MSc in Railway Systems Engineering and Integration

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Dissertation - Network Energy Strategy: Rolling Stock Gap Analysis

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Executive Summary

The electrification of railways is a preferred state of technology due to performance, whole life cost, and the environmental sustainability of power at the point of use. However despite current programmes to increase the electrified extent on the GB network, there will remain a need for roughly 3,000 self-powered passenger vehicles to retain the current level of services. This report reviews both the network and fleet situation and explores the potential for different vehicle power options in the future, given the increasing unacceptability of diesel use in urban and city areas.

Having undertaken a qualitative review by passenger franchise area, it was found that there are nine areas which are at risk of having either a moderate, considerable or substantial gap in the provision of electrification. One franchise area – Midland Main Line and East Midlands Regional – was considered as having a substantial gap, and this area was chosen for detailed analysis.

On the assumption that diesel-only traction will not be acceptable for most services by 2040 – 2050, the following options were considered as alternatives to bridge the electrification and rolling stock gaps:

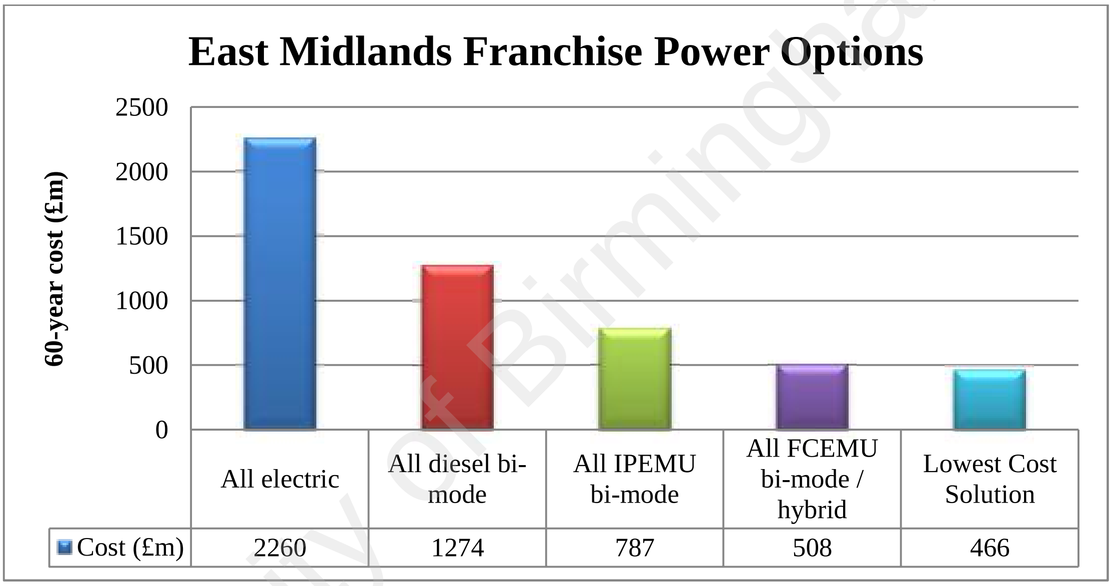
- Full electrification – as per existing schemes and architectures;
- Diesel bi-mode – trains powered by a diesel engine on non-electrified lines, and a pantograph wherever overhead wires are available, as per the soon-to-be-introduced Class 801 IEP units;
- The Independent Powered Electric Multiple Unit (IPEMU) – a bi-mode configuration that uses battery clusters to provide traction power over a limited distance (typically several 10s of miles) when on non-electrified track that then recharge when the unit is back under the overhead wire;
- The Fuel Cell Electric Multiple Unit (FCEMU) – a bi-mode, hybrid configuration that uses fuel cells boosted by batteries to provide traction power on extended or exclusively non-electrified lines, but which can also draw power from the overhead wires on electrified sections of line. The fuel is hydrogen (with clean emissions), and the projected range of the trains without refuelling is several hundreds of miles.

The routes that make up the East Midlands franchise area were reviewed in relation to the extent of electrification following the projected main line programme due to be complete sometime around 2023. Each service route was assessed for the length and proportion of electrified and self-powered operation. The fleet size for each route was calculated and the CAPEX and OPEX costs were estimated for each to create a fully electrified baseline case, a diesel bi-mode case, an IPEMU case and a FCEMU case. The costs were projected and discounted over a 60 year period to inform comparisons between the options, effectively producing benefit to cost ratios (BCRs) to inform the strength of each option.

The output of the business case analysis can be summarised as follows:

- Electrification of the gaps is difficult to justify due to the CAPEX costs;
- The cost of the diesel bi-mode option is lower than, but close to, that for electrification in many cases;
- IPEMU is only preferred where the majority of the route is electrified;
- FCEMU is the best option when there is a smaller proportion of the route electrified.

The optimum infrastructure and rolling stock solution for the East Midlands franchise therefore is a mixture of wholly-electrified units, IPEMU units and FCEMU units. However, financial and operational efficiencies may lead to a more homogenous fleet, in which case FCEMU would be the preferred option for self-power, as shown below:



The comparison model appears robust to sensitivity changes. However, simplifications in the assumptions and base costs have been identified and present an opportunity to enhance the analysis prior to using this methodology on other franchise areas.

The key message however is that diesel bi-mode is likely not to be the optimum solution in the future of the railway from a business case perspective and independently of the issues regarding pollution and environmental sustainability. The difference between full electrification and the FCEMU / IPEMU options is significant, but does not take into account demand change associated with the so-called 'sparks effect'.

The key finding of the work contained herein is that the analysis suggests that there are substantial whole life cost savings to be made by considering alternative power, including bi-mode battery and fuel cell options.

The key recommendation is that this initial study be developed into a full business case for consideration by the Department for Transport and other industry stakeholders for inclusion into policy and franchise scopes:

- The business case analysis should be refined in the following ways:
    - Use of ‘bottom-up’ electrification capital costs
    - Use of modelling to better inform energy consumption
    - Take account of auxiliary power and the increasing demands through the diversity of trains systems requiring electrical power
    - Better estimations of future train mass based on trends in recent and existing fleet designs
    - Comparison of track access charging models
    - More accurate battery sizing estimates
    - The operational concept should be modelled using operating timetables
    - The strategic and economic business cases in favour of electrification should be better studied, particularly in respect of demand increases
    - The carbon efficiency of all options should be considered
- Any forthcoming trials using either IPEMU or FCEMU architectures should be closely monitored to determine improvements to the business case assumptions and the corresponding base values;
- Discussions should be held with the likes of DfT, NR, RSSB, ROSCOs, TOCs and train suppliers to test the understanding and the assumptions made in the analysis;
- Once refined, the analysis should be expanded and replicated over the other franchise areas;
- Consideration should be given as to how the analysis could be used to assess the future of other GB rail users such as freight operators, open access operators and any other operators previously not considered.

It is suggested that the outcome of the wider analysis could then be used to inform future power strategy for all stakeholders in the GB railway industry.

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Glossary of Terms / List of Abbreviations

Term	**Explanation / Meaning / Definition**
AC	Alternating Current
ATOC	Association of Train Operating Companies
BAA	British Airports Authority
BCR	Benefit / Cost Ratio
BR	British Railways
CAPEX	CAPital EXpenditure
DC	Direct Current
DfT	Department for Transport
DLR	Docklands Light Railway
DMU	Diesel Multiple Unit
DECC	Department of Energy and Climate Change
DEFRA	Department for Environment, Food and Rural Affairs
DEMU	Diesel Electric Multiple Unit
DMU	Diesel Multiple Unit
DTI	Department for Trade and Industry
EC4T	Electric Current for Traction
ECML	East Coast Main Line
ECS	Empty Coaching Stock
EGIP	Edinburgh – Glasgow Improvement Plan
EMU	Electric Multiple Unit
ETCS	European Train Control System

Term	Explanation / Meaning / Definition
EU	European Union
FCEMU	Fuel Cell Electric Multiple Unit
FOC	Freight Operating Company
GB	Great Britain (England, Scotland and Wales)
GHG	Greenhouse Gas
GNER	Great North Eastern Railways
GWEP	Great Western Electrification Programme
GWML	Great Western Main Line
HLOS	High Level Output Strategy
HOPS	High Output Plant System
HS1	High Speed 1 – dedicated high speed route between Folkestone and St Pancras
HS2	High Speed 2 – planned high speed route from London to the North
HSE	Health and Safety Executive
HST	High Speed Train
HVAC	Heating, Ventilation and Air Conditioning
Hybrid	Power architecture using stored energy added to the prime energy source
IC125	BR diesel-electric High Speed Train capable of 125m/h
IC225	BR electric High Speed Train capable of 225km/h
IEP	Inter-city Express Project – replacement programme for the HST
ITEA	Integrated Transport Economic Appraisal division of the DfT
IPEMU	Independently-Powered Electric Multiple Unit
LSWR	London and South Western Railway
MML	Midland Main Line
MOSL	Motor Open Standard Lavatory (railway vehicle designation)
NFRIP	National Fleet Reliability Improvement Programme
NIC	National Infrastructure Commission
NMT	Network Measurement Train
NPV	Net Present Value
NR	Network Rail
OLE	Overhead Line Equipment
OPEX	OPerational EXpenditure
ORR	Office of Rail Regulation
PDFH	Passenger Demand Forecasting Handbook
PSR	Permanent Speed Restriction
RA	Route Availability

Term	**Explanation / Meaning / Definition**
RDG	Rail Delivery Group
RGS	Railway Group Standards
RIA	Railway Industry Association
ROSCO	Rolling Stock Company
RS	Rolling Stock
RSSB	Railway Safety and Standards Board
RTFO	Renewable Transport Fuel Obligation
RTS	Rail Technical Strategy
RUS	Route Utilisation Strategy
S&C	Switches and Crossings
SNCF	Société Nationale des Chemins de fer Français (French National Railways)
SRA	Strategic Rail Authority
SSL	Sub-Surface Lines of London Underground – namely the Metropolitan, District, and Hammersmith and City Lines
TEN	Trans-European Network
TfL	Transport for London
TOC	Train Operating Company
TPE	Trans-Pennine Express
TPH	Trains Per Hour
TPWS	Train Protection and Warning System
TS	Transport Scotland
TSAG	Technical Strategy Advisory Group
TSLG	Technical Strategy Leadership Group
TSR	Temporary Speed Restriction
UK	United Kingdom (Great Britain and Northern Ireland)
VOT	Value of Time
VUC	Variable Usage Charge
VTI	Vehicle Track Interface (or Interaction)
VTISM	Vehicle Track Interface Strategic Model
WCML	West Coast Main Line
WTT	Working Timetable
WWI	World War One – from the general perspective of conflict between July 1914 and November 1918
WWII	World War Two – from the general perspective of conflict between September 1939 and September 1945

1 Introduction

1.1 Scope

Roughly one third of passenger vehicles on the GB railway network are powered by or propelled by on-board diesel engines (Marsden C. , 2016). A significant portion of these vehicles are already operating following life extension work, and therefore are likely to be replaced by 2030 (Department for Transport, 2015). Environmental regulations, public health concerns and the sustainability of diesel fuel each contribute to a significant level of doubt over the future of diesel as a source of motive power for the railway industry (Institute for Public Policy Report, 2016). This in turn affects the choices of future replacement rolling stock procurement.

Electrification removes the need for on-board power generation, yet only one third of the UK network (by route mileage) is currently electrified (Network Rail, 2009). Further electrification schemes are in progress in the Northwest and on Great Western, with more planned. However construction is slow and expensive, and delays and budget increases all raise doubts about the future viability of such schemes and the business cases that justify the works in the first place (Sawer, 2016). Even if the network could be electrified beyond the existing plans, there is no guarantee that sufficient grid power would be available with increasing concerns over the UK power generation capacity (Stacey, 2016).

In answer to some of the above problems, several initiatives have been and are being conducted exploring alternative self-power options using technology such as fuel cells and batteries. In addition new trains such as the IEP offer bi-mode operation – operating a mixture of electrified traction and diesel self-power where electrification is absent. However, there does not appear to be a cohesive strategy to manage the development of these technologies and their implementation into the mix of the long-term traction power solution.

The aim of the work in the dissertation is to understand the potential gaps in future rolling stock requirements, the extent of future electrification and the needs for self-power rolling stock into the next 50 years. This time period has been selected so as to embrace the anticipated life-expiry of diesel powered rolling stock procured and commissioned over the next 10 years. Within the limitations of the scope for this study, a single GB franchise area will be analysed in terms of the power and rolling stock gap.

1.2 Methodology

The methodology employed in this research is set out as follows

- **Scene-setting**: a brief history of electrification in Great Britain up to the present situation and a definition of the extent of current and planned electrification; a summary of the existing and planned diesel-powered fleet along with an overview of self-powered railway vehicle technologies, taking in the latest developments of self-powered traction and energy storage;

- **Literature review**: compilation of the available sources of data to create a narrative explaining the shift in attitudes towards electrification and energy strategies since the early 2000s to the present day, rolling stock trends and aspirations and areas of concern and legislation which might affect the future use of diesel engines.
- **Stage 1 – Electrification extent**:
    - Listing of the existing extent of GB electrification schemes
    - Listing of committed GB electrification schemes, cognisant of the recent review of Network Rail commitments and budget
    - Review of the GB network based on current franchise zones and operations, listing both electrified and self-powered services, and the rolling stock provision to meet these services
    - Discussion of the effect of the committed and aspirational electrifications schemes within the franchise area
    - A qualitative gap analysis of rolling stock requirements based on assumed end-of-life for different rolling stock types and ages
    - A summary of the overall power and rolling stock gaps identified by franchise area
- **Stage 2 – Detailed Franchise Area Route Review**
    - A suitable franchise area with a significant power and/or rolling stock gap will be selected for detailed analysis
    - The routes within the area will be assessed for existing electrification overage, rolling stock requirements to meet the current timetable and the actual rolling stock provision
    - The above exercise will then be repeated to determine the state of electrification by 2040 – 2050 and the basic rolling stock requirements will be determined
- **Stage 3 – Rolling Stock Options**
    - Current forms of traction will be reviewed, particularly with a view on the current technology levels and those which may be applicable to more sustainable technologies in the future
    - Options for projected acceptability will be identified and for each option the basic assumptions which drive costs will be identified. These will include aspects such as mass, power requirements, and equipment CAPEX
    - General cost values pertaining to the different options will then be sources, such as track access charges, energy consumption and fuel charges and infrastructure costs. Business case rules will be established

- **Stage 4 – Business Case Analysis**
  - From the Stage 3 outputs, the options for each route will be assessed for cost over the selected life for the business case. Each option will then be considered against another until a matrix of effective cost / benefit ratios (BCRs)
  - The results will be summarised and reviewed to determine what the optimum investment and fleet mix is for the selected area
  - The business case methodology and inputs will be assessed for robustness and accuracy, with recommendations for improvements if necessary.

  The intent is that further works to review the railway energy strategy will be better informed with specific recommendations for how future research may be conducted.

- The above will form the basis of the overall conclusions and recommendations.

A flow diagram of the process is shown in Figure 1.

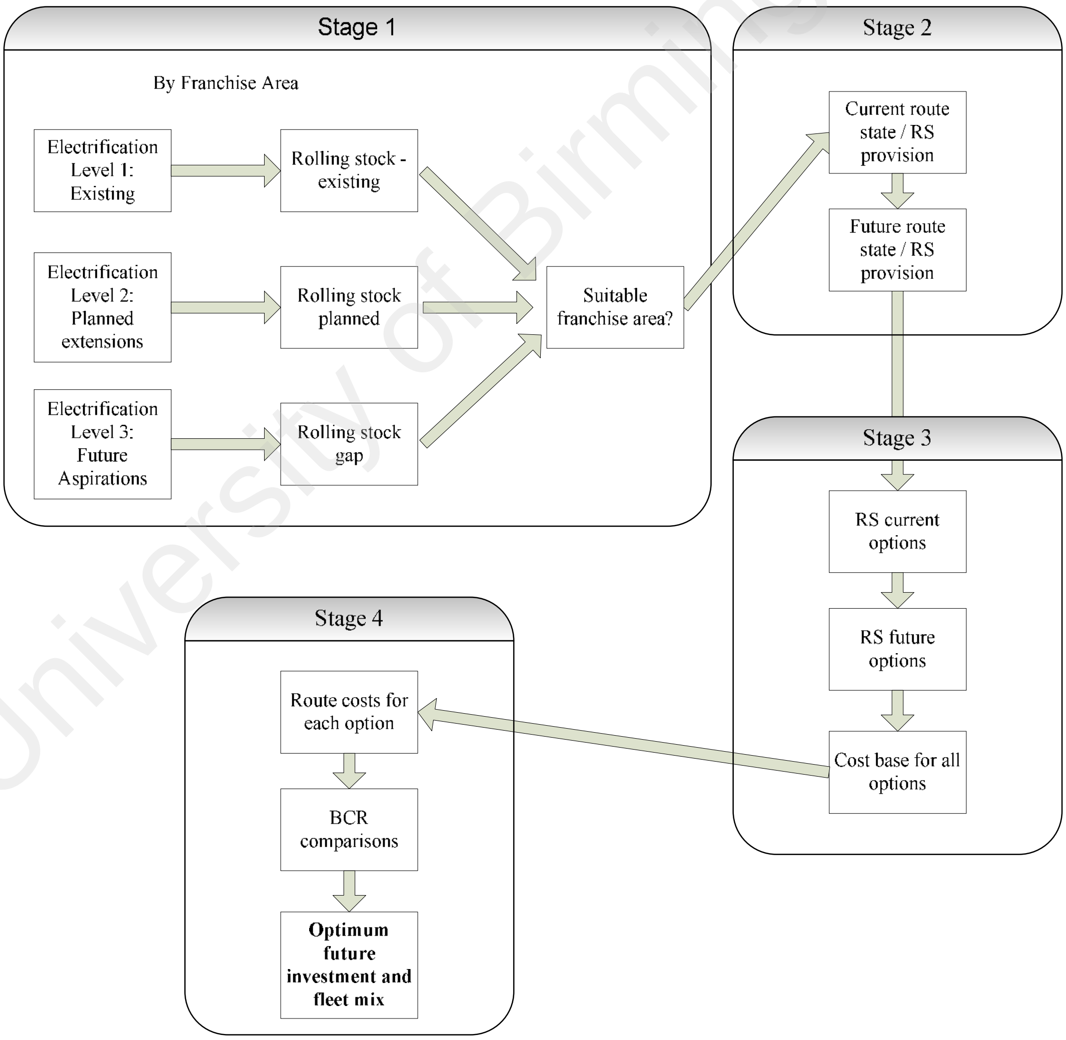


Figure 1 – Methodology Flow Diagram

1.3 Assignment Structure

The assignment adopts the following structure to report on the task activities and findings:

- The introduction, scope and methodology are contained in Section 1;
- Section 2 contains the background to the GB electrification extent and plans, and a summary of the national passenger fleet;
- The literature review is contained in Section 3.
- Stage 1 of the study - a quantitative view of the GB electrification extent, the planned and aspired works, and the rolling stock profile which fits each epoch – is contained in Section 4;
- A detailed study of the selected franchise area (Stage 2) is contained in Section 5;
- Section 6 contains Stage 3 of the study – a study of rolling stock options and proposals for the options to be considered in the business case;
- Stage 4 of the study – the business case analysis – is contained in Section 7.

