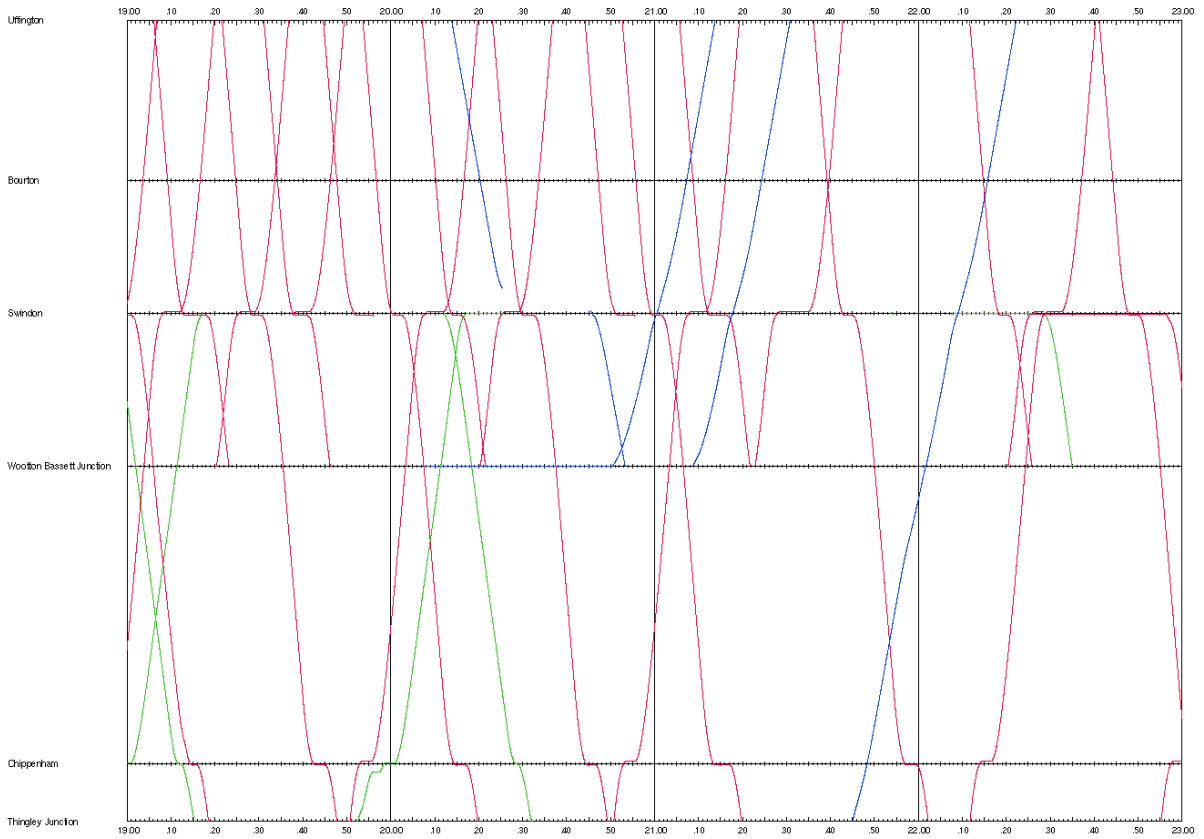
### Swindon - Kemble



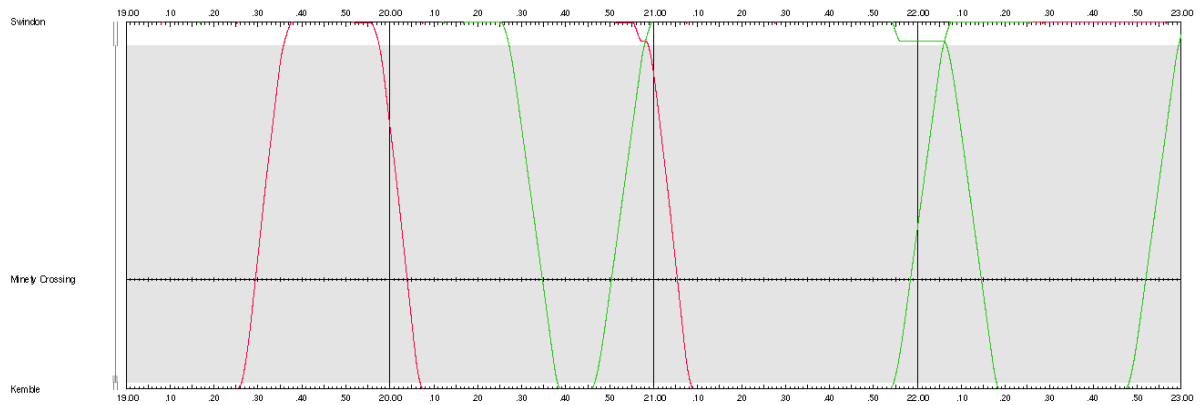
### Woolton Bassett Junction - Hullavington