The conclusions and recommendations are made in Section 8.

1.4 Exclusions

The following exclusions should be noted:

- The business cases put forward for electrification and electric traction are not considered in depth. It is assumed that electrification is the 'higher' state of technical evolution due to being more apt to sustainable energy capabilities, public health, operational performance and efficiency, and curious benefits such as the 'sparks effect' – by which passenger numbers rise when a line is electrified beyond that which would be consistent with the performance enhancements alone (Moss J. , 1978);
- In connection with the above, the validity of previous business cases or the verification of their individual assumptions is not considered herein;
- Only mainline passenger operations and rolling stock will be assessed in detail. Freight requirements will be acknowledged and commented on in the overall analysis;
- The following rolling stock types are excluded from this study:
    - Rolling stock used solely for charter rail operations;
    - Heritage lines and rolling stock;
    - Departmental rolling stock and track plant;
    - Depot and private user rolling stock
- Eurostar is a self-contained operation, more aligned with continental technical attributes and requirements and currently not connected to the existing network. However, SouthEastern operations over HS1 onto the classic rail network are considered;

- Whilst part of the franchise currently operated as South West Trains, the Island Line on the Isle of Wight is a small self-contained system with low ridership (less than 500k passengers per year). This line is not considered in the study;
- Light rail, metro and tram systems are not considered, except where there is current or planned interaction, e.g. London Underground sharing Network Rail lines, the Sheffield Tram-Train project, etc.;
- Private narrow-gauge railways (including those on the Isle of Man) are not considered in the study;
- Shunting vehicles and rescue locomotives are not considered in the study;
- It is assumed that the demand for rail continues without cessation due to economic downturn, war, or technological or social changes.

It is considered that each of these aspects warrants further study in connection with the issues addressed herein, but that there is not the opportunity to do so within the scope of the work or the time in which the work is to be carried out.

Note: all figures, images and tables are the work of the author unless stated.

2 Background

2.1 A Brief History of Electric Traction in the UK

The first major railway to employ electric traction was the City and South London Railway – best known today as London Underground's Northern Line. In some ways this was a happy accident as the railway had originally been intended to be cable-hauled until the cable contractor ceased trading (Moss P. , 2014).

With London's underground railways having realised the benefits of electrification as early as the 1890s, some of the surface railways began to experiment with different forms of electrification, the London and South Western Railway's suburban network design being preferred by the Southern Railway in the 1920s. This choice has resulted in almost all of the railways south of the Thames being electrified with 3rd infrastructure (Haresnape & Swain, 3rd Rail DC Electric Multiple Units, 1989).

Other schemes installed on either side of WWII were as diverse as side-contact 3rd rail at 1,200V DC and overhead wiring at 1,500V DC. These were generally isolated installations and with the exception of the 3rd rail network around Liverpool, all were to be removed or superseded by the early 1980s (Simmons & Biddle, 1997).

2.2 Electrification 1956 – 1994

By the time of the Modernisation Plan in 1955, it was clear that electrification offered substantial benefits over self-powered traction and several major schemes were projected for immediate implementation. Following successful testing by SNCF in the early 1950s, BR selected overhead current collection at 25kv AC as a standard electrification specification (British Transport Commission, 1955) (Haresnape, 1983).

There followed a series of works which resulted in the full coverage of the WCML by 1974, the Midland as far as Bedford by 1981, the Great Eastern routes to Norwich by 1985, the ECML to Edinburgh by 1991 and the West Anglian routes to Kings Lynn by 1992.

Just prior to the privatisation of BR in 1994, work began on the short stretch of line between Paddington and Heathrow as part of the Heathrow Express project, which was taken over and completed in 1998 by BAA.

2.3 Electrification 1995 – 2009

Following railway privatisation, there was an investment hiatus for several years. When spending recommenced, most of it went into new rolling stock – largely to satisfy HSE requirements following the Clapham and Cannon Street accidents of 1988 and 1991 respectively (Office of Rail Regulation, 1999) – safety systems such as TPWS, following the

Southall and Ladbroke Grove accidents, and wholescale track renewals in the aftermath of the Potter's Bar crash of 2000 (Hall, 2003).

The other significant project of this period was the upgrade of the WCML which absorbed much financial and human resource. As such the only new electrification to take place on what became Network Rail infrastructure was the 13km between Crewe and Kidsgrove, and the start of work on the Airdrie to Bathgate scheme. During this period, many commentators lamented the lack of consideration or ambition for new electrification schemes (Crowhurst, 2012) (Ford, 2007).

However, the July 2007 HLOS papers (Department for Transport, 2007) hinted that electrification might return to the agenda for railway improvements, whilst at the same time cautioning that "it would not be prudent to commit now 'all-or-nothing' projects, such as network-wide electrification or a high-speed line, for which the longer-term benefits are currently uncertain and which do not reflect today's priorities."

2.4 2009 – Present: A New Era of Electrification?

Under Andrew Adonis' leadership as first Minister of State and then Secretary of State for Transport the business case for both electrification and high-speed rail was finally made, and in July 2009 the Great Western Electrification Programme (GWEP) was announced (Department for Transport, 2009) proposing a scheme to electrify from Airport Junction to Reading, Bristol and Cardiff, and incorporating some of the Thames Valley lines.

The announcement also stated that further electrification of the Midland Mainline and the "Northwest Triangle" – the busy regional lines connecting Manchester and Liverpool with Preston and Blackpool.

Following the comprehensive spending review at the outset of the Coalition government in 2010, these schemes were not only safeguarded but complemented in a CP5 plan that included the following (Department for Transport, 2012):

- Extension of GWEP from Cardiff to Swansea
- Electrification of the 'Valley Lines' for local services around Cardiff
- Renewal and electrification of the East-West rail link between Bletchley and Oxford
- Electrification of the Trans-Pennine core route between Manchester and York
- Fill-in sections to provide an 'Electric Spine' which would facilitate electric passenger and freight trains to be operate from Scotland and the North of England to the South Coast ports of Southampton and Portsmouth

Of particular interest, the last item would include a re-electrification of the LSWR route south of Basingstoke which is currently equipped with 3rd rail. Due to previously published concerns over the limitations of 3rd rail, the intention is to replace this with OLE (Stanton, 2013).

2.5 June 2015 – Scaled Back Ambitions

Issues over the ability of Network Rail to deliver the North West Triangle on time were raised mid-way through the first phase (Rail Business Intelligence, 2013) and by late on in 2014 concerns were raised about both the budget and the timescales of GWEP (Rail Technology Magazine, 2014) (BBC, 2015).

In June 2015 the Secretary of State for Transport, announced the 'pausing' of the Midland Mainline and Trans-Pennine electrification with no mention of the fate of the lesser schemes (McLoughlin, 2015). Network Rail's own statement on the matter cited the ambitions of the parallel schemes from the outset and the inability of Network Rail or the supply chain to match the resource level required to deliver the projects (Network Rail, 2015). As well as project running late, it was made clear in the statement that the funds available in CP5 were not sufficient to complete all of the projects.

With rolling stock plans geared around electrification projects which were previously considered to be 'committed', the European legislation tightening the restrictions around diesel power units, and local authorities eager to see new schemes beyond those originally proposed (Railway Gazette, 2015), the pausing of key schemes leaves a great deal of uncertainty hanging over both the network strategy for electrification and for the rolling stock which will operate over the network in the future.

2.6 September 2015 – Situation Update

One of the incoming NR chairman, Peter Hendy's first tasks is to complete the CP5 review following the June 2015 parliamentary announcement. Reports surrounding the terms of reference for this review (Department for Transport, 2015) speculated – with some apparently informed briefing – that MML and trans-Pennine route electrification work is not affordable within CP5, and that some of the GWEP items would be deferred or delayed (Railway Gazette, 2015). The implications of this may be significant for each of these routes, with rolling stock approaching life-expiry on the MML and capacity limitations becoming ever more apparent on Liverpool – Newcastle services (Cox, 2013).

The outcome of the review surprised some railway commentators but announcing the immediate restart of electrification of both Trans-Pennine and MML projects (Hendy, 2015). However whilst the work would restart within CP5, the timescales would be extended with completion of the MML to Corby completed by 2019 and the remaining work to Nottingham, Derby and Sheffield reached by 2023, four years after the original date. Likewise the Trans-Pennine scheme is now envisaged to be completed by 2022. Further industry reporting suggests that the driving influence of this announcement is political rather than through the review of the business case and operating issues (Railway Gazette, 2015). The background details of the review should be assessed to inform this study when available.

2.7 GB Passenger Fleet Summary

To provide an initial view of the state of the GB passenger fleet, the power source and the train types currently used in operation have been used to generate train and vehicle population numbers. The compilation of data by fleet is contained in Appendix A, with a summary of the data shown in Table 1. The categories of train type are not fully comprehensive but should be sufficient to provide a level of basic analysis at this stage:

- Suburban – trains generally limited to 120 km/h maximum speed, high-density seating, range of less than 80 km;
- Mid-distance – trains capable of up to 160 km/h maximum speed with lower density seating, toilets and up to 200 km range;
- Intercity – trains capable of operating over 175 km/h maximum speed, catering facilities and range of up to 1000 km.

There are some fleets which contain sub-fleets of both high and medium density seating for different applications. However for the sake of simplicity these distinctions have been ignored at this stage. As part of the analysis in section 4 these distinctions will be identified and addressed accordingly.

Table 1 – GB Fleet numbers: train and vehicle by traction and train type

Traction	Train type	Trains	Vehicles
Electric	Suburban	687	2473
	Mid-distance	1334	5325
	Intercity	131	1180
Diesel	Suburban	391	838
	Mid-distance	641	1484
	Intercity	221	1334

The proportion of electric to diesel traction is shown in relation to train in Figure 2 and the same value in relation to vehicles is shown in Figure 3. A further breakdown of the proportions of train types are shown in Figure 4 and Figure 5.

These numbers demonstrate that electric traction makes up approximately 2/3 of the current GB fleet, mainly as a result of the density of lines and services around London, Liverpool and Glasgow. Of the three train type categories, diesel only has the majority in the intercity type, due to the extremities of many trunk routes not yet electrified. The data supporting these values is contained in Appendix A.

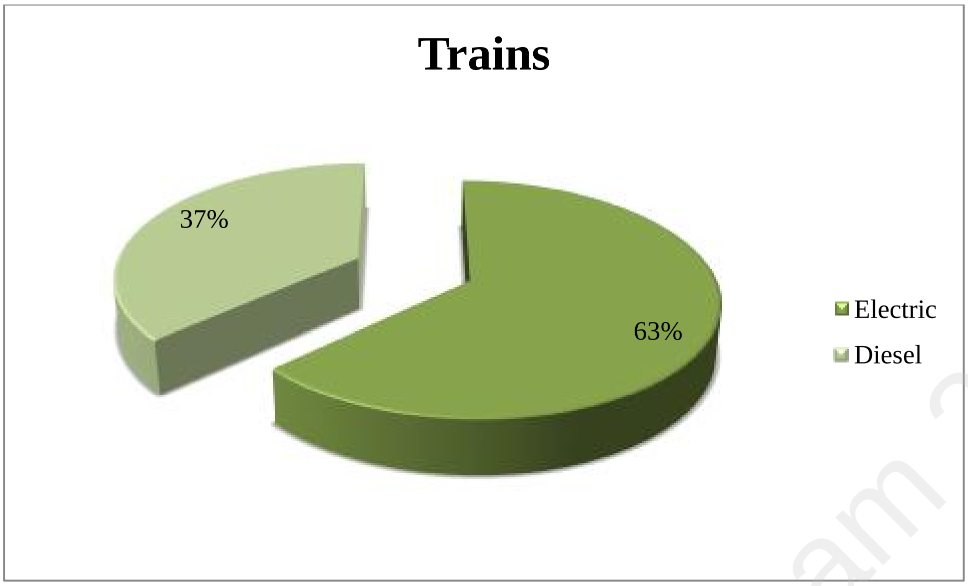


Figure 2 – Proportion of power sources for the GB fleet (trains)

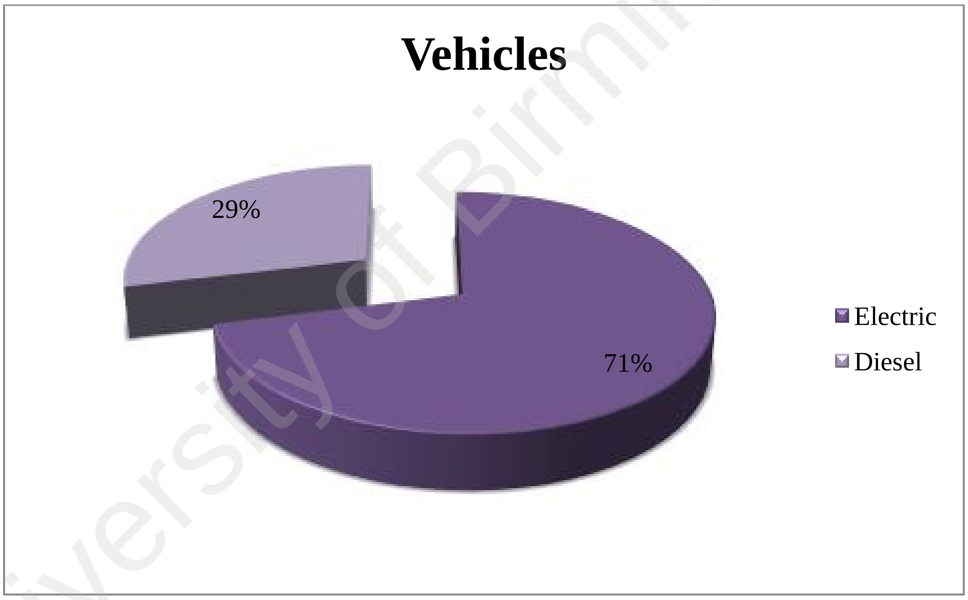


Figure 3 – Proportion of power sources for the GB fleet (vehicles)

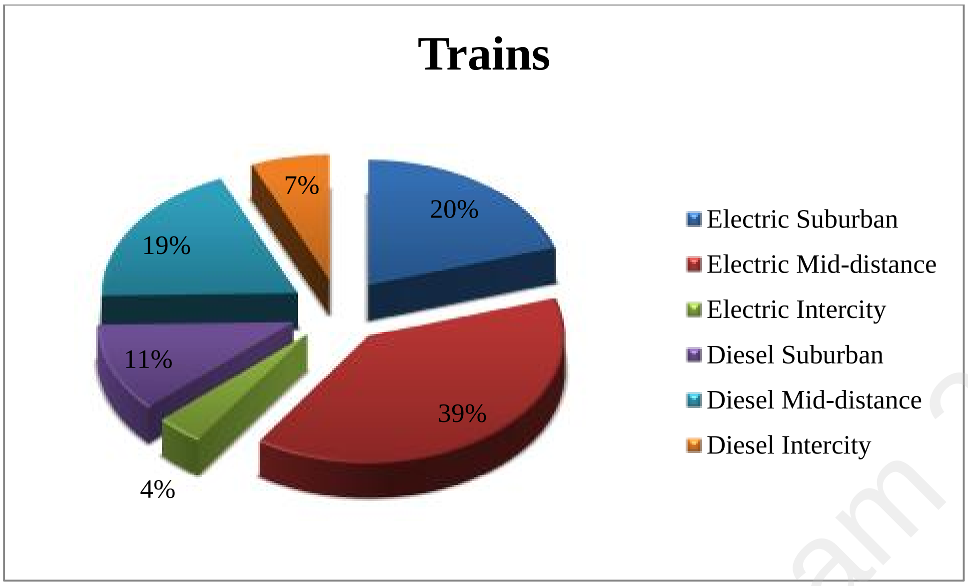


Figure 4 – Proportion of power sources for the GB fleet by train type (trains)

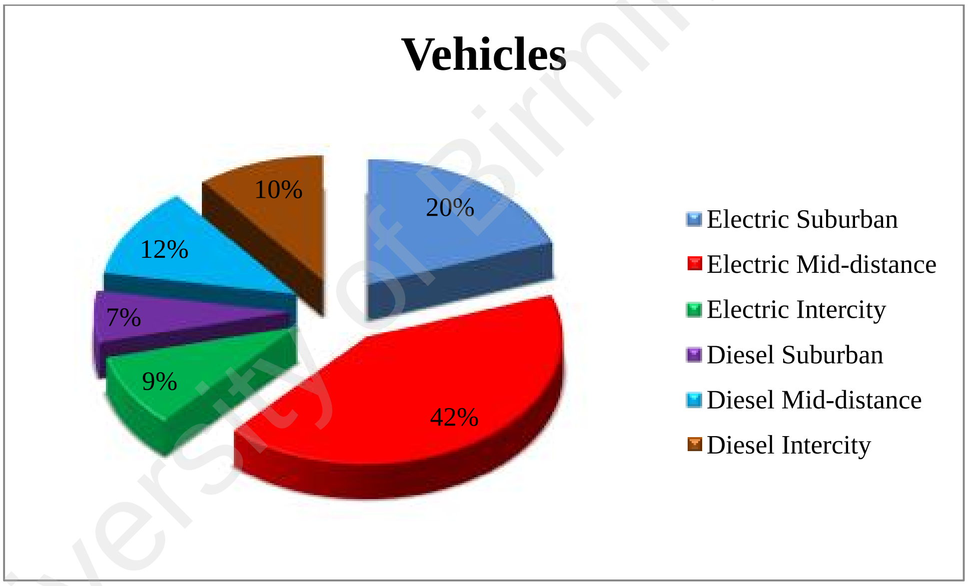


Figure 5 – Proportion of power sources for the GB fleet by train type (vehicles)

2.8 Electrified Power Collection Technology Overview

This brief study is to provide a picture of the dominant electrification technologies and in turn provide an understanding of the likely options for future electrification of both new and extension or infill schemes.

2.8.1 25 kV AC 50 Hz Overhead Line Equipment (OLE)

Since the 1950s the preference for main line electrification has been 25 kV AC supplied at 50 Hz from overhead line equipment (OLE). This technology was employed as a fundamental part of the Modernisation Plan of 1955 with routes around London and Glasgow being electrified at the time, with the WCML electrified soon thereafter (Simmons & Biddle, 1997). Other forms of main line OLE supply have subsequently been converted to 25 kV and all future schemes incorporate this technology.

The installation involves a large and complex amount of equipment, as shown by example in Figure 6. Irrespective of the visual aspect, minimum electrical clearances can result in costly infrastructure enabling works such as the raising of bridges or the lowering of tunnel floors prior to installation (Baxter, 2015).

Figure 6 – Leeds station approach, OLE gantries and wiring in evidence (Chris McKenna)

Nevertheless, overhead line electrification is the converged and predominant solution both in the UK and Europe in electrified areas (Ian Allan, 2015).

2.8.2 650 – 750 V DC 3rd Rail

First used by the London and South Western Railway in WWI, this form of electrification was promulgated throughout the majority of the Southern region – services south of the Thames – as well as those on MerseyRail (Simmons & Biddle, 1997). Proposals in the 1990s and the 2000s for electrification extensions, such as Basingstoke – Exeter and Biston – Wrexham, are understood to have been refused on safety grounds and the ORR presumes that new 3rd rail electrification schemes cannot be practicably justified in relation to safety (Office of Rail Regulation, 2012). More recently the technical limitations of 3rd rail have been highlighted, with suggestion that some core routes may be converted to 25 kV OLE (Rail, 2011). It is therefore assumed that there would be no extensions granted to the existing 3rd rail system, and further electrification would be in the form of new 25 kV OLE.

2.8.3 GB Alternatives

There are a number of alternative power collection designs which are used in Great Britain, such as the following:

- 1500 V DC OLE (used on Tyne and Wear Metro)
- 750 V DC OLE (used on modern tramway applications)
- 600 – 750 V DC, 3rd and 4th rail (used by LUL)

[It should be noted that the latter infrastructure is shared with Network Rail's 3rd rail supply in a limited number of areas such as the suburban lines out of Euston and the Chiltern Line to Aylesbury between Harrow-on-the-Hill and Amersham. For the sake of this research, the distinction between the two is ignored. Where 3rd rail operations already exist on these areas it is considered as 3rd rail only, whereas in the case of self-power operation over 4th rail tracks the line is considered as if it is completely non-electrified.]

Power limitations and the lack of existing heavy-rail infrastructure preclude any of these options from being used for electrification extension or new schemes.

2.8.4 Conclusions

It is concluded from the above that only 25 kV OLE will be considered for new and extension / infill electrification schemes. It is further concluded that some existing 3rd rail areas may be supplemented or supplanted by OLE depending upon operational requirements.

3 Literature Review

3.1 Background to Recent Electrification Strategy

3.1.1 Department for Transport White Paper, The Future of Rail, 2004

In the aftermath of Railtrack's demise and towards the end of large projects such as the WCML upgrade, TPWS implementation and the replacement of slam-door rolling stock, the government's white paper (Department for Transport, 2004) set out a new structure for the industry with the abolition of the SRA and control of Network Rail coming directly under the DfT. Whilst the operational management therefore became more centralised, decision making was partially devolved to local TPEs and other regional bodies.

Moreover, the paper demonstrates a clear governmental recognition of the wider benefits of rail, such as being an enabler to economic growth, helping to meet CO_2 reduction targets, and providing high density transit into highly populated areas and over long distances. The call for clearer understandings of costs and benefits to be established, along with the allowance of wider benefits to be incorporated can be seen to have paved the way for business cases to have been considered in terms of capacity benefits as well as metrics such as demand and generalised cost.

At this juncture electrification was not being considered directly. However the paper acknowledges railway's environmental credentials, citing carbon emissions per passenger as being 2/3 of those of road vehicles. Further, the new structure of the industry is that in which the changing attitudes to electrification were allowed to form. The modern era of electrification – and the recognition of the value of railways generally beyond that of the fare revenues – can therefore be thought of as having its origins in this paper.

3.1.2 2006 – 2009: A Period of Intense Discussion and Change

The change in attitudes to electrification occurred over a relatively short period of time and through a succession of reviews and research initiatives. In 2006 there was no plan for a future electrification programme; by 2009 the first major electrification programme for two decades was announced with other schemes following soon thereafter. The following list attempts to summarise the key steps in the industry turnaround:

- Soon after the publication of the wide-ranging Stern report on climate change (Stern, 2006), former British Airways CEO Sir Rod Eddington conducted a report into the state of the UK transport infrastructure and the effects on the national economy (Eddington, 2006). The report recognised the need for efficient rail as part of the national infrastructure, and echoed the economic and social benefits previously highlighted in the 2004 DfT White Paper. There is no specific recommendation for electrification but Eddington recommends a pricing strategy that incentivises reduced emissions.

- Consistent with the tone of EU regulations governing the separation of accounts between railway infrastructure and operations (Hans Van Den Broek, 1991) the EU Commission White Paper, Roadmap to a Unified Transport Area, 2007, considers the state of the main transportation modes within the EU and concludes that the current situation is unsustainable in terms of capacity, interoperability and the reliance on carbon-based fuels (European Commission, 2011). Whilst not citing electrification specifically, it can be surmised that the imperative to eliminate barriers and to reduce carbon emissions requires electrification on the TEN routes at the least, where none or limited extents currently exist.
- The UK Government White Paper: Planning for a Sustainable Future, also in 2007, report represents the views and aspirations of four government departments – including the DfT – in relation to better planning and the need to build better homes and infrastructure in a sustainable manner (HM Government, 2007). The report states that a failure to implement such change will result in “energy shortages, mounting congestion and increased pollution”. The report calls for all development to be carried out integrated with sustainable public transport and as part of a conversion to a “lower carbon economy”.
- Following on from the White Paper described above, the White Paper on Delivering a Sustainable Railway asserts that government railway funding to that point has been largely to repair and consolidate following the “flawed privatisation process” but that the railway was in a stronger position and ready for investment to meet increasing passenger demand and environmental challenges (Department for Transport, 2007). A useful, if somewhat political, part of the narrative is that: “The story of the railway used to be about managing decline. Now it is about enabling growth.” However, whilst the report acknowledges that the railway can provide ‘green’ transport choices for both passenger and freight users, it is silent on the potential for further network electrification.
- The Rail Technical Strategy Paper (Department for Transport, 2007) is a cross-industry influenced White Paper set out to be the first over-arching strategy paper for the UK railway industry (Department for Transport, 2007). It identifies long term themes that the industry should work towards as:

    Optimised vehicle track interface (VTI) through developments such as lighter rolling stock
    High reliability and availability
    Optimised traction power and energy

Despite this last point, the emphasis of the paper is on energy-saving technology, regenerative braking and better use of existing electrification with "selective extension where justified by business need". Hydrogen and biofuels are cited as alternative portable energy sources to traditional fossil fuels and the report casts doubt over the potential for electrification business cases due to the increasing maturity of these newer technologies. The paper also states that whilst seeming attractive, a national electrification strategy would divert resources from other capacity improvement objectives. The report concludes by describing the architecture and mechanisms for effecting change and executing the programmes which will deliver the high-level objectives. Amongst these are the High Level Output Specifications (HLOS) and Route Utilisation Strategies (RUS).

- Immediately following the above, the RSSB-led Study on Further Electrification of Britain's Railway Network (Atkins, 2007) was the first significant study in more than a generation to explore the possibilities of further electrification in any great extent. Several scenarios were analysed, with the business cases for Midland mainline and Great Western mainline presenting the strongest business cases for electrification, and rebuts the idea of electrification dismantling as being an attractive proposition (The Scotsman, 2003).

  The report concluded that for an electrification business case to be successful the following conditions must be met:

  - The route must be heavily in demand and operating almost at capacity within the bounds of the existing infrastructure;
  - There must be a high density of service provision

  The report was highly influential and appears to have built upon the momentum for change within the industry and reaches out to the politicians and decision-makers in a way that effectively led subsequent policy.

- The Network Rail 2009 Electrification RUS represents Network Rail's fundamental review of the electrified network, identification of gaps and potential projects, and provided BCRs for each accordingly (Network Rail, 2009). Building on the Sustainable White Paper the Rail Technical Strategy, the Great Western Main Line (GWML) and MML were confirmed as providing the strongest business cases for electrification. The remainder of the electrification gaps and those with the strongest business cases are contained in Appendix B.

At the end of this period therefore, it is evident that the commitment to restart a national electrification programme was supported both by quantitative justification around issues such as sustainability and social benefits, and with economic model output demonstrating the value for money of new electrification projects.

3.1.3 2010 – Present: Electrification in Progress

With committed schemes underway, a series of studies to support and supplement the electrification programme were commissioned:

- To provide a better overview of the carbon footprint of the railway and to integrate this into the wider UK sustainability efforts, RSSB conducted research to determine the direction required to deliver "an environmentally, economically and socially sustainable railway" in line with the then government's 2050 carbon reduction targets (Rail Safety and Standards Board, 2010). The research acknowledges climate change and refers to the concept of 'carbon budgets' as determined in legislation (HM Government, 2008) and aiming for an 80% reduction in carbon emissions throughout the UK from 1990 levels to 2050. Whilst only representing 2% of the country's carbon footprint, it was recognised in the rail industry that a substantial effort would be needed to contribute to an acceptable and appropriate degree. Recognising that traction power provided the greatest source of carbon emission from the railway, the decarbonisation target was set at 7% by 2025 and 27% by 2050.
- With a brief that recognises the shortcomings in the 3rd rail system on UK routes South of the Thames, RSSB conducted a study in the light of the renewed attitudes towards electrification within the industry as a whole (Rail Safety and Standards Board, 2011). This report concludes in support of the eventual replacing of 3rd rail with 25kV OLE whilst recognising the considerable size of the existing electrification and rolling stock asset base built around 3rd rail systems.
- With responsibility of the RTS having moved to the Technical Strategy Leadership Group (TSLG), the 2012 paper (Technical Strategy Leadership Group, 2012) recognised that the approach of the industry had changed in the intervening five years. The paper sets out a 30-year vision to transform the railway, reducing the costs of system failure (estimated here at approximately £600m per year) and to improve in the four key areas represented by the 4C concept: increasing Capacity; reducing Carbon emissions; lowering Costs (operating costs as opposed to the system costs mentioned above) and improving Customer satisfaction.

  The paper suggests that the largest change since the 2007 publication was the publication of the Rail Value for Money report (McNulty, 2011) and the government's introduction of a rolling plan of improvements to deliver better value for money over the 30-year period. The paper endorses the government recognition of railways adding economic benefits to the country as a whole and also cites the EC single European transport area roadmap white paper (European Commission, 2011) which identifies the need to move passenger and freight road transport towards rail to reduce congestion in addition to economic and environmental reasons.

The vision statement calls for a continuously operating railway with optimised capacity, carbon emissions reduced through electrification and energy-capture systems on the remaining non-electrified routes. In particular there is a call for "Sustainable Development Principles [to be] embedded in the design, construction and operation of infrastructure and rolling stock assets. The specific objectives for energy reflect these aspirations with a strategy that includes more network electrification at 25kV, 'energy-intelligent' rolling stock and infrastructure specifications and traffic management systems." There is particular desire for electrification to be both low cost and robust.

The rolling stock focus is on the reduction in vehicle mass through the use of better materials and design techniques, more modular and interchangeable design of sub-systems (particularly for future upgrades) and better drivetrain technology. There is a call for more bi-mode investment, which is envisaged as electric / diesel at present but invites energy storage and alternative stored energy technologies as alternatives to carbon fuels in the near future.

On the back of the new attitudes to electrification, several more schemes have been explored and proposed:

- Written on behalf of the DfT, the GWEP review (Arup, 2013) was carried out in the context of the initial GWEP electrification extent to the south west of Reading being Newbury. The report investigated four options of increasing electrification extent beyond Newbury: i) to Bedwyn, ii) to Westbury; iii) to the freight quarry lines to the north west of Westbury, and iv) completing the circle to Chippenham and Bath Spa. The results of the analysis showed that only option i demonstrated a positive NPV and BCR of greater than 2. It should be noted that this conclusion was taken up by NR for GWEP, although it could be argued that this should have been part of the original extent given the marginal capital cost and the hourly train service between Paddington and Bedwyn (Network Rail, 2014).
- Building on the justifications for electrification made by RSSB / Atkins and NR, a group of local councils supported by West Yorkshire PTE commissioned a study into the feasibility of electrifying the route connecting Leeds and York via Harrogate (Holmes, 2013). On the assumption that TranPennine electrification was already in place, the report concluded with a positive business case and recommended that options should be explored to implement the scheme.

Notwithstanding the positivity of the studies and position papers above, the course of the electrification programme has not been simple. Elements of the North-West Triangle scheme encountered delays, and then the GWEP became subject to worse delays and ever-increasing costs. In September 2015, Rail Business Intelligence published a high-level analysis of the increasing costs of GWEP (Railway Gazette, 2015). The report quotes a Treasury 'optimism' factor which enhanced the £625m estimate to the £800m budget when the project was sanctioned in 2009. Costs had increased to £850m by 2011 and to 1.7bn by December 2014. By comparing costs with the ECML upgrade of the 1980s and 1990s, the analysis concludes that the GWEP cost per single line km is £1.7m as opposed to £447k for the ECML (adjusted to present prices). This includes for variables in the infrastructure enabling costs, additional safety costs for modern HSE requirements, and the fact that ECML project director identified that BR should probably have spent 20 – 30% more on the electrification scheme to make it more robust and reliable. The analysis also comments that the HOPS electrification machine was procured to enable adjacent line working and thereby reduce Schedule 4 compensation payments, although it does not state how effective the HOPS machine has been, nor how widely it is being used.

A subsequent edition of the journal in October (Railway Gazette, 2015) stated that the inflated infrastructure costs are caused in part by the TSI requirement of 1.8m OLE clearance to bridge parapets instead of the assumed 1.5m, and also due to the poor state of the existing substructures and earthworks. NR appears unable to exact the best efficiency from the HOPS machine due to having to close the adjacent running line and also because of shortcomings in the production design meaning a constant redeployment of the machine.

3.1.4 Summary

It is clear that the UK is more committed to progressive electrification than at any time since the 1960s, and that the existing projects will inevitably lead to further schemes being approved. The increase demand that these schemes have the potential to generate may also provide further motivation to increase the electrification extent along with the attractiveness of electrified rail from a sustainability perspective. However, governments have a habit of retreating from large capital expenditure if they have no confidence in the estimates being presented to them, and a fundamental review is needed of the cost basis on which the business cases have been built. It is evident that much useful information can be gleaned from the costs of the schemes currently under construction, and a study should be carried out in the near future. This should be carried out with a review of the benefits being promoted to understand if there is a better way of constructing the justifications for future electrification. These aspects are not considered in this study.

3.2 The UK 'Energy Gap'

As might be expected by the carbon-fuel dependency of the other modes of transport, Rail accounts for 96% of electrical energy consumption in the UK, with a total annual consumption of 4.13TWh (Department of Energy and Climate Change, 2015). This forms just over 1% of the total electrical consumption of the country. However this includes buildings power, transmission losses and other non-traction use. Recent data is difficult to come by but earlier studies would suggest a reasonably consistent fleet traction usage of around 3TWh with a specific consumption of 2kW/vehicle km (ATOC, Bombardier, National Express, 2006).

The introduction of more electric services on the newly electrified lines will increase the overall consumption, and the specific per km rate may also increase due to the increased mix of intercity type trains with their higher traction loads on the East Coast, Great Western and Midland lines.

At the same time as there will be an increase in electricity demand from the railways, question marks hang over the ability of the UK power generation industry to maintain the current levels of supply, let alone provide an increased capacity (The Guardian, 2016) (Lodge, 2008). Even at the time of writing the planned increase in the UK's nuclear generating capability to bridge the gap of decommissioned coal and obsolete nuclear reactors appears to be in doubt (BBC, 2016) (Stacey, 2016).

Both the building of energy-generating facilities and the electrification of railways are long-term programmes, and it is hoped that by the time new train services are commissioned sufficient supplies of energy will be available. For schemes considered by this study, the implications of those schemes in terms of electricity demand must be calculated, taking account of the following:

- New electrification power losses
- Traction power density
- Regenerative braking effects
- Energy saving techniques, such as smart driving, power-save modes, etc.
- Offline power requirements, such as may be needed to energise fuel-cell propellant supplies

The calculation of marginal supply requirements is not considered in this study, but should be carried out as a further exercise.

3.3 Diesel Emission Developments

In recent months, the increasing concerns over diesel emissions appears to have escalated with ever increasing coverage given to localised pollutant measurements (Cecil, 2016).

Whilst it is not currently conceivable that diesel and related fuels will be banned in the near future, it is likely that restrictions beyond those already legislated for will be introduced, particularly in built-up conurbations (Institute for Public Policy Report, 2016). This may therefore increase the impetus to electrify services in towns and cities where diesel is still the prime mover. It could also be argued that the railways could be perceived as a ‘soft target’ for legislation when compared with road and aviation as it is arguably easier to modify railway infrastructure and vehicles to eliminate diesel than the other transport modes mentioned. Railway electrification could then be used to offset any wider pollutant targets which may be imposed (Johns, 2016) (Alwakeel, 2016).

3.4 Rolling Stock Power Developments

This overview provides a high-level review of self-power sources for rolling stock, and draws on some of the author’s previous work (Pettit, 2014).

3.4.1 Coal / Nuclear / Steam

For comparison with other power generation technologies, safety and environmental concerns aside, coal and nuclear power are highly unlikely to be adopted due to the equipment needed to raise steam and thence convert the power once more to a usable form.

‘Modern’ steam motive power has recently been researched by the 5AT group (Newman, 2013). However, whilst the performance of the locomotive is superior to those being designed and built towards the end of the steam era in the 1950s, it is still not comparable with modern diesel or electric traction (Krug, 2016). Appealing more to nostalgia and targeting the charter train market, the group has not secured funding beyond the feasibility stage and this perhaps provides sufficient warning against pursuing steam as a viable alternative to existing traction.

3.4.2 Sustainable Power

Sustainable power sources that are land or shore based do not lend themselves to mobile applications. Wind power is not consistent enough and turbines are likely to cause significant gauging issues. Similarly, solar power is neither consistent enough nor has sufficient power density, although it might be considered as a supplementary source for hotel power when the train is stabled.

Recently efforts have been made to use cleaner or more sustainable fuels in conventional internal combustion engines. For instance a number of engines have been designed or modified for gas in North America, and particular attention has been placed on Liquid Natural Gas (LNG) as a means of reducing greenhouse gas emissions (Lo, 2013).

Virgin conducted tests with a 20% biodiesel blend (Greenenergy / Virgin, 2007) although debates continue as to the true sustainability of biofuel (Lin, 2010) and it should be noted the six-month trial was not extended.

3.4.3 Electrical Energy Storage Technology

Power sources such as diesels, gas turbines and the electric supply grid arguably all work best when they provide constantly loaded power. However, the stop-start nature of train operations means that demand is very 'peaky'.

Hybrid systems work by storing energy when the power demand is low and using the stored energy when demand is high. There is therefore a need for one or more power sources coupled with an energy storage system.

The traditional method of storing electrical energy is by using batteries, although more recent trends are towards fuel cells. Many car manufacturers have developed vehicles which can operate over a moderate range (~300km) using hydrogen for fuel, but these also use batteries to allow for regenerated energy to be stored (Fuel Cells 2000, 2012). However, the hydrogen re-fuelling and storage infrastructure is limited and some commentators consider that the automotive industry will follow the technological investment and innovation surrounding batteries (Paglee, 2014). Nevertheless, there is clear impetus within the industry to make fuel cells an option for cleaner railway energy, as evidenced by the level of papers presented at the 2016 International Hydrail Conference in Birmingham, by future thinking of eminent industry experts (Goulding & Morrell, 2015), statements of intent by train suppliers (Railway Gazette, 2014) and actual developments such as the use of fuel cells in railway applications (Railway Gazette, 2016).