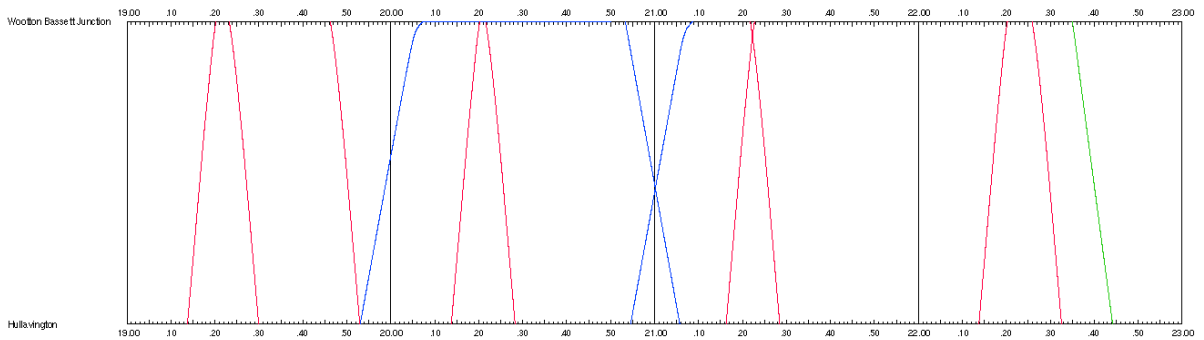
Uffington - Thingley Junction



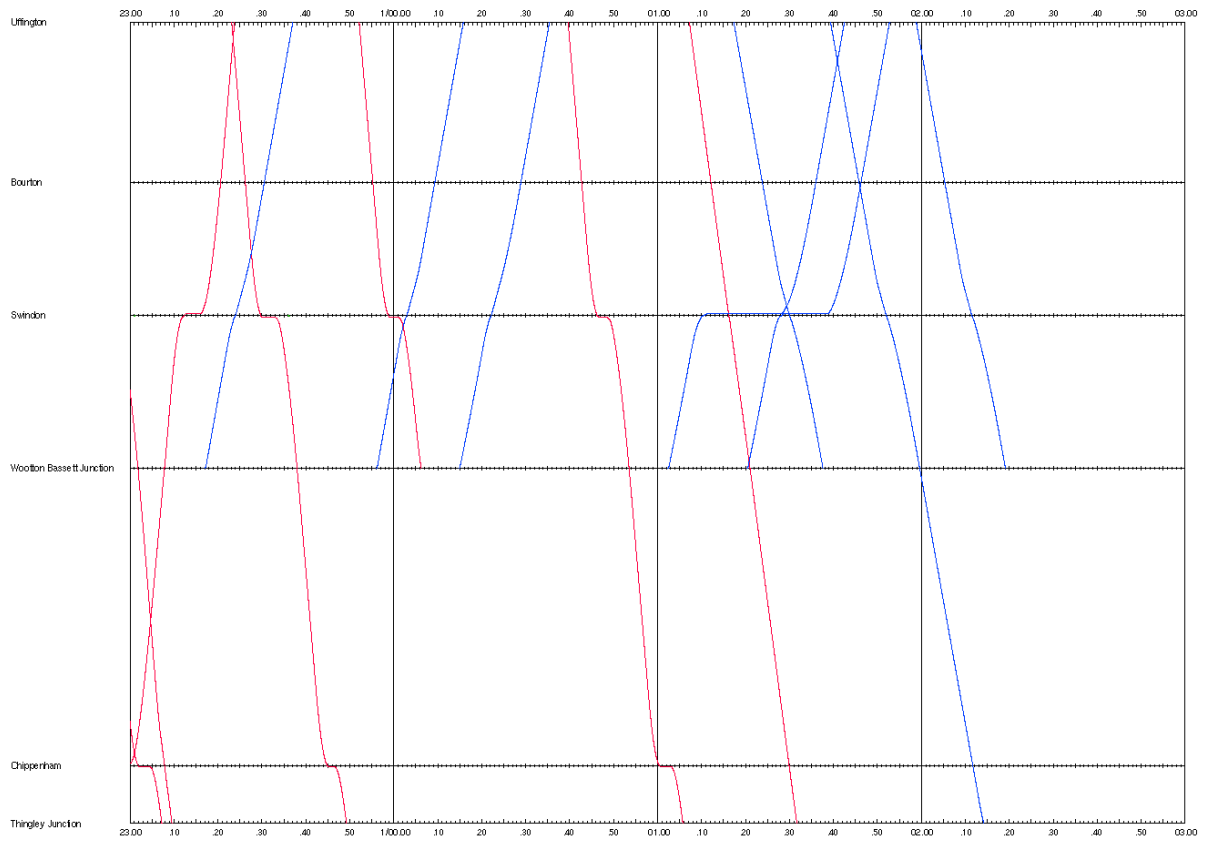
Swindon - Kemble



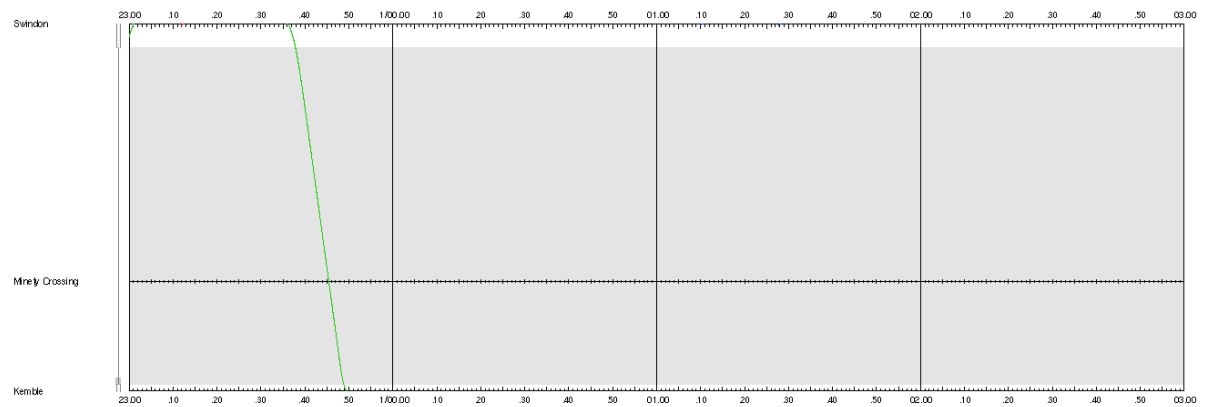
Wootton Bassett Junction - Hullavington



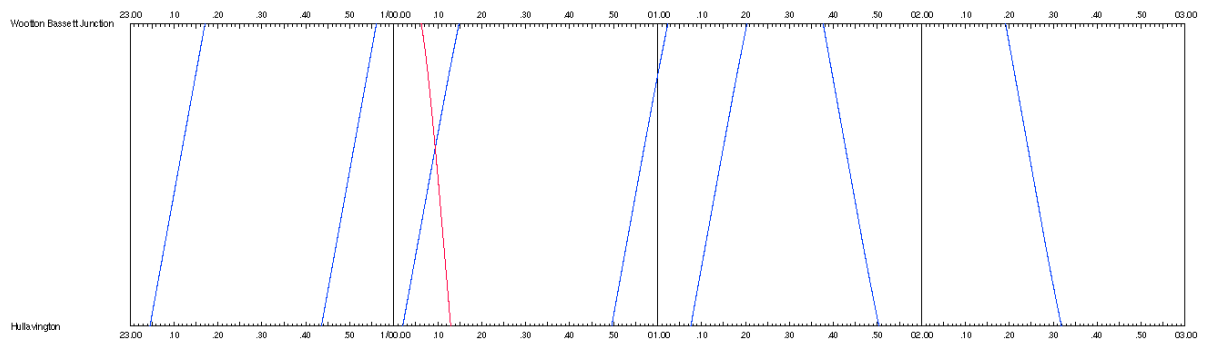