FutureRailway and the DfT part-funded the highly publicised trial of an Independently-Powered Electric Multiple Unit (IPEMU) on a converted Class 379 unit using batteries for marginal self-powered movement on a largely electrified route. The use of lithium-ion magnesium batteries was preferred following trials of different types of batteries (Network Rail, 2014) as shown in Figure 7.

Figure 7 – Class 379 IPEMU trial unit (Network Rail)

3.4.4 Flywheels

Finally, it should be acknowledged that flywheel technology has been explored and implemented to a lesser extent in the UK, with Parry People Movers operating the half mile route between Stourbridge and Stourbridge Junction – as shown in Figure 8. Limitations such as the need for an onboard generator, difficulties on long gradients, etc. - have meant that these designs have not been promulgated and it is not yet considered as a viable alternative to electric traction.

Figure 8 – Parry People Mover operating on the Stourbridge Line (P L Chadwick)

Ricardo has done much to promote its flywheel technology in rail (Ricardo Rail, 2015) however this is aimed at fuel savings for DMUs rather than replacing the diesel as the prime mover.

3.4.5 Bi-Mode Rolling Stock

Other than the electro-diesels which operated on the Southern region from the late 1950s to the 1990s (Marsden C. J., 2011) there has been limited experience of bi-mode rolling stock on the GB network to date. However, the Hitachi AT300 platform from which the IEP is derived, is providing an opportunity for a diesel bi-mode intercity train to be employed for the first time and several operators have already placed orders (Marsden C. , 2016).

3.5 Rolling Stock Procurement Trends

At the privatisation of the GB railways in the mid-1990s, rolling stock ownership and provision was via the three Rolling Stock Companies (ROSCOs) who were sold off from British Rail with approximately one third each of the then rolling stock assets. The model was that rolling stock would be leased from the ROSCOs by the TOCs, the money then being used to finance new rolling stock procurement. The permanence of the ROSCOs would allow for better rates of finance to be available for such procurement in preference to the transient nature of the TOC franchisees, therefore enabling longer term investment in rolling stock (Glover, 1998). Within a decade of privatisation, all three ROSCOs had invested significant amounts in new rolling stock, mainly to meet the slam-door replacement requirements driven by the Hidden report. However, all three ROSCOs were also by that time owned by banks and had gained a reputation for sweating BR assets with questionably high leasing rates apportioned to rolling stock which was already two decades old and less than state-of-the-art (Competition Commission, 2009). This led to investigations into the behaviour and practices of the ROSCOs, the outcome of which has been successive governments' efforts to bring new leasing companies into the market, such as Agility Trains, etc.

Just as the levels of competition within the industry were increasing, the original three ROSCOs were sold off, being seen as non-core activities for banks suffering in the aftermath of the financial crisis of 2008. This resulted in the access to capital for new trains being limited, and the rate of new rolling stock purchases slowed significantly. However, Angel, Porterbrook and Eversholt still had a large population of the latest generation of trains on their books which following the pattern of the previous years, should be marketable for several decades to come. Since 2008 therefore, it is the author's observation that the attention of the original three ROSCOs appears to have turned to modernising fleets built in the 1980s, with the intention of gaining another 10 – 15 years of life and therefore revenue. Hence the industry has seen re-tractioning programmes for Class 317 (Angel), 321(Eversholt) and 455 (Porterbrook), along with projects to ensure compliance to the PRM TSI, and even efforts to make the Pacer design seem contemporary.

Another aspect that needs to be understood is that which has been happening in the rolling stock supply industry as well. Back in the late 1990s and early 2000s, UK train manufacturing was limited to the traditional suppliers under new brands: BREL became AdTranz and then Bombardier whilst Metro-Cammell was subsumed into Alstom via GEC. The latter lost out in the rolling stock procurement of that time and withdrew from having a UK presence, instead supplying support and the occasional new builds – such as the Jubilee Line stock and the Class 390 enhancements – from France, Italy and Spain.

With Bombardier as virtually the sole supplier in the UK, South West Trains were left without an option to fulfil the slam-door replacements by the deadline of 2004 and they effectively introduced Siemens into the market, the German manufacturer having previously only been involved in a joint venture with CAF to supply the small batches of EMUs for Heathrow Express and West Yorkshire TPE. On the back of the Desiro supplies to SWT, Siemens then sold further designs to Trans-Pennine, Greater Anglia and what is now London

Midland, and with apparently superior financing were then in prime position to win the large-scale Thameslink replacement contract in 2011.

At the same time as Siemens' authentic entry into the UK, the UK government recognised Hitachi's efforts to demonstrate a compliant technology platform (they had been operating a verification train with their traction system since 2002) and awarded them the contract to supply the Class 395 high speed train to operate on the CTRL-domestic services. This gave Hitachi a permanent presence in the UK and having won the IEP contract, they have subsequently moved their head office for global rail operations to London.

With Siemens and Hitachi now set up as suppliers to the UK market, and with a large programme of rolling stock procurement projected by the government, other suppliers have been keen to get in on the act; CAF has recently won contracts to supply the Caledonian sleeper stock and a mixture of EMUs and DMUs for Northern; Stadler is targeting the GB market and has followed on success in winning the contract to supply new rolling stock to the Glasgow Subway with significant contracts to supply mainline rolling stock for Anglia and MerseyRail; Alstom is making efforts to re-establish itself with more of a local presence, and; companies such as Mitsubish and the recently formed CRRC are known to be aggressively chasing a foothold in the European market.

The result is that the landscape has changed immeasurably in the last eight years, with competition in both financing and rolling stock supply. This has the potential to change the existing model significantly, with prospective franchisees now having the option to propose new rolling stock in place of that which may only be a few years old, let alone life-expired. The situation is further compounded by the growing emphasis on - and the associated tender evaluation rewards – for rolling stock enhancements within franchise ITTs (Rail Business Intelligence, 2016).

This analysis is largely support by the latest long term strategy publication (Rail Delivery Group, 2016), however the report makes assumptions over much more extensive electrification by 2040 than this author has optimism for.

Further complication of the issue and the future of the ROSCOs has come to light in the wake of the UK European Referendum result of June 2016, with decisions on franchising being delayed and the suddenly weaker pound causing market instability (Railway Gazette, 2016).

In conclusion, and for the sake of simplicity in this instance, the rolling stock assumption for the long-term procurement will be that rolling stock is new rather than being cascaded or modified to accommodate future energy technical options.

4 Stage 1 – GB Electrification Extent

4.1 Existing Electrification Extent Overview

The existing extent of electrification in the UK is described as follows:

- 3rd rail:
  - London and South Eastern
  - London and Southern, excluding the coastal route from Ashford to Eastbourne and Oxted to Uckfield
  - London and South Western, excluding Basingstoke to Exeter
  - Euston to Watford suburban line, including the Kensington Olympia line to Clapham Junction
  - North London Line, Acton Central to Richmond
  - East London Line, Dalston Junction to New Cross
  - Merseyrail, excluding Bidston to Wrexham
  - Thameslink, Farringdon to Blackfriars
  - Great Northern suburban line, Moorgate to Drayton Park
- OLE:
  - London, Tilbury and Southend line
  - Great Eastern Suburban lines, excluding Marks Tey to Sudbury
  - Great Eastern main line to Norwich
  - East Anglian suburban lines, main line to Kings Lynn
  - Great Northern suburban lines
  - East Coast Main Line to Leeds and Edinburgh
  - Midland Mainline from St Pancras / Farringdon to Bedford
  - West Coast Main Line to Glasgow, including:
    - Watford to St Albans Abbey
    - Northampton Loop
    - Birmingham / Wolverhampton loop
    - Colwich Junction to Manchester via Stowe
    - Weaver Junction to Liverpool
    - Weaver Junction to Manchester
    - Manchester Airport
    - Crewe to Kidsgrove
    - Norton Bridge to Stone
    - Carstairs to Edinburgh
  - Paddington to Heathrow
  - Birmingham Cross-City Line from Lichfield to Redditch
  - Airdale lines from Leeds / Bradford to Skipton / Ilkley

    - Glasgow suburban lines out of Central Station and Queen Street Low Level, to such as:
        - Ayr
        - Ardrossan
        - Largs
        - Wemyss Bay
        - Gourock
        - Hellensburgh
        - Ballock
        - Milngavie
        - Lanark
        - Springburn
        - Cumbernauld
        - Paisley Canal
        - Larkhall
        - Newton
        - Neilston
    - Edinburgh to Glasgow via Airdrie and Bathgate
    - Edinburgh to North Berwick

4.2 Future UK Electrification Schemes

The following is the list of committed electrification currently planned or in progress (all OLE schemes) (Department for Transport, 2012) (Ernst & Young, 2013):

- North West Triangle / TransPennine
    - Manchester to Liverpool (complete)
    - Manchester to Preston via Bolton
    - Preston to Blackpool North
    - Manchester to Colton Junction
    - Huyton to Wigan
- Great Western Main Line
    - Airport Junction to Bristol via Bath
    - Swindon to Bristol, Cardiff and Swansea
    - Didcot to Oxford
    - Marlow / Henley on Thames / Windsor
    - Reading to Newbury
- Midland Main Line
    - Bedford to Corby
    - Kettering to Nottingham

  - Trent Junction to Derby and Sheffield
- Wallsall to Rugeley Trent Valley
- EGIP:
  - Glasgow to Cumbernauld
  - Edinburgh to Glasgow via Falkirk
  - Cumbernauld to Falkirk
- Valley Lines: Cardiff suburban lines to Treherbert, Merthyr Tydfil, Aberdare, Rhymney, Ebbw Vale and Maesteg. Cardiff to Bridgend via Llantwit Major.

4.3 GB Network Division

As a convenient way of capturing the electrification gaps in relation to passenger services, the operational divisions already laid out in the franchise maps are used (Marsden C. , 2016). A representation of each franchise's area of operation or significant routes is shown alongside a narrative description of the operations and current rolling stock.

Open access operators are considered in a separate section but with a lower priority of requirements, given the 'piggy-back' nature of their operations and the lack of tie-down to a particular franchise area. Similarly, sleeper services are propelled by whichever locomotive power is relevant for each portion of track worked over. As such, sleeper operations are not given prominence in the analysis.

4.4 GB Network Analysis

4.4.1 London and South Eastern

Operating under the SouthEastern franchise name, this network covers all operations from the London terminals of Victoria, Blackfriars, Cannon Street, Charing Cross and London Bridge to the likes of Tonbridge, Folkestone, Dover, Ashford, Canterbury, Rochester and Ramsgate. The entire network is 3rd rail electrified. CTRL-Domestic services are also operated under OLE from St Pancras to Ashford where they transfer to the 3rd rail for onward services to Dover, Ramsgate and Faversham.

The fleet is a mixture of Electrostar and Networker 3rd rail EMUs and dual voltage Class 395 units for High Speed operations to St Pancras.

There are no electrification gaps and therefore future rolling stock replacements or enhancements will not be affected by self-power options.

4.4.2 Thameslink ,Great Northern Suburban and Southern (TSGN)

This ‘super-franchise’ now incorporates all of the Thameslink operations between Bedford and Brighton, The Great Northern suburban routes out of Kings Cross and Moorgate and the Southern services from Victoria and London Bridge to South Coast destinations such as Brighton, Eastbourne, Worthing and Littlehampton. There is also a service between Milton Keynes and Gatwick Airport via Kensington Olympia, although this has been something of an ‘Off-and-On’ service in the past.

The route is currently being upgraded as part of the Thameslink Programme in which new rolling stock and control systems are being procured for longer and more frequent trains through the core section. A link from the Great Northern lines is being built so that trains from Peterborough and Kings Lynn can travel directly to South Coast destinations. However, none of this work effects the extent of electrification which is currently OLE north of Farringdon and Drayton Park (and between Willesden Junction and Milton Keynes), and 3rd rail throughout the majority of the remainder of the routes.

The non-electrified lines are limited to the ‘Marshlink’ route between Ashford and Hastings and from Oxted to Uckfield. These are currently serviced by Class 171 DMUs which date back to the mid-2000s. They are therefore likely to operate until at least 2040.

4.4.3 London and South Western

The London and South Western routes are those out of Waterloo to Portsmouth, Southampton, Weymouth, Salisbury, and Reading via Staines. The network has a majority of 3rd rail coverage with only the long-distance commuter service between London and Exeter via Salisbury operated by Class 159 DMUs, the electrification extent finishing at Basingstoke. There is an additional circular service from Romsey to

Salisbury via Romsey which is electrified only between Eastleigh and Redbridge.

The Class 159 DMUs were built in the late 1980s and will be due for replacement by around 2030.

4.4.4 Great Western (including Heathrow Express)

The Great Western routes can be divided into the following operations:

- Mainline operations between Paddington, Bristol, Cardiff, Swansea, Plymouth and Penzance
- Thames Valley local operations from Bedwyn, Worcester, Oxford and London dormitory destinations such as Reading, Windsor, Maidenhead, Twyford and Basingstoke
- Devon and Cornwall local services between Exeter and Penzance
- West of England services from South Wales to Gloucester, Weymouth and Portsmouth.
- The Heathrow Express link which operates from Paddington to Airport Junction and thence to the various terminals at Heathrow.

At present only the Heathrow Express route is fully electrified with OLE. However the Great Western Electrification Programme (GWEP) is currently underway which sets out to electrify the mainline through to Oxford, Swansea and Bedwyn. The Thames Valley services will then be mainly operated by new Class 387 EMUs with a handful of Class 16x DMUs continuing to operate branch lines. The rest of the Class 16x units will be cascaded to the West of England, displacing the Class 158 units which will move to Devon and Cornwall services, thereby removing the requirement for the Class 14x Pacers and many of the earlier Class 15x designs.

The mainline HST fleet will be replaced by Class 800, 801 and 802 units – a mixture of EMU and bi-mode Hitachi IEP designs. The franchise will therefore be largely renewed within the coming decade.

4.4.5 Chiltern Lines

One of the longest-term franchises on the GB network, the Chiltern Lines comprises the routes out of London Marylebone to Aylesbury, Bicester and Banbury. The franchise has expanded significantly since privatisation with through services to Birmingham Moor Street and Snow Hill stations, taking on the Stratford-on-Avon services from Thames Trains in 2004 and under the Evergreen Project, to Oxford via Haddenham and Thame Parkway since October 2015. Since 2010, Chiltern has been using an ever-growing fleet of Class 67 and 68 loco-hauled MkIII sets which provide intercity services between London and Birmingham. Services around London are fulfilled with Class 165 DMUs which were incumbent from the time of privatisation, with longer-range services provided by a mixture of Class 168 and 172 DMUs.

Whilst there have been substantial infrastructure upgrades, there has never been a concerted plan to electrify the route. However, it should be noted that the 'Electric Spine' from Southampton would overlap the Birmingham routes between Banbury and Leamington Spa.

4.4.6 London Midland

A composite of several other original franchises disbanded in 2007, London Midland covers the majority of suburban services around Birmingham and the Trent Valley, the semi-fast WCML services between Euston and Liverpool and services over the Abbey line (London to St Albans) and the Bedford – Bletchley line. The WCML sections are electrified, including the Rugby – Birmingham – Stafford section, along with the Cross-City line between Redditch and Lichfield Trent Valley and the New Street – Walsall stretch. Under current works, the whole of the Chase line between New Street and Rugeley is due to be electrified by 2017. This line is therefore not considered in the analysis.

Whilst the branch between Nuneaton and Coventry may be electrified as part of the 'Electric Spine' there are no other committed plans for further electrification of the London Midland routes. This route is included in the analysis in the eventuality that electrification does not take place.

4.4.7 Greater Anglia

As the name would suggest, this franchise covers the majority of services within what is generally understood as the Anglian region – namely Essex, Suffolk, Norfolk and Cambridgeshire. The operations are centred on Liverpool Street, Colchester, Ipswich, Norwich and Cambridge.

The electrified Great Eastern mainline between Liverpool Street and Norwich is operated by loco-hauled MkIII rolling stock, and the electrified Great Eastern branches to Upminster, Southend Victoria, Southminster, Clacton, Walton and Braintree are serviced by a combination of BR-era Class 321 EMUs and more recent Class 360 units. The West Anglia services to Cambridge and King's Lynn are operated by Class 317 units and the newest fleet of Class 379 is used mainly on Stansted airport services, although they can also be used on the Great Eastern services. Indeed, the recent IPEMU experiment was conducted using a battery-equipped Class 379 on the non-electrified branch between Marks Tey and Sudbury.

All other lines are non-electrified. The local lines out of Norwich are serviced by a mixture of Class 153 and 156 units, whilst the longer distance services between Ipswich and destinations such as Peterborough and Cambridge are operated by a small fleet of Class 170 DMUs. Under the new franchise which began in October 2016, the entire fleet will be replaced by regional EMUs based on Bombardier's Aventra platform, Stadler EMUs for the London to Norwich mainline services and electro-diesel bi-mode units replacing the existing DMUs (Railway Gazette, 2016).

4.4.8 London, Tilbury and Southend

Also referred to as Essex Thameside and the commercial name of c2c, this is a self-contained franchised operating out of Fenchurch Street station to Tilbury and Shoeburyness via Southend Central. There is also a shuttle service between Liverpool Street and Barking. The entire network is covered by OLE and the fleet is formed of a homogenous Electrostar design which is not due for replacement until 2040 or thereabouts. There are no electrification gaps and therefore future rolling stock replacements or enhancements will not be affected by self-power options.

4.4.9 East Coast Mainline

Currently operated by Virgin Trains East Coast (VTEC), this franchise covers all of the intercity services out of Kings Cross to Leeds, Newcastle, Edinburgh, Aberdeen and Inverness. The franchise historically has also operated to Glasgow, offering an alternative to the London – Glasgow services operated over the WCML. However this service is being phased out in favour of Cross Country services from Edinburgh to Glasgow via Carstairs Jn. It is also noted that services are advertised to Harrogate, however this are occasional and are ignored within the study. Open access operators using the ECML to other destinations are covered in section 4.4.19.

The line is electrified to Leeds and Edinburgh, and the current fleet is a mixture of IC225 and IC125 formations. These trains are to be supplanted by a fleet of IEP units which should enter service in December 2018. There are no plans to electrify north of Edinburgh, however there are plans for line speed and capacity improvements on the line to Inverness (Network Rail, 2015).