Uffington - Thingley Junction



Swindon - Kemble

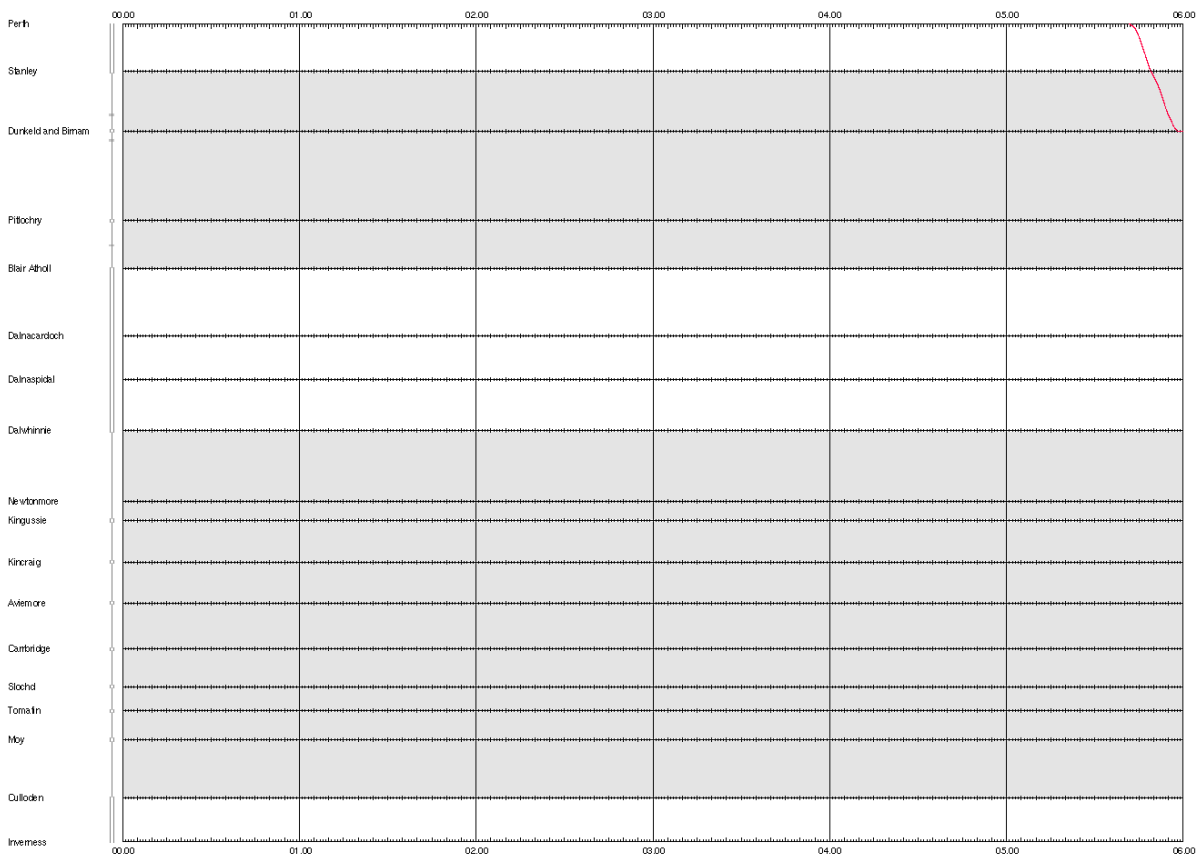


Wootton Bassett Junction - Hullavington