4.4.10 Midland Mainline, East Midlands Regional Routes

Currently operated by Stagecoach under the banner of East Midlands Trains (EMT), this franchise includes the intercity services from St Pancras to Leicester, Nottingham, Derby and Sheffield, regional express services between Liverpool and Norwich, and a diverse set of regional services which centre on East Midlands cities. These local services include:

- Nottingham – Matlock
- Nottingham – Worksop
- Nottingham - Skegness
- Leicester – Lincoln and Cleethorpes
- Derby – Crewe
- Peterborough – Doncaster via Lincoln

The intercity fleet is a mix of IC125 sets and Class 222 Meridian DEMUs. The regional sets are formed from Class 153, 156 and 158 units.

The Midland Mainline is due for electrification which, after delays previously described will extend the existing infrastructure between St Pancras and Bedford to Corby, Nottingham and Sheffield via Derby. None of the regional routes are due for electrification.

4.4.11 West Coast Mainline

Currently operated by Virgin, the West Coast main line is arguably the highest profile railway on the GB network, connecting London with the major cities of Birmingham, Manchester, Liverpool and Glasgow. The majority of the route is electrified, with only the North Wales route from Crewe to Holyhead via Chester requiring diesel traction. When first introduced, the Class 390 units were dead-hauled over this section by diesel locomotive. However, growth in ridership since the speed enhancements launched in 2004 has meant that Class 390s are at a premium for other services and changes to the franchise have allowed the Class 221 Voyager DEMUs to be

deployed on this route instead. There are no current NR plans to electrify this route, although politicians have stated that the case for electrification is strong (BBC, 2015).

Whether or not this section of the franchise is electrified may be of secondary importance when compared with the potential impact of High Speed 2 (HS2). Due to start operations in 2026, HS2 will assume the main intercity duties currently operated over the WCML and may reduce the current franchise to secondary or relief duties. This may, in turn, release a large number of Class 390 units for re-leasing onto the market. However, by 2033 the oldest member of the fleet will be 30 years old and possibly at life expiry.

4.4.12 Northern

One of the largest operations in terms of numbers of routes and geographical diversity, the Northern franchise is currently held by Arriva, having been awarded the latest contract for a nine-year period starting in April 2016. The franchise covers all local and regional service (non-intercity) in the north of England, including:

- North Eastern lines around Middlesborough and Newcastle, including the Newcastle to Carlisle Line
- The Cumbrian Coast line
- North Western suburban services around Manchester, Bolton, Preston and Blackburn
- West Yorkshire suburban services around Leeds, Bradford, Huddersfield and Wakefield
- South Yorkshire and North Lincolnshire services around Sheffield, Doncaster, Lincoln and Grimsby

Some of the routes share existing electrification, such as on the WCML and ECML, whilst other routes have been electrified as extensions and fill-ins, such as the Airedale lines out of Leeds and Bradford. The Northern Triangle scheme between Manchester, Liverpool and Blackpool offers more electrified routes whilst the electrification of the TransPennine route from Leeds to Manchester will provide more opportunities to operate electric or bi-mode trains.

The franchise is famous for relying on a diverse set of cascaded and mainly older rolling stock designs, such as Class 142 and 144 Pacers, every form of Class 15X DMUs, Class 321, 323, and 333 EMUs and Class 319 units recently cascaded from Thameslink to work the

Northern Triangle services. Currently there are a handful of loco-hauled coaching stock and Class 185 DMUs sub-leased from other operators. However, under the new franchise agreement, Arriva has ordered new DMUs and EMUs from CAF to replace legacy BR-built units.

4.4.13 TransPennine

Born out of the precursor to the existing Northern franchise TransPennine Express (TPE) services were intended to differentiate from the slower suburban services in the north of England and improve connectivity between the conurbations and major cities of the North.

As the name would suggest, the core routes of the services cross the Pennine range from East to West, the exception being the Manchester to Glasgow service on the WCML which could arguably be said to parallel the line of the Pennines. East – West services are as follows:

- Newcastle, Middlesborough, Scarborough and Hull to Manchester and Liverpool via Leeds
- Cleethorpes to Manchester Airport via Sheffield

It is intended to extend Newcastle services to Edinburgh via the ECML under the new franchise agreement which clearly sets TPE out as an intercity operation.

Current rolling stock includes Class 170 and 185 DMUs, however with the core Manchester to Leeds route being electrified TPE has already announced the procurement of Hitachi AT300 bi-mode units similar to the IEP and is expected to order more vehicles in the near future. This means that most of the existing DMUs will be available for cascading to other operators.

4.4.14 ScotRail

Currently operated by Abellio, ScotRail was first established as a brand under BR in the 1980s and the operational boundaries remain largely unchanged since then. However, political devolution has encouraged a great deal of investment and under the Edinburgh – Glasgow Improvement Plan closed lines have been reopened and existing lines electrified.

Operations range from high-density inner suburban services around Glasgow and Edinburgh to outer suburban express services from the likes of Ayr and Ardrossan into Glasgow, to slower and more remote services on the West Highland line to Oban and Kyle and to Thurso and Wick.

Due in part to the electrification plans of the WCML in the 1960s and 1970s, much around Glasgow is already electrified. Services are operated with a mixture of BR-legacy EMUs such as Class 314, 318 and 320, supplemented by more recent designs such as Class 334 and 380 units. A further tranche of EMUs from Hitachi is on order for EGIP services.

4.4.15 Wales

Operating presently as Arriva Trains Wales (ATW), this franchise incorporates all services within Wales and cross-border services which originate in or predominantly operate in Wales. These can be summarised as follows:

- North Wales Lines
  - Chester and Manchester to Llandudno and Holyhead
  - The Conwy Valley Line between Llandudno and Blaenau Ffestiniog
  - The Borderlands Line from Bidston to Wrexham
- Mid Wales
  - The Cambrian Line from Aberystwyth and Pwllheli to Birmingham

    - The Heart of Wales Line from Swansea to Shrewsbury via Llandridnod
- South Wales
    - Camarthen to Manchester via Cardiff and the Welsh Marches route
    - The Valley lines around Cardiff
- The Premier Service operation between Holyhead and Cardiff

Rolling stock is a mixture of loco-hauled MkIII sets for the Premier Service, Class 158 and 175 DMUs for the cross-border, long-distance services, Class 150 and 153 DMUs for the rural services and Class 142 and 142 DMUs for the Valley Lines operations.

Following the GWEP electrification to Cardiff and Swansea, it is planned that the Valley Lines are to be electrified, with cascaded EMUs from London to replace the unpopular Pacer units.

4.4.16 MerseyRail

A largely self-contained, 3rd rail network centred around Liverpool and the Wirral, MerseyRail is currently operated by a joint venture of Serco and Abellio.

The rolling stock fleet is formed of the BR-legacy Class 507 and 508 units which are due to be replaced in the coming years.

As the entire network is electrified there are no electrification gaps. Extensions of electrification and therefore the service boundaries of Merseyrail have been proposed recently, such as Bidston – Wrexham, Kirby – Wigan and Ormskirk – Preston. Despite not currently planned or in progression, there is a good deal of political pressure for one or more of these schemes to be realised. The impact of such a scheme would result in electric trains being used, whether these are 3rd rail or dual voltage. A new order for EMU rolling stock has been placed with Stadler (Railway Gazette, 2016) and therefore alternative power architectures do not warrant further consideration in this study. However this would impact on the services and therefore rolling stock needs of Northern as the neighbouring franchise.

4.4.17 Cross Country

Until the rise of TPE, the Cross Country franchise – currently held by Arriva – was the only intercity route without serving London. The routes form a large ‘X’ across the country with Birmingham New Street as the apex through which all service pass. Destinations are as follows:

- North East: Newcastle, Edinburgh, Aberdeen and Glasgow (via the ECML)
- North West: Manchester
- South East: Stansted, Bournemouth
- South West: Bristol, Cardiff, Plymouth, Penzance, Paignton, Newquay

The fleet consists of Class 220 and 221 Voyager DEMUs, the latter originally tilt-capable when the franchise ran further up the WCML but since with tilt disabled. These units are supplemented by a number of IC125 sets. The north western leg of the route is electrified along the length of the WCML and prior to the introduction of multiple units these services were often hauled by electric locomotives with a changeover to diesel locomotives at Birmingham. Whilst the north eastern route is electrified from Doncaster and Wakefield to Edinburgh, there is a large gap between Birmingham and Sheffield. This will be filled in part when the Derby to Sheffield section is electrified as part of the MML scheme. In addition, the GWEP scheme will electrify the Reading to Oxford section of the south eastern leg. The argument in favour of bi-mode train operation is therefore strengthening, however the discussions over the possibility of an ‘E-Voyager’ collapsed due to costs, and the favoured bi-mode option now seems to be the Hitachi IEP derivative.

4.4.18 London Overground

A recently formed operator, London Overground supplements the Underground and other transport modes owned and controlled by Transport for London. The services are operated under a management contract rather than a leasing arrangement which ensures continuity of brand and means overall control remains within TfL.

The routes radiate from a circular line formed from the North London line, East London line and South London line, starting and terminating at Clapham Junction. Radial lines include those from Euston to Watford, Liverpool Street to Enfield and Dalston Junction to Crystal Palace. CrossRail operations from Maidenhead to Shenfield are also considered under the Overground banner, although the management contract is let separately. The only non-electrified section of Overground operations is that of Gospel Oak to Barking, which is due to be electrified by 2017. This will release the handful of Class 172 units currently used.

Future plans to incorporate more of the London-centred inner suburban services such as those from London Bridge to Dartford are already electrified. There is therefore no need for inclusion of Overground in the gap analysis study.

4.4.19 Open Access Operators

4.4.19.1 Hull Trains

Owned by First Group, Hull Trains currently operates Class 180 DMUs from Kings Cross to Hull on the electrified ECML as far as Selby. Despite electrification of the Selby to Hull line being promised in the 2015 budget, Hull Trains have ordered a new fleet of IEP-derivative bi-mode trains to take advantage of the existing electrification (Railway Gazette, 2015).

4.4.19.2 Grand Central

Grand Central (GC) operates out of Kings Cross to Sunderland and Bradford Interchange, both destinations reached off the ECML. GC currently uses IC125 sets and Class 180 DMUs. There are no plans to extend the electrification extent currently available to GC.

4.4.19.3 Proposed First Group London Edinburgh Services

It was announced in May 2016 that First Group had been granted a further open access agreement to operate trains from Kings Cross to Edinburgh. It is suggested that First will order new high speed EMUs to operate this service (Railway Gazette, 2016).

4.5 Conclusions

Having reviewed the mileages of existing electrification, planned electrification, planned rolling stock replacements and future franchise commitments, a qualitative assessment of each of the franchise areas has been completed and is shown in Table 2.

It is clear that there are several franchise areas which will be at risk of clear energy strategy in the coming decades. As a franchise for which decisions over rolling stock have been deferred, in line with the delay of electrification, the East Midlands area (including the Midland main line services) perhaps lends itself to further analysis at this stage. The area also covers intercity, regional express and local stopping services and this diversity also lends itself to further study.

Table 2 – GB Franchises assessed for future rolling stock and energy gaps

Franchise Area	Electrification extent	Electrification planned	New rolling stock planned	Future electrification / RS gap?
London & South Eastern	full	n/a	n/a	no
TSGN	almost full	none	none	minor
London & South Western	almost full	none	none	minor
Great Western	none	substantial	substantial	moderate
Chiltern	none	partial	none	considerable
London Midland	partial	none	likely	moderate
Greater Anglia	partial	none	substantial	moderate
London, Tilbury & Southend	full	n/a	n/a	no
East Coast Mainline	almost full	n/a	substantial	minor
East Midland, Midland Main	Partial	partial	n/a	significant
West Coast Mainline	almost full	none	none	minor
Northern	minor	partial	substantial	moderate
TransPennine	partial	substantial	substantial	minor
ScotRail	partial	partial	partial	considerable
Wales	none	partial	partial	considerable
Merseyrail	full	n/a	substantial	no
Cross Country	partial	minor	none	considerable
London Overground	almost full	partial	n/a	no

5 East Midlands Route Review

5.1 Current Situation

The franchise map for all routes currently operated by East Midlands Trains with all major stations is shown in Figure 9. Note that the Barton by Humber branch is currently operated by the Northern franchise holder but that this will transfer to the East Midlands franchise in 2017. Future rolling stock plans will be assessed with the inclusion of this service.

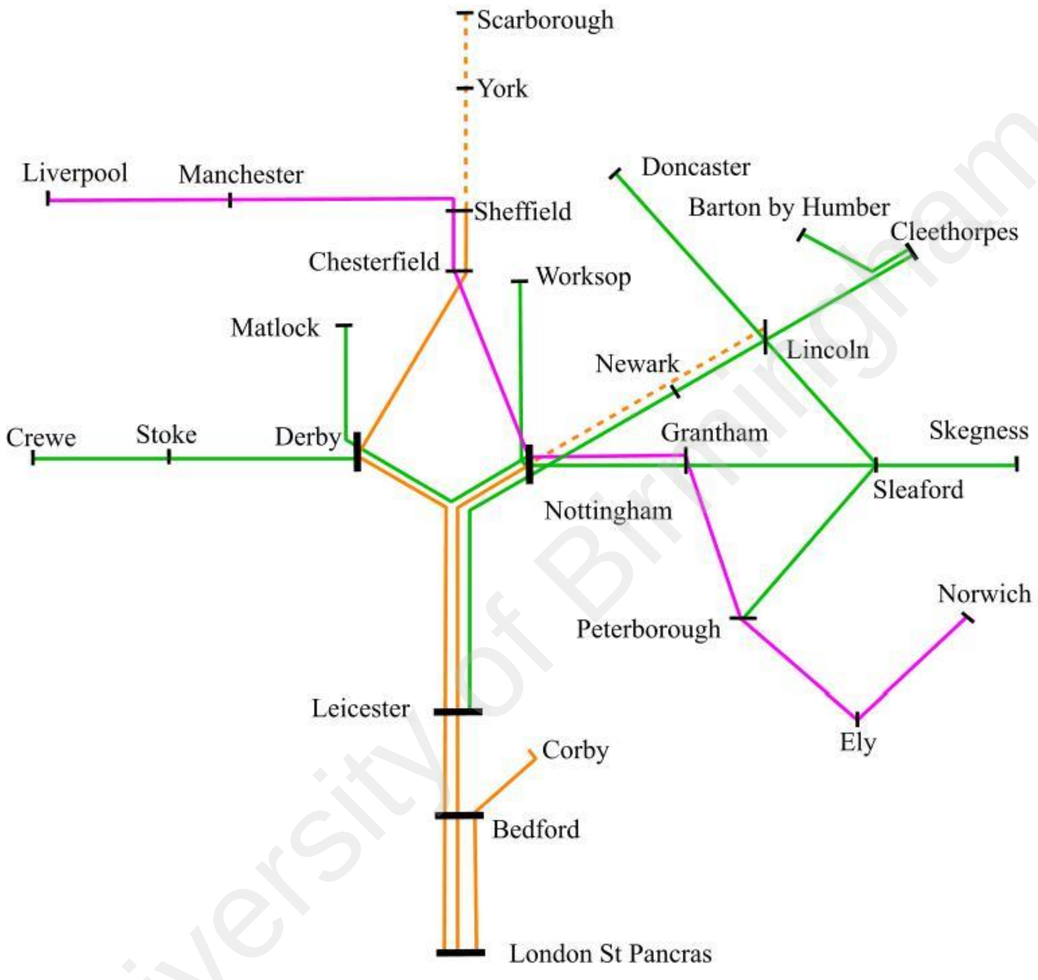


Figure 9 – Midland mainline and East Midlands franchise map

For consistency with the route data – timetables, sectional appendices, etc. – distances are recorded in miles rather than kilometers. Route mileages are taken from published line diagrams (TRACKmaps) (TRACKmaps, 2006) (TRACKmaps, 2010) (TRACKmaps, 2013) (TRACKmaps, 2008).

Existing fleet operations and numbers are taken from (Marsden C. , 2016) and the number of trains needed per service is calculated with the formula:

$$No\ of\ trains = \frac{(\text{headway} + \text{turnaround})\ \text{x2}}{60}$$

The total numbers of vehicles is projected from the maximum numbers of vehicles used in trains during peak periods. There are therefore two elements of conservatism which may cause the calculated numbers of trains and vehicles to exceed those actually in the fleet:

- Train lengths at peak will not be perpetuated throughout the duration of services considered in the calculation, especially services which are longer in duration;
- There is no account of marginal train usage, i.e. the train terminating after one service being employed directly on a different service rather than in a direct turnaround onto the same service. Synergies of different routes are therefore not accounted for.

However, the calculated values particularly of vehicles needed may be of some use in that peak times may extend over time to accommodate passenger growth where capacity is limited. The calculated values may therefore be more reflective of what may be needed in future operations.

The extent of electrification on the franchise at present is shown in Figure 10. The following key is used to denote the extent of electrification:

- Non-electrified lines:
- OLE lines:

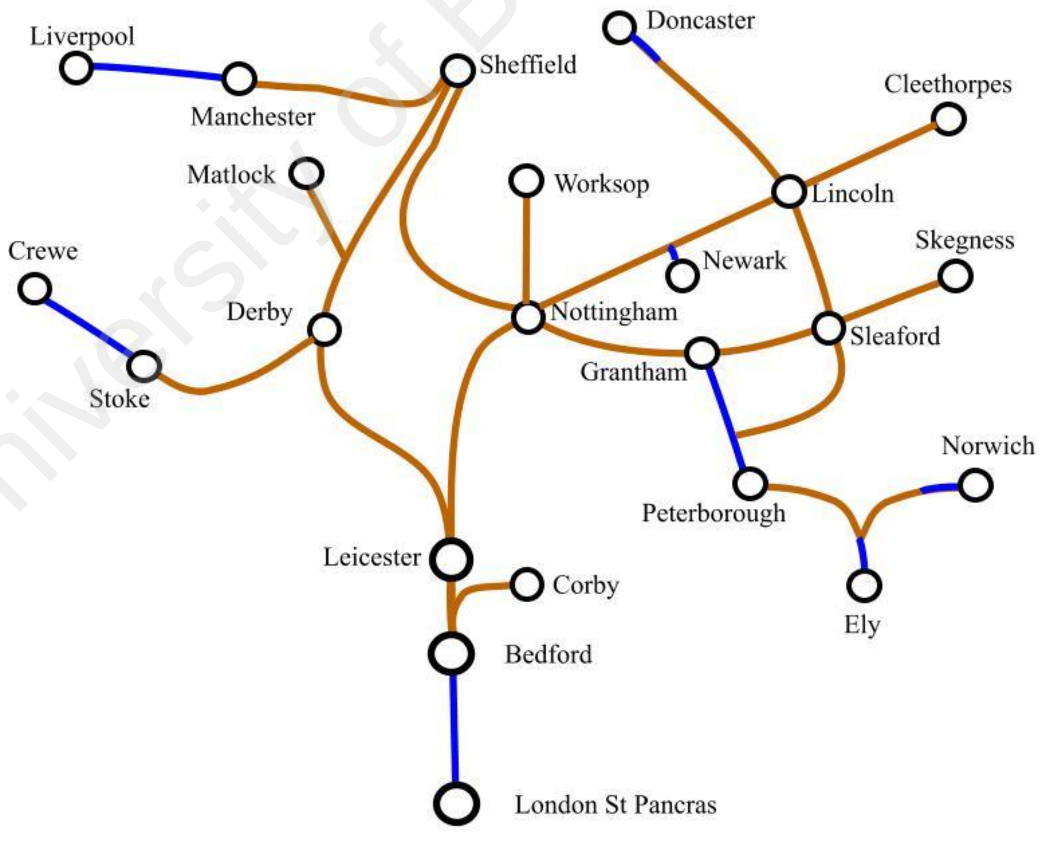


Figure 10 – Midland mainline and East Midlands current electrification map

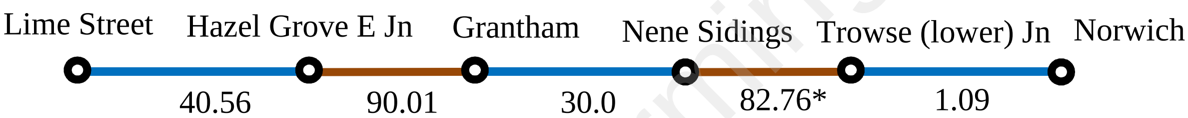
__Present Service Analysis:__

- St Pancras to Corby – 1 tph

- St Pancras to Nottingham – 2 tph

- St Pancras to Sheffield – 2 tph

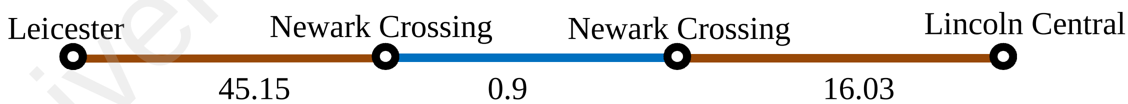
- Liverpool to Norwich – 1 tph



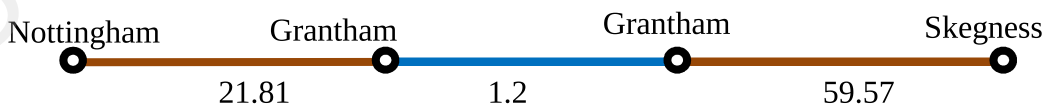
*Includes 1.73 miles of electrified operation at Ely

- Nottingham to Worksop – 2 tph
  31.5 miles – no electrification
- Derby to Crewe – 1 tph

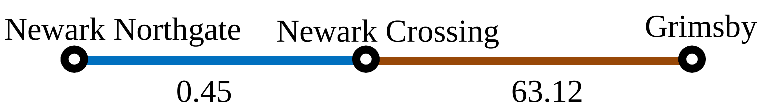
- Leicester to Lincoln Central – 1 tph



- Nottingham to Skegness – 1 tph



- Nottingham to Matlock – 1 tph
  33.25 miles – no electrification
- Newark Northgate to Grimsby – 1 tph



- Peterborough to Doncaster – 1 tph

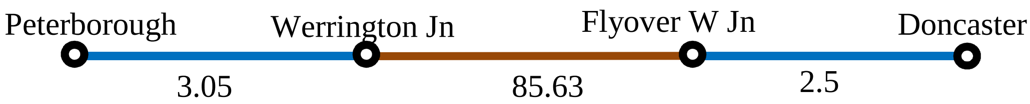


Table 3 – East Midlands franchise area – electrified vs. non-electrified route analysis

Service	Route distance / miles	Self-power distance / miles	Self-power distance / proportion	Distance without recharging / miles
St Pancras - Corby	79.5	29.75	37%	59.5
St Pancras - Nottingham	126.5	76.75	61%	153.5
St Pancras - Sheffield via Derby	165	115.25	70%	230.5
Liverpool - Norwich	244.4	172.75	71%	90.01
Nottingham - Worksop	31.5	31.5	100%	63
Derby - Crewe	50.5	35.1	70%	70.2
Leicester - Lincoln Central	62.2	61.3	99%	122.6
Nottingham - Skegness	82.58	81.38	99%	119.14
Nottingham - Matlock	33.25	33.25	100%	66.5
Newark Northgate – Grimsby	63.57	63.12	99%	126.24
Peterborough - Doncaster	91.18	85.63	94%	85.63

As a general commentary on the above results, the longer distance trains do benefit from electrification coverage over 30 – 40% of the route distance. However they also require long distances without any kind of electric 'top up'.

Most of the regional routes have very little electrification coverage at present and there appears to be no potential for bi-mode operation under the existing infrastructure.

Rolling Stock Fleet Analysis:

Table 4 – East Midlands Franchise Area – current peak provision requirement

Service	Journey time / min	Turnaround time / min	Trains per hour (peak)	Trains required	Max. vehicles per train	Vehicles required
St Pancras - Corby	71	5	1	3	5	15
St Pancras - Nottingham	100	12	2	8	9	72
St Pancras - Sheffield via Derby	140	19	2	12	9	108
Liverpool - Norwich	334	30	1	13	4	52
Nottingham - Worksop	67	5	2	6	2	12
Derby - Crewe	69	6	1	3	1	3
Leicester - Lincoln Central	55	9	1	3	2	6
Nottingham – Skegness	145	15	1	6	2	12
Nottingham – Matlock	66	11	1	3	2	6
Newark Northgate - Grimsby	90	6	1	4	2	8
Peterborough - Doncaster	147	20	1	6	1	6
Total						**300**

Table 5 – East Midlands Franchise Area – current self-powered provision

Vehicle Class	Type	No. of vehicles per unit	No. of units in fleet	No. of vehicles in fleet	Projected life-expiry
153	DMU	1	17	17	2025
156	DMU	2	15	30	2025
158	DMU	2	26	52	2025
222	DEMU	4	4	16	2040
222	DEMU	5	17	85	2040
222	DMU	7	6	42	2040
HST	Loco-hauled	8	10	80	2020
Total			95	322	

A summary of the rolling stock requirements by type is shown in Table 6.

Table 6 – East Midlands Franchise Area – current fleet summary

<table>
<tr><th>Rolling Stock Type</th><th>No. required</th><th>No. in fleet</th></tr>
<tr><td>Regional</td><td>51</td><td>47</td></tr>
<tr><td>Regional Express</td><td>52</td><td>52</td></tr>
<tr><td>Short-form intercity</td><td rowspan="2">186</td><td>101</td></tr>
<tr><td>Long-form intercity</td><td>122</td></tr>
</table>

The low number of intercity vehicles required compared to the fleet numbers is possibly due to some of the occasional services not being analysed, such as London – Lincoln and the summer services to York and Scarborough. East Midlands Trains has been known to sub-lease some of its HST sets to other operators when demand requires (Wikipedia, 2016) (125 Group, 2016).

5.2 Situation Post-Electrification

Current, published electrification plans show that the main branches of the main line will be electrified from the end of the existing extent at Bedford to Corby, Nottingham and Sheffield via Derby. There is no indication that any of the connections between Chesterfield and Trent Junction or Nottingham via the Erewash Valley will be electrified, nor the connection north from Sheffield to either of Doncaster or Wakefield, although without the latter the 'Electric Spine' will arguably be incomplete without a connection north of Sheffield.

A revised map of the projected electrification extent is shown in Figure 11. The colour scheme is the same as for Figure 7.

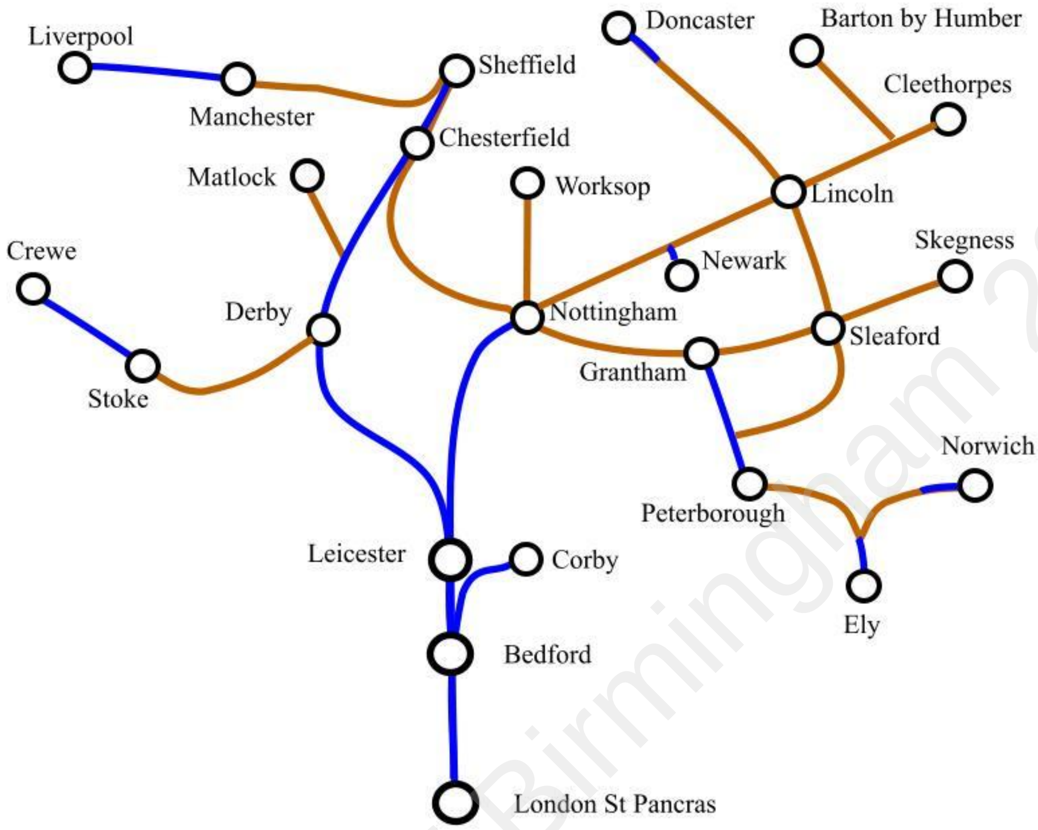


Figure 11 – Midland mainline and East Midlands future electrification map

The following will be assumed for the purposes of possible extension services outside the existing franchise map:

- Sheffield to Wakefield (and therefore Leeds) will be electrified as a completion of the Electric Spine;
- Leeds to York will be electrified as part of the TransPennine modernisation;
- York to Scarborough will not be electrified
- Lines north of Sheffield other than to Wakefield will not be electrified
- The Hope Valley Line (between Manchester and Sheffield) will be modernised but not electrified

5.3 Rolling Stock Future Requirements

Currently, the electrification work on the MML and lines affecting East Midlands services is due for completion around 2025, although some doubt remains as to whether electrification will actually extend north of Kettering (Railnews, 2017). This coincides with the probable life-expiry of the Class 15x units. At present, these could be replaced by new or cascaded DMUs. However further like-for-like replacement is assumed to be unlikely beyond this.

The intercity trains post-electrification may be a stop-gap loco-hauled fleet, with EMUs and bi-mode intercity trains subsequently.

Whilst HST formations are likely to continue in some form for a few years, MkIII vehicles are known by the author to be anachronistic in terms of suspension and other technologies, and maintenance activities will increase in cost to the effect that operations beyond 2030 are not considered viable, irrespective of how they are hauled.

It is assumed that electrification will result in a 10% improvement in journey times over those currently achieved, valid for the portion of the route under which electrification can be taken as a benefit. This benefit will be assumed for services working over the Hope Valley Line despite it not being electrified.

It is also assumed – based on the increase in ridership in the past two decades – that there will be a 50 – 100 % increase in capacity needed by 2050. Changes in demand due to projects such as HS2 are considered to be part of this uplift. For regional services this will be achieved through longer consists, whereas for intercity services this will be achieved by new train diagrams.

The following additional services to the core current franchise commitments will be considered:

- St Pancras – Lincoln (short-form intercity train)
- St Pancras – Barnsley (short-form intercity train)
- St Pancras – Leeds (long-form intercity train)
- St Pancras – York (short form intercity train)
- Liverpool – Norwich will take the form of a short-form intercity train, in line with the way in which TransPennine are moving long-distance operations towards this form of service.

Depending upon the pattern of rolling stock purchases or cascades, it is possible that a new franchise area fleet will be needed in the period 2040 – 2050. The following analysis attempts to understand what the functional fleet makeup might be.

Future Service Analysis:

- St Pancras to Corby – 2 tph
  79.5 miles, full electrification
- St Pancras to Nottingham – 3 tph
  126.5 miles, full electrification
- St Pancras to Sheffield – 2 tph
  165 miles, full electrification

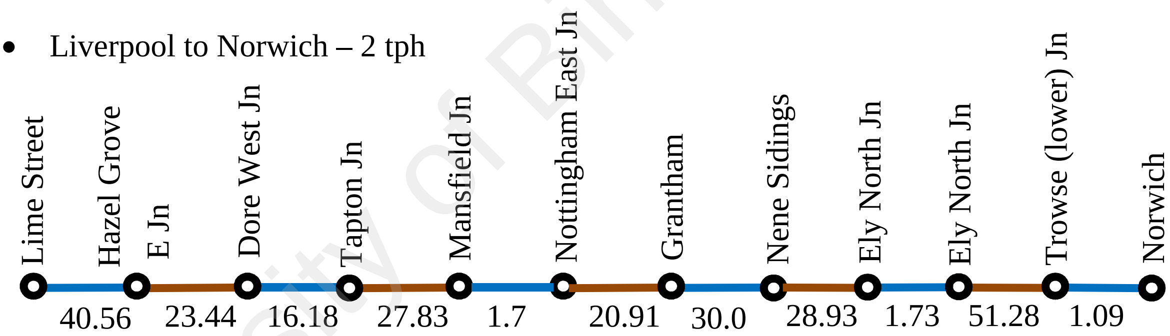
- St Pancras to Leeds – 1 tph
  201.35 miles, full electrification
- St Pancras to Scarborough – 1 tph

- St Pancras to Barnsley – 1 tph

- St Pancras to Lincoln via Nottingham – 1 tph (no stop at Newark Northgate)

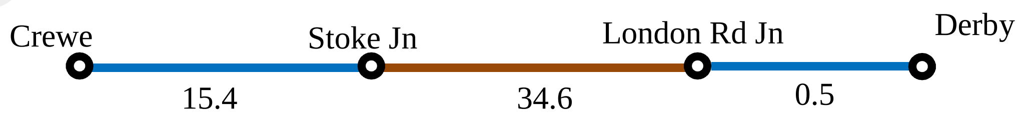
Note: the above amounts to 11tph in the St Pancras – Kettering corridor, which would require ETCS level 2 or equivalent as an enabling technology. It is assumed that this work would be carried out over the coming decades and the costs of which will not be considered in any analysis contained herein.

- Liverpool to Norwich – 2 tph

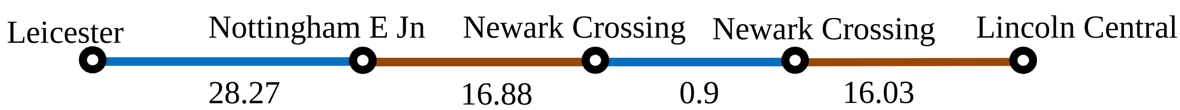


- Nottingham to Worksop – 2 tph

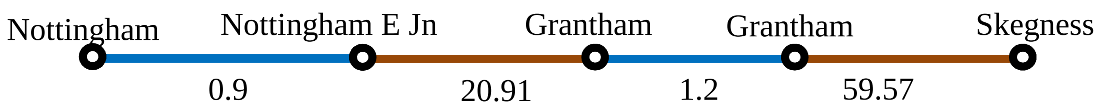
- Derby to Crewe – 1 tph



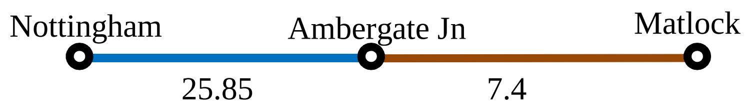
- Leicester to Lincoln Central – 1 tph



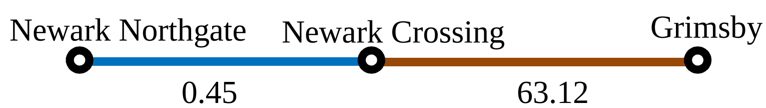
- Nottingham to Skegness – 1 tph



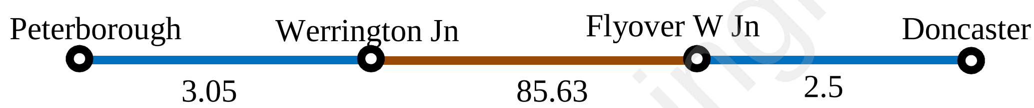
- Nottingham to Matlock – 1 tph



- Newark Northgate to Grimsby – 1 tph



- Peterborough to Doncaster – 1 tph



- Cleethorpes to Barton on Humber – 1 tph
  22.75 miles, no electrification

Intercity service requirements

It is assumed that turnaround times for the intercity services can be reduced to 10 minutes.

Table 7 – East Midlands Franchise Area – post-electrification intercity route analysis

Service	**Route distance / miles**	**Self-power distance / miles**	**Self-power distance / proportion**	**Distance without recharging / miles**	**No. of stations in largest self-power region**
St Pancras - Corby	79.5	0	0%	0	0
St Pancras - Nottingham	126.5	0	0%	0	0
St Pancras - Sheffield via Derby	165	0	0%	0	0
St Pancras - Leeds	201.35	0	0%	0	0
St Pancras - Scarborough	268.89	42.06	16%	84.12	5
St Pancras - Barnsley	181.3	13	7%	26	1
St Pancras - Lincoln	160.2	33.1	21%	66.2	3
Liverpool - Norwich	244.4	152.39	62%	51.28	1

Table 8 – East Midlands Franchise Area – post-electrification peak provision requirement

Service	Existing Journey time / min	Modernised Journey time / min	Turnaround time / min	Trains per hour (peak)	Trains required	Max. vehicles per train	Vehicles required
St Pancras - Corby	71	64	5	2	5	5	25
St Pancras - Nottingham	100	90	10	3	10	9	90
St Pancras - Sheffield via Derby	140	126	10	2	10	9	90
St Pancras - Leeds	180	162	10	1	6	9	54
St Pancras - Scarborough	260	240	10	1	9	5	45
St Pancras - Barnsley	160	146	10	1	6	5	30
St Pancras - Lincoln	152	142	10	1	6	5	30
Liverpool - Norwich	320	304	10	2	21	5	105
Total	-	-	-	-	**73**	-	**469**

Regional service requirements

It is assumed that turnaround times for the regional services can be reduced to 5 minutes.