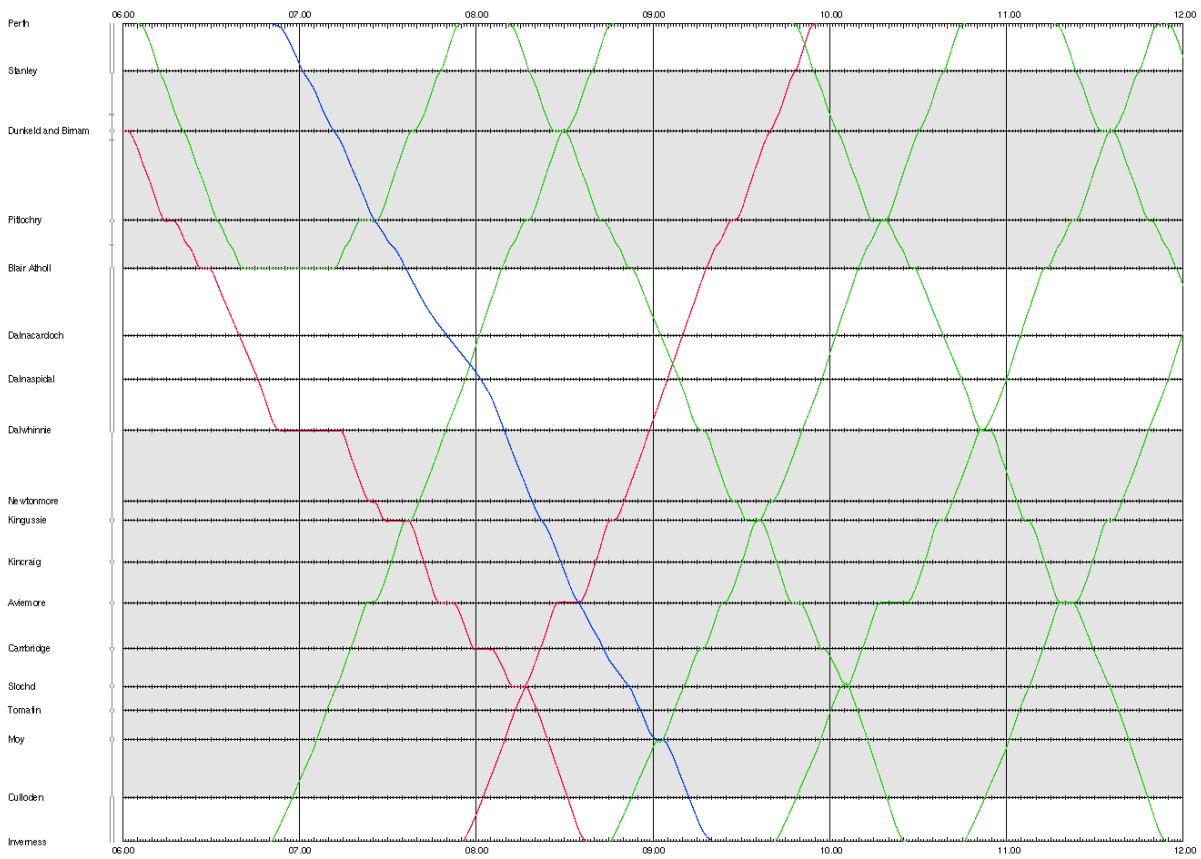


### C.3.Highland Main Line

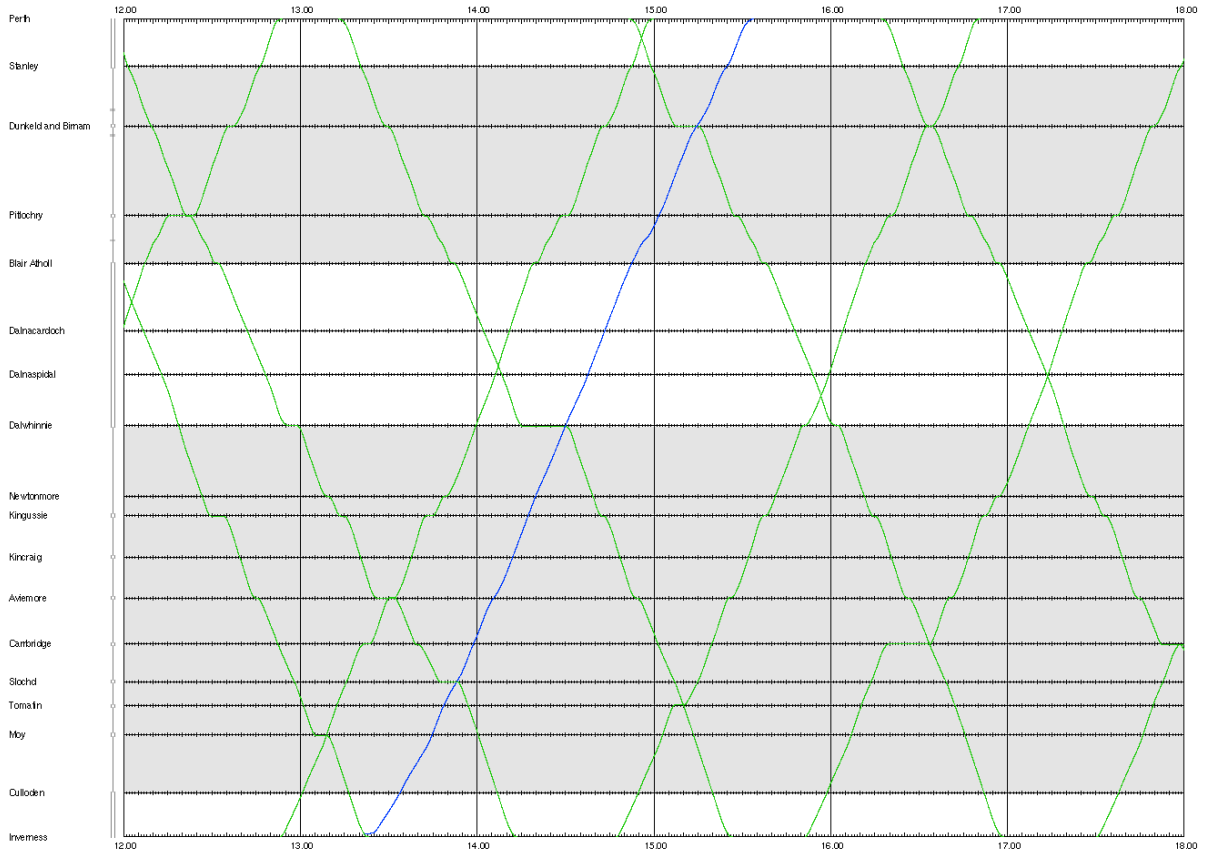
Perth - Inverness