Table 9 – East Midlands Franchise Area – post-electrification regional route analysis

Service	Route distance / miles	Self-power distance / miles	Self-power distance / proportion	Distance without recharging / miles	No. of stations in largest self-power region
Nottingham - Worksop	31.5	30.7	97%	61.4	21
Derby - Crewe	50.5	34.6	69%	34.6	5
Leicester - Lincoln Central	62.2	33.1	53%	16.88	8
Nottingham - Skegness	82.58	80.48	97%	119.14	21
Nottingham - Matlock	33.25	7.4	22%	14.8	9
Newark Northgate - Grimsby	63.57	63.12	99%	126.24	21
Peterborough - Doncaster	91.18	85.63	94%	171.26	7
Cleethorpes - Barton on Humber	22.75	22.75	100%	45.5	25

Table 10 – East Midlands Franchise Area – post-electrification self-powered provision

Service	Existing Journey time / min	Modernised Journey time / min	Turnaround time / min	Trains per hour (peak)	Trains required	Max. vehicles per train	Vehicles required
Nottingham - Worksop	67	67	5	2	5	3	15
Derby - Crewe	69	69	5	1	3	3	9
Leicester - Lincoln Central	55	52	5	1	2	3	6
Nottingham - Skegness	145	145	5	1	5	3	15
Nottingham - Matlock	66	61	5	1	3	3	9
Newark Northgate – Grimsby	90	90	5	1	4	3	12
Peterborough - Doncaster	147	147	5	1	6	3	18
Cleethorpes - Barton on Humber	90	90	5	1	4	3	12
Total	-	-	-	-	**32**	-	**96**

A summary of the future rolling stock requirements by type is shown in Table 11

Table 11 – East Midlands Franchise Area – post-electrification fleet summary

Rolling Stock Type	No. required	No. in existing fleet
Regional	96	47
Regional Express	n/a	52
Short-form intercity	235	101
Long-form intercity	234	122

As might be expected from the projected uplift in demand, the future fleet size is considerably greater than the existing fleet, and these numbers will be used to establish the costs associated with different power options in the business case analysis.

6 Rolling Stock Options

It is necessary to review examples of current technologies in relation to bi-mode rolling stock both in the UK and in other countries to inform later analysis on where technology convergence may be by 2040 – 2050.

6.1 Existing Rolling Stock Designs

6.1.1 BR-legacy DMU architecture

From the mid-1980s, the 2nd generation of DMUs were designed and built with a drivetrain for each vehicle as such:

Underfloor diesel engine → Voith hydraulic transmission → final drive

At each stage, power is transmitted through Cardan shafts and one bogie per vehicle is powered (Gibbons, 1990). This architecture applies to all Classes: 14X, 15X, 16X, 17X and 18X designs (Marsden C. J., Traction Recognition - 3rd Edition, 2014). The exception is the Class 172 units which use a ZF Mechatronic transmission, however all other aspects of the drivetrain architecture is the same. This author has previously proposed that the units could be converted to hybrid units with electric motors in place of the hydraulic transmission and power generation and conversion equipment in place of the diesel engines (Pettit, 2014). The vehicles are likely to be life-expired by 2040, and any vehicles procured within the next decade will always be at the end of life by 2050.

6.1.2 Bombardier eVoyager Project

The Class 220 and 221 designs are DEMU fleets which are operated over the WCML and Cross Country core routes, and are similar to the Class 222 fleet which is operated over the MML. In all cases the units operate diagrams which are partially electrified. The power architecture for these units is as follows:

Underfloor diesel engine → generator → AC motor → Cardan shaft → final drive

In the aftermath of the decision to award the new Thameslink fleet contract to Siemens (BBC, 2011) discussions were held with Bombardier following proposals to build a pantograph-equipped vehicle which could have been inserted into the existing DEMU consists (Milmo, 2011). The eVoyager project would have enabled the units to become bi-mode and to take advantage of the extents of electrification available on routes such as Euston – Holyhead (~158 miles of a total of 261 miles) and Edinburgh – Plymouth (~236 miles of a total of 540 miles).

However, government warnings were given over the rising costs of the project (Railnews, 2011) and the following year it was noted that the project had been impacted by changes to the national electrification strategy (Johnson, 2012).

The e-Voyager appears an attractive proposal despite the running costs associated with hauling diesel engines and fuel under the wires, and the recent announcements delaying some of the committed electrification schemes as discussed in section 2.5 may still appeal, however the residual life of the existing vehicles is likely to stop any further examination of this project.

6.1.3 VivaRail D-Train

Recently replaced as part of the London Underground SSL upgrades, the District Line D-stock, built between 1978 and 1981 was seen as possibly being scrapped ahead of its time, particularly when compared to the 1960s stock from the Metropolitan and Hammersmith and City Lines being replaced as part of the same programme. In addition, a refurbishment programme in the mid-2000s replaced the original bogies with new Bombardier Flex-frame designs which are far from being life-expired.

On disposal by LUL, the stock was purchased speculatively by VivaRail with the intention of re-engineering the fleet and proposing a main line alternative the unloved Class 14X fleets, as shown in Figure 12. To enable operation off the 3rd rail system, each motor vehicle has been equipped with two small diesel engine-generator sets, fitted in a modular way which allows for rapid replacement. The commercial success of this proposition is yet to be determined, and with a maximum speed of 60 mph the opportunities for operation over long lengths of main line are limited, however the architecture is of interest. In particular the modular aspect of providing alternative electrical power to a traditional motor bogie design could be a strategy adopted in future self-power multiple unit designs.

Figure 12 – D-stock to Class 230 conversion: before (mattbuck) and after (Alice Gillman)

6.1.4 Hitachi AT300 / IEP

In the early 2000s it was recognised that a UK-wide replacement for the HST would be required and the DfT issued a contract notice for the Intercity Express Programme trains in 2005. Recognising the mix of electrified and un-electrified lines operated by the existing HST sets, the ITT asked for sub-fleets which were wholly electric powered, self-powered and bi-mode.

In 2009 the contract was awarded to Hitachi who have subsequently designed the AT300 platform, now given the Class 800 and Class 801 designations. The bi-mode options are equipped with MTU V12 underfloor engines for working in non-electrified areas, and a proportion of three motors for a 5-car set and five motors for a 9-car set. The requirements for the trains specify that the trains can switch between modes either stationary or at speed. This is consistent with existing technology which allows systems such as the pantographs to be controlled by boundary controls such as balises which instruct the train to switch operational modes.

6.1.5 Parry People Mover

The Parry People Mover is a flywheel powered railcar which operates over the short spur from Stourbridge Junction to Stourbridge town. As described in section 3.4.4 this energy source is not considered sufficient for longer distances, and requires a further energy conversion (mechanical) when considered in the mix of the other self-power options (chemical and electrical). Indeed, it is considered that the use of electric motors as the traction mover with changeable supply provides the most flexible system.

6.1.6 Class 379 IPEMU

As previously mentioned, Bombardier modified a Class 379 Electrostar unit to operate as an Independently Powered Electric Multiple Unit (IPEMU) in a series of trials on the Great Eastern main line and the Manningtree branch in early 2015. The MOSL vehicle was fitted with six rafts of lithium-iron-magnesium-phosphate batteries with a total mass of eight tonnes to be able run off-wire (Rail Engineer, 2015). The projected performance was to provide a range of 60 miles with a 2-hour recharge required for every hour of operation. To support this requirement the batteries have been designed to provide 500kWh (Bombardier Inc., 2015).

6.1.7 Overseas Examples

There appear to be only a handful of bi-mode designs throughout the rest of the world, the majority of which are electro-diesel multiple units from the likes of Bombardier and Stadler. Some electric-powered locomotives have a ‘last-mile’ capability provided by an auxiliary diesel generator (UK Class 800 EMUs have a single diesel fitted for this purpose) and some American locomotives have been converted to battery operation for shunting functions only.

A single 2-car IPEMU has been built by J-TREC for operation on the Tohoku main line and on the branch to Karasuyama, which has been equipped with a recharging facility. The branch is just less than 16 miles in distance and the unit is fitted with batteries which provide 190 kWh. The EV-E300 series train is shown in Figure 13.

Figure 13 – JR-East battery-powered EMU EV-E300 set V1 at Utsunomiya station (Comyu)

Despite becoming more widespread in the automotive industry, there appears to be only a single example of fuel-cell powered train design which is being built for commercial use. This is a tramcar designed by China South Rail Corporation (now part of CRRC – China Railway Rolling Stock Corporation) for use on the growing number of tram systems being planned in China.

6.2 Technology Options for Analysis

6.2.1 Baseline – EMU Architecture

It will be assumed for the business case analysis that the basic platform for new rolling stock procurement will be a conventional EMU. Units will not be equipped with tilting equipment and will be conventionally bogied (as opposed to articulated formation). It is assumed that for each of the following options, the mass of power equipment and auxiliaries is equally distributed throughout the train:

- 3-car regional option:
    - Mass per vehicle: 40t tare, 50t crush
    - Total train mass: 120t tare, 150t crush
    - Axle load: 10t tare, 12.5t crush
    - Mean power per vehicle: 300kW
    - Total train power: 900kW

- 5-car intercity option:
  - Mass per vehicle: 45t tare, 53t crush
  - Total train mass: 225t tare, 265t crush
  - Axle load: 11.25t tare, 13.25t crush
  - Mean power per vehicle: 400kW
  - Total train power: 2000kW
- 9-car intercity option:
  - Mass per vehicle: 45t tare, 53t crush
  - Total train mass: 405t tare, 477t crush
  - Axle load: 11.25t tare, 13.25t crush
  - Mean power per vehicle: 400kW
  - Total train power: 3600kW

Whereas the volume of additional equipment to enable bi-mode operation is not considered, the mass of the additional equipment will be considered, both in terms of the difference in track access charges and in relation to the maximum axle load. To this end, the maximum axle loads are assumed to be RA1 for the regional units (approximately 13.2t maximum) and RA3 for the intercity units (approximately 16.25t maximum).

6.2.2 Diesel Bi-Mode

Given the movement away from diesel and the increasing level of legislative restriction over the use of diesels, particularly in urban and built-up areas it is considered that new-build diesels would only be acceptable as part of bi-mode architecture. It is assumed for this study that a diesel generator would be acceptable as a modular ‘plug-in’ to the existing EMU power equipment. Whilst directly-sourced manufacturer information is not readily available, there is sufficient speculative information to suggest the following key data for use in the analysis (Railway Gazette, 2012) and these are consistent with industry-used values:

- Regional design:
  - Additional mass per vehicle: 3t
  - Additional CAPEX per vehicle: £0.5M
- Intercity design:
  - Additional mass per vehicle: 5t
  - Additional CAPEX per vehicle: £0.8M

It will be assumed that each vehicle will accrue an additional £50k each year for maintenance over and above that incurred by a standard EMU.

It is assumed that the addition of the diesel generator will directly substitute off-wire for the on-wire power level.

6.2.3 IPEMU (Battery Bi-Mode)

The following assumptions are made for the battery component of the IPEMU architecture:

- The power density of the batteries is assumed to be 100kWh per tonne. The discharge rate may alter the battery size requirement, however this is not considered here.
- The cost of batteries is constantly changing, largely driven by developments in the automotive industry. For a conservative estimate of battery costs by 2040, the assumption will be £100 per kWh.
- It is assumed that the batteries will need replacing every 5 years at the same cost as the initial CAPEX. This is based on a general survey of electric vehicle battery replacements and the general correlation with a general passenger train heavy overhaul periodicity.

The batteries will be assumed to charge at approximately 80% efficiency and will incur EC4T charges equivalent to the time spent running under OLE at the same rate.

6.2.4 Fuel-Cell (Bi-Mode/Hybrid)

Whilst referred to as a bi-mode in that there are two prime energy sources (overhead line and fuel cell), this option is in reality also a hybrid as it will rely on battery storage to boost the power when operating in fuel-cell mode. Based on architecture devised by the University of Birmingham in conjunction with Hitachi and Fuel Cell Systems (Kent, Gunawardana, Chicken, & Ellis, 2016), a viable, hydrogen-based fuel cell system would incorporate batteries to level the supply and demand among traction and braking, and would allow for regenerative braking to be applied. This architecture has been sized for a range of roughly 500 miles and is therefore not limited within the ranges of self-power already calculated for the East Midlands franchise area.

The need to refuel means that there would need to be an infrastructure upgrade to enable refuelling at depot and stabling points. It is considered likely that two such facilities would be needed on the network, although these costs are not included for individual line assessments.

The following assumptions are made based on the University of Birmingham report:

- The mass of the fuel cell system in addition to the existing traction equipment is 3.3t tonnes per vehicle for the regional unit and 4.8t per vehicle for the intercity unit;
- The cost of the fuel cell system is £384k per vehicle for the regional unit and £563k for the intercity unit;
- Infrastructure costs for refuelling is £24.4m for two facilities;
- Fuel operating costs are estimated as 22 pence per vehicle mile;

Note: neither of battery technology nor fuel cell technology is fully converged as yet, and it is likely that the assumptions contained in 6.2.3 and 6.2.4 will need updating on a continual basis in line with technology levels.

6.3 Other Rolling Stock Business Case Inputs

6.3.1 Track Access Charges

To compare track access charges for trains of different masses, the Variable Usage Charge (VUC) calculator issued by Network Rail for Control Period 5 has been used.

For the regional trains, the existing database comparator used is the Class 375 Electrostar, and for the intercity train the Class 395 data has been adopted. A sensitivity analysis of the comparison of rates is contained in Table 12. In each case, the rates from 2014/2015 have been selected and a loaded value of 80 seats per vehicle is used irrespective of train type.

Table 12 – VUC rates for comparator vehicles, pence per vehicle mile

		Base	+1 tonne	+2 tonne	Average difference
Class 375	Motor	8.14	8.40	8.68	0.27
	Trailer	6.03	6.22	6.42	0.20
Class 395	Motor	9.77	10.04	10.34	0.29
	Trailer	9.52	9.80	10.10	0.29

From these values, the track access charge sensitivity to mass additions to the baseline EMU architecture shall be assumed to be 0.24 pence per tonne per vehicle mile for the regional design and 0.29 pence per tonne per .vehicle mile for the intercity design.

6.3.2 Electricity Charges

EC4T charges are based on a set rate for a given unit class per vehicle mile. For this analysis it may be more useful to use the charter rate of absolute blended energy cost, which is taken as being around 11 pence per kWh.

6.3.3 Diesel Fuel Charges

From the 2009 RUS document (Network Rail, 2009) a value of 50 pence per mile per vehicle of diesel fuel is assumed.

6.3.4 Power Demand

From published EC4T data, the three reference trains can be mapped to existing designs by comparison:

- 3-car regional: Class 334 unit, averaged consumption of circa 15.0 kWh / train mile

- 5-car intercity: Class 395 unit, averaged consumption of circa 22.0 kWh / train mile
- 9-car intercity: Class 390 unit, averaged consumption of circa 30.0 kWh / train mile

These values comprise all aspects of power demand including acceleration, constant speed, coasting and regenerative braking input. They are averaged over all routes. For the business case work the changes to these values due to increases in mass or pattern of station stopping will not be enacted in this analysis.

6.3.5 Electrification Costs

Based on the most recent reviews of current electrification projects (Railway Gazette, 2015), the CAPEX cost per mile of single track electrification is estimated as being £1.5M.

Due to the low potential usage on regional lines and the shared usage on intercity lines, there is no OPEX considered for OLE maintenance in this analysis.

6.3.6 General Business Case Assumptions

For simplicity, only the Benefit to Cost Ratio will be used (BCR). This is the DfT preferred measure and it takes into account that much of the investment will be 'sunk', i.e. that there may not be an intrinsic payback as the justification will be societal or economic on a community scale rather than in relation to the railways in isolation. The BCR value acts as a useful comparator for the 'least-worst' case investment for the Government or other funding body.

As such, the following rules are applied:

- Assessment over a 60 year period – assumption is that rolling stock replacement would be equal between options, unlike maintenance or line item replacements, such as batteries, etc.
- On the assumption that the rolling stock is replaced at 30 years, the following replacement / maintenance assumptions are made:
    - Diesel engine overhaul / maintenance, ½ of the CAPEX value every 10 years;
    - New diesel (and full CAPEX) required at the 30 year mark for the delta in new rolling stock costs;
    - Battery replacement at full CAPEX every 5 years;
    - Based on an assumption of the fuel cell stack power-draw life of 20 – 25,000 hours, it is estimated that replacement of this component will be every 5 years. FCEMU batteries will be replaced at the same interval. The stack costs are estimated as £17.5 per kW (Markinkoski, Spendelow, Wilson, & Papageorgopolous, 2015).
    - The hybrid system contains a battery pack for peak load which boosts the output of the fuel cell under traction and stores regenerated braking energy.

The battery size is assumed as 20kWh per vehicle for the regional unit and 30kWh per vehicle for the intercity unit, based on previous battery sizing calculations (Kent, Gunawardana, Chicken, & Ellis, 2016).

- The discount rate applied is 3.5% for the first 30 years with 3.0% being applied thereafter. This is in accordance with UK Government guidelines (H M Treasury, 2003).

7 Business Case Analysis

7.1 Financial Methodology

The raw costs elicited from the technology options and other inputs considered in sections 6.2 and 6.3 are contained in Table 13.

Table 13 –Business Case Input Data Summary

Electrification Costs		
Electrification CAPEX	1.5	£m/mile
EC4T	0.11	£/kWh
Electricity consumption		
Regional	15	kWh / train mile
5-car IC	22	kWh / train mile
Electricity Costs		
Regional	1.65	£/train mile
5-car IC	2.42	£/train mile
Power requirement		
Batter power density	100	kWh / tonne
Battery CAPEX	100	£/kWh
Diesel CAPEX		
Regional	1.5	£m/train
5-car IC	4	£m/train
Diesel OPEX delta		
Regional	0.15	£m/train/year
5-car IC	0.25	£m/train/year
Diesel fuel		
Regional	1.5	£/train mile
5-car IC	2.5	£/train mile

VUC delta		
Regional	0.0024	£/tonne/ mile
5-car IC	0.0029	£/tonne/ mile
Fuel cell CAPEX		
Regional	1.15	£m/train
5-car IC	2.82	£m/train
Fuel cell fuel costs		
Regional	0.66	£/train mile
5-car IC	1.1	£/train mile
Stack Replacement costs		
Regional	13.1	£k/train
5-car IC	29.4	£k/train
FCEMU Battery costs		
Regional	6.0	£k/train
5-car IC	15.0	£k/train
Fuel cell station CAPEX	12.2	£m

Four possible solutions are considered with the costs and / or cost deltas calculated in each case:

- Electrification: CAPEX is based on a direct application of the £1.5m per track mile, assumed to take place over two years. Most areas are double-tracked, with the exception being the Barton-on-Humber branch. No sidings or S&C have been considered. The delta in OPEX is simply the additional EC4T incurred on the electrified section;
- Diesel bi-mode: The CAPEX is the delta in cost for the diesel generators incurred in the first year, at train build. This is repeated at year 31 and the assumed rolling stock replacement. OPEX costs include the additional maintenance costs, the fuel on the non-electrified section and the track access charge (VUC) delta for the additional mass being carried for the whole of the route. No penalty is incurred for the direct environmental impact;
- IPEMU (battery bi-mode): The CAPEX is based on the battery sizing calculation, which is based on the longest distance operating in self-power mode. The OPEX

consists of the VUC delta of the additional mass and the equivalent EC4T charges for the battery recharge, calculated at 80% of the efficiency as if the train were operating under the wires.