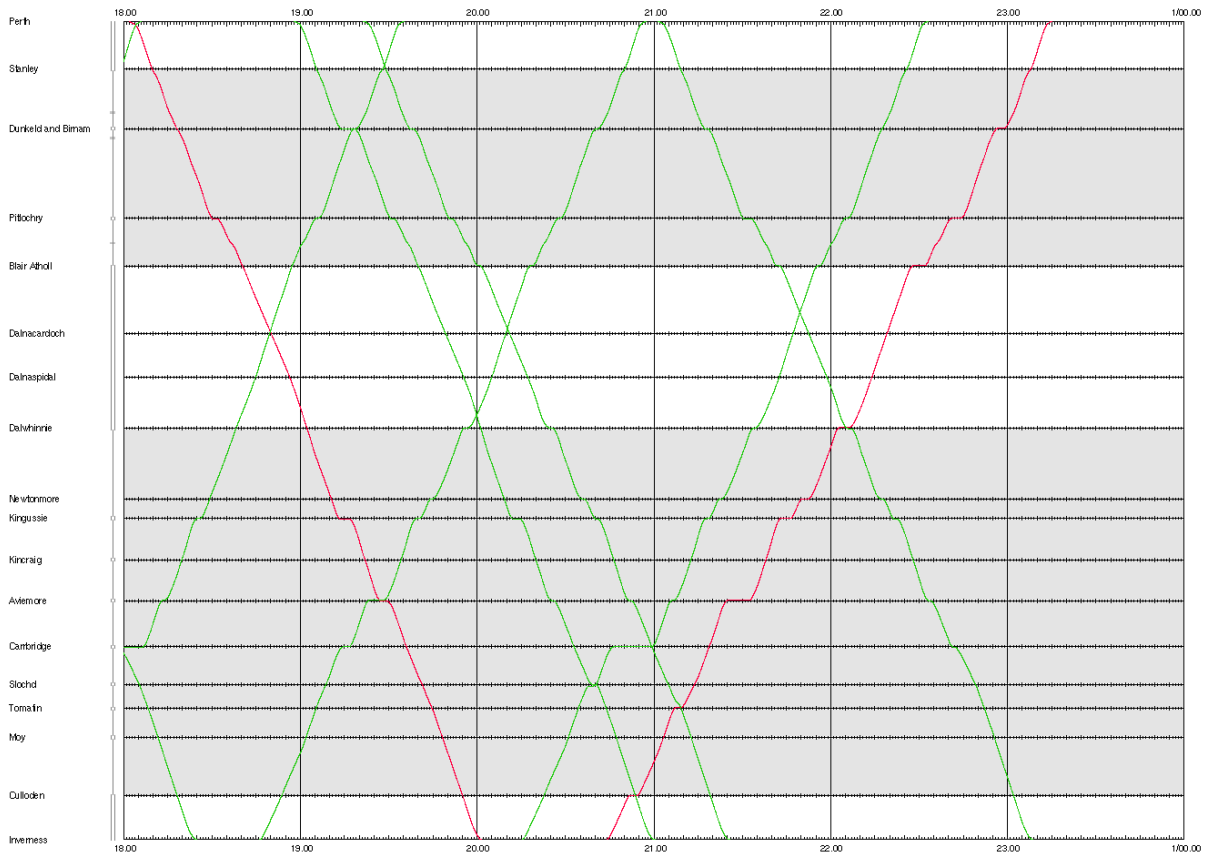
Perth - Inverness



Perth - Inverness



Perth - Inverness



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