- FCEMU (fuel-cell bi-mode): CAPEX includes the initial delta in the technology needed for new trains, repeated after 30 years, plus the one-off fuel point installation. It is assumed in the first instance that this cost is needed for each route, although the effects of sharing an installation are considered in the narrative analysis. OPEX costs are the fuel consumption and the VUC delta for the additional mass.

As a worked example, the data input table for the St Pancras to Scarborough route is shown in Table 14. All values are in £m except where stated. The route mileages are taken from Table 7 and Table 9. These are multiplied up by the trains per hour (both directions) and are assumed to operate for 18 hours per day and 360 days per year. The CAPEX and OPEX expenditure is calculated for each case and the annual costs are tabulated in Appendix C. These costs can then be compared in a discounted benefit / cost ratio for each of the comparative scenarios.

The initial presumption is that electrification is the default option. Each of the diesel bi-mode, IPEMU and FCEMU options are then compared with the electrification 'costs' considered as benefits as the option to not spend in the first instance. Further, diesel is then used as the next default and compared with IPEMU and FCEMU options. Finally, the IPEMU costs are considered as the benefits when compared with the FCEMU costs.

Continued/

Table 14 –St Pancras to Scarborough route input table, cost units in £m

Route	**St Pancras - Scarborough**
Trains per hour, per direction	1
Fleet size	9
Electrified miles, per direction	226.83
Non-electrified miles, per direction	42.06
Annual electrified train miles	2939717
Annual non-electrified train miles	545098

Electrified option

Electrification CAPEX	**126.2**
EC4T delta, annualised	**1.32**

Diesel option

Diesel fleet CAPEX	**36.0**
Diesel maintenance	2.25
Diesel fuel, annualised	1.36
Additional train mass (tonnes)	25.00
Deisel VUC delta, annualised	0.25
Deisel OPEX, annualised	**3.87**

Battery option

Self-power requirement / kWh	1851
Battery size needed / tonnes per train	18.5
IPEMU fleet CAPEX	**1.67**
Battery VUC delta, annualised	0.19
Battery charging (EC4T/80%)	1.65
IPEMU OPEX, annualised	**1.84**

Fuel cell option

Fuel cell train fleet CAPEX	25.3
Fuel cell fuel point CAPEX	12.2
FCEMU CAPEX	**37.5**
Fuel cell fuel	0.60
Additional train mass (tonnes)	24.0
Fuel cell VUC delta, annualised	0.24
FCEMU OPEX, annualised	**0.84**
Fuel Cell Stack Replacement Cost	0.26
Battery Replacement Cost	0.14

An example of the calculation comparing the discounted cashflows resulting in the Benefit to Cost Ratio (BCR) is shown in Appendix D. Each of the BCRs in the following sections are calculated in the same way.

7.2 Options BCRs

7.2.1 Intercity Options

7.2.1.1 St Pancras – Scarborough

	Diesel	IPEMU	FCEMU
Electric	1.04	2.73	2.58
Diesel		2.63	2.49
IPEMU			0.95

The BCRs show that diesel is marginally better value than electrification, but far better value from the IPEMU and FCEMU options. If the number of trains per hour were increased to two, electrification wins out over diesel and improves in comparison to the IPEMU but still loses out to FCEMU by a value of 2.31. IPEMU is marginally better at 1 train per hour, but FCEMU is a clear winner at a value of 1.29 if this increases to 2 tph. As the track is predominantly used by TPE, there is an argument that sharing of costs between the franchises might promote electrification, however the number of trains needed to justify the electrification CAPEX would be of a metro nature rather than the occasional trains operating on the York to Scarborough section.

7.2.1.2 St Pancras - Barnsley

	Diesel	IPEMU	FCEMU
Electric	0.55	2.98	1.23
Diesel		5.39	2.24
IPEMU			0.41

The short stretch of non-electrified line between Sheffield and Barnsley demonstrates the paucity of the argument for diesel traction, and the option to electrify is close to that of the FCEMU, mainly as a result of the comparable levels of CAPEX for each. In this case the IPEMU clearly wins out. The route between Sheffield and Barnsley is reasonably busy and there is potential for a sharing of the electrification CAPEX with the Northern franchise area. However the BCRs come level only when traffic reaches 6tph or more. In addition, all of the Northern services between Sheffield and Barnsley travel north to the likes of Leeds and Huddersfield, and may therefore be difficult to justify in their own right. Therefore the IPEMU remains the optimum choice for this route.

7.2.1.3 St Pancras - Lincoln

	Diesel	IPEMU	FCEMU
Electric	1.18	3.00	2.69
Diesel		2.54	2.28
IPEMU			0.90

On this route the IPEMU and FCEMU options are close in terms of value, both outperforming the electrification and diesel options. Sharing the electrification CAPEX with the regional service reduces the IPEMU and FCEMU BCRs to around just over 1, so there may be a case for electrification. However, under current assumptions the final choice the ICEMU is marginally better than the FCEMU, however if the fuel point costs were to be shared the FCEMU BCR wins with a values of 1.11.

7.2.1.4 Lime St - Norwich

	Diesel	IPEMU	FCEMU
Electric	1.30	1.96	3.51
Diesel		1.51	2.70
IPEMU			1.79

This route clearly favours the FCEMU option, with the constant ‘on-off’ nature of the wiring incurring a large re-charge OPEX for the IPEMU. Interestingly this is the worst-case for the IPEMU in terms of the battery mass needed, at 4.4 tonnes per vehicle. However this is still within the estimated mass of the fuel cell equipment. Nevertheless, the FCEMU is clearly the option for this cross-country route.

7.2.2 Regional Options

7.2.2.1 Nottingham – Worksop

	Diesel	IPEMU	FCEMU
Electric	1.98	2.67	3.82
Diesel		1.35	1.93
IPEMU			1.43

As a route with little proposed electrification, the diesel option has a BCR of nearly 2.0, although it is questionable as to whether a bi-mode would be worthwhile for the 0.8 miles of usage in each route direction. The IPEMU option is optimistic as the layover time at Nottingham to recharge would incur an increase in the fleet numbers. However, the whole life cost of, say doubling the fleet size is still significantly preferable to electrification. Irrespective of this, the FCEMU is the preferred option.

7.2.2.2 Derby – Crewe

	Diesel	IPEMU	FCEMU
Electric	3.33	4.77	5.05
Diesel		1.43	1.52
IPEMU			1.06

With electrification at both ends of the route, and a substantial proportion of the route electrified at one end, the IPEMU is a strong performer, however it marginally loses out to the FCEMU. Given that an increase in traffic substantially increases the margin of benefit of the FCEMU, it would appear that this is the preferred option. However, Derby is currently not a strategic location for re-fuelling infrastructure and IPEMU may have to be considered unless the service is extended to Nottingham, as occurred in the past.

7.2.2.3 Leicester – Lincoln

	Diesel	IPEMU	FCEMU
Electric	3.91	4.66	5.15
Diesel		1.19	1.32
IPEMU			1.11

With 50% of the route electrified, it is perhaps a surprise that the diesel option appears so strong in comparison to electrification. As discussed in section 7.2.1.3, the sharing of electrification CAPEX does not help the business case significantly. This leaves a marginal competition between IPEMU and FCEMU with the fuel cell option apparently winning out. An increase in traffic significantly increases the comparative value of the FCEMU. Further, sharing of the fuel-cell fuelling point CAPEX – such as with the St Pancras service – conclusively changes the BCR to 2.07 in favour of the FCEMU.

7.2.2.4 Nottingham – Skegness

\	Diesel	IPEMU	FCEMU
Electric	3.89	4.34	7.72
Diesel		1.11	1.98
IPEMU			1.78

As per the Worksop service, the small amount of electrification provides a strong case for the diesel option, although the FCEMU is clearly the preferred option with a BCR of almost 2.0 over the diesel option. The IPEMU is stretched in terms of the distance, and would require an additional 8 tonnes of equipment per vehicle. This would put the train into RA2, and almost RA3 which would be severely restrictive for a regional multiple unit.

7.2.2.5 Nottingham – Matlock

	Diesel	IPEMU	FCEMU
Electric	1.17	4.60	1.44
Diesel		3.93	1.23
IPEMU			0.31

The large portion of electrification clearly favours the IPEMU. The FCEMU beats electrification by only a moderate amount in this case. Even if the fuel-cell fuelling point CAPEX was shared with other routes, the BCR would not come close to challenging that of the IPEMU.

7.2.2.6 Newark Northgate – Grimsby

	Diesel	IPEMU	FCEMU
Electric	3.83	4.37	6.93
Diesel		1.14	1.81
IPEMU			1.59

This sparsely electrified route clearly favours the FCEMU, and again, the battery mass required for the IPEMU is significant, although not as much as for the Skegness route.

7.2.2.7 Peterborough – Doncaster

	Diesel	IPEMU	FCEMU
Electric	3.70	4.24	7.71
Diesel		1.15	2.08
IPEMU			1.82

Whilst this route has electrified portions at each end of the route, the level of coverage is not sufficient to enable the IPEMU to match the FCEMU, and the long non-electrified distances require heavy battery sets.

7.2.2.8 Cleethorpes – Barton on Humber

	Diesel	IPEMU	FCEMU
Electric	1.76	3.58	2.81
Diesel		2.04	1.60
IPEMU			0.78

None of this route is electrified or scheduled to be electrified. Therefore the apparent success of the IPEMU is somewhat disingenuous. At the very least there would need to be a significant charging point at one end of the route. Given that the route shares a good portion of mileage with the Newark to Grimsby route, there might be a case for sharing electrification CAPEX over some of the shared mileage. However this does not improve the Newark to Grimsby business case significantly and the FCEMU is the most feasible option.

7.3 Lowest-Cost Solution

A summary of the power options considered against each of the relevant routes is as shown in Table 15 for the intercity services and

Table 15 – Preferred power option by route: intercity services

Route	Power Option
St Pancras – Corby	Fully Electric
St Pancras – Nottingham	Fully Electric
St Pancras - Sheffield via Derby	Fully Electric
St Pancras – Leeds	Fully Electric
St Pancras – Scarborough	IPEMU
St Pancras – Barnsley	IPEMU
St Pancras – Lincoln	IPEMU
Liverpool – Norwich	FCEMU

Table 16 – Preferred power option by route: regional services

Route	Power Option
Nottingham – Worksop	FCEMU
Derby – Crewe	FCEMU
Leicester - Lincoln Central	FCEMU
Nottingham – Skegness	FCEMU
Nottingham – Matlock	IPEMU
Newark Northgate – Grimsby	FCEMU
Peterborough – Doncaster	FCEMU
Cleethorpes - Barton on Humber	FCEMU

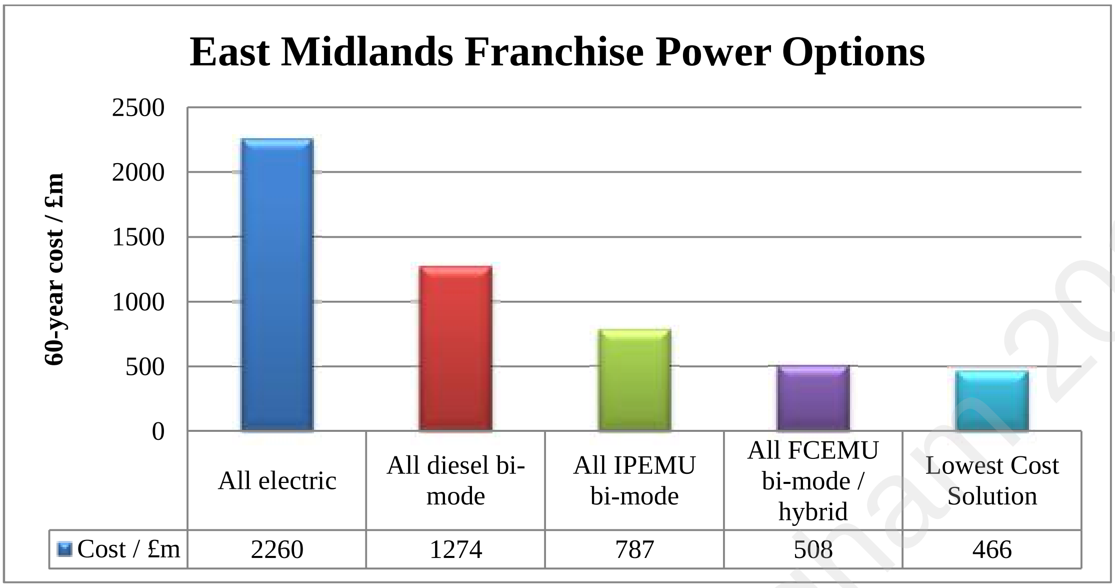
Clearly, there are savings to be made by sharing the fuel-cell fuelling point costs. These might be best based at an existing maintenance facility, of which the current East Midlands franchise has the following:

- Cricklewood – shared stabling point north of St Pancras
- Nottingham Eastcroft – DMU running maintenance depot
- Derby Etches Park – DMU and HST running maintenance depot
- Leeds Neville Hill – HST heavy maintenance depot
- Norwich Crown Point – shared light maintenance depot
- Boston – stabling point
- Crewe Works – occasional light maintenance

Based on the services which would be FCEMU operated, a clear choice for one of the fuelling points is at Nottingham. This could potentially serve the Worksop and Skegness routes, and is on the routes for the Lincoln services and the Liverpool – Norwich service although each of these would have to be broken to enable refuelling to occur. A fuelling point at Cricklewood could serve the services from St Pancras, although having the fuelling point further north, such as Leicester, would enable more fuelling options for the regional services. Whilst the fuelling of the services originating in Newark could be facilitated by either an ECS move or a marginal service originating in Nottingham, the ECS moves required for the Peterborough – Doncaster and the Cleethorpes – Barton on Humber might be excessive. A further fuelling point at Lincoln could service trains of up to five different routes and would reduce ECS moves with only the Cleethorpes – Barton on Humber trains needing to move off diagram to be refuelled. However, fleet rotation would mean that units would move from diagram to diagram and fuelling would be carried out at a more optimum juncture. The third fuelling point would also provide network resilience should there be an issue at any of the other fuelling points.

It is therefore considered that three fuelling points would be necessary for the FCEMU portion of the fleet. The whole-life cost over 60 years for the FCEMU fleet as calculated on a route by route basis is £527m. However, when the capital costs for the fuel point installations are reduced to three (instead of one per FCEMU route), the whole-life cost comes down to £508m. The lowest cost option is a mixture of IPEMU and FCEMU services with a whole-life cost of £466m. The comparison of this with other option costs is shown in Table 17.

Table 17 – Whole life cost for each option and the lowest cost solution



The lowest cost solution is therefore marginally more cost effective than an all FCEMU solution and in theory offers the optimum power solution to fill the electrification gap. The fleet composition based on the above results would therefore be as shown in Table 18.

Table 18 – East Midlands Franchise area – optimum fleet composition

Intercity	Trains	Vehicles
5-car fully electric	5	25
9-car fully electric	26	234
5-car IPEMU	21	105
5-car FCEMU	21	105
Regional	**Trains**	**Vehicles**
3-car IPEMU	3	9
3-car FCEMU	29	87

7.4 Analysis Observations

The following observations are made in relation to the nature of the analysis:

- Clearly, in relation to the parameters that have been fixed and those that are variable, the output of the BCR model depends largely on the extent of existing electrification, and the number of trains operated per hour;
- The CAPEX costs weigh heavily against the electrification baseline, as demonstrated by the lack of route options which come close to justifying extension of the proposed electrification coverage;

- The diesel bi-mode option is also not a strong performer when compared to the IPEMU or FCEMU options, mainly due to the heavy OPEX costs of diesel fuel and additional maintenance attention. The CAPEX is large but not prohibitive, and reducing the purchase values do not improve the BCRs to the extent where diesel would out-perform either of the other non-electrified options on the East Midland routes;
- The IPEMU option is a favourite where there is a significant existing electrification coverage, mainly due to requiring a low level of CAPEX;
- On all other routes, the FCEMU is the preferred option due to the cost-efficiency of the fuel and the assumption that the equipment will remain relatively maintenance-free during the life of the rolling stock.

In terms of identifying the final fleet solution, it is observed that there is a deficiency in the assumptions that may result in a deviation from the mix of IPEMU and FCEMU units. Whilst the saving of £100m over 60 years might appear attractive, operators are known to favour homogenous fleets for the following reasons:

- Simplicity of operation – it doesn't matter which unit operates on a particular route, and it matters less where units end up at the end of a day in terms of the start positions for the next day;
- Simplicity of maintenance operations – in terms of depot equipment provision, spares, maintenance and overhaul procedures and periodicities, etc;
- Reduction of complexity for drivers and operational staff.

It should also be recognised that the economies of purchasing a single large fleet over that of two smaller fleets is attractive, particularly to the financing body. It should also be noted that the operational timetable can be optimised with a single fleet to ensure that the overall fleet size could be reduced. The CAPEX reduction on these two points might be enough to persuade government and potential operators that a single-technology solution may actually be the optimum for the East Midlands franchise area.

Note on freight: whilst fuel cells in freight applications has been limited to shunting and switching locos to date (Bush, 2009), studies have already considered the potential for fuel cells to be used in long distance freight hauling operations (Zenith, Møller-Holst, & Thomassen, 2016). There are several key streams of freight which pass through the East Midlands franchise area (Swlines Ltd, 2016):

- West Midlands – North Lincolnshire, approx 23 trains per day in each direction
- West Yorkshire – South East, approx 50 trains per day in each direction
- West Midlands – Felixstowe and East Midlands aggregate fields, approx 80 trains per day in each direction

The inclusion of benefits for freight could be studied in future, noting the following:

- Fuel cell infrastructure costs could be further amortised
- The West Yorkshire – South East service are likely to be fully electrified as part of the Electric Spine objective
- The function of Toton as a core locomotive depot should be assessed in some depth

The benefits to freight alone should be assessed in the first instance, although it should be noted that the passenger route BCRs for the different options may be changed by the incorporation of freight benefits.

7.5 Areas for Improving the Analysis

Whilst the BCR comparison model appears to provide consistent results and is robust to sensitivity testing, the assumed inputs are largely taken at face value and some parameters might benefit from a 'bottom-up' approach or a more diverse set of empirical data where possible. In addition, the operational aspects of the railway have been simplified and the analysis could be refined by a deeper consideration of the overall operational concept. Finally, the number of costs and benefits of each option have been reduced to those which are immediately tangible and this may have a significant effect – particularly in respect of electrification.

These three areas are considered in more detail in the following sections.

7.5.1 Parameter Accuracy

Electrification costs: for the purposes of this study, the latest and possibly most pessimistic rate of electrification per mile has been used. This is an aggregated value and comes from the overall project costs for GWEP. Given that this project is the first large-scale project in the UK for almost two decades it is possible that marginal costs might reduce through operational efficiency and project experience, particularly if the follow-on schemes occur in rapid succession. In addition, the technical problems and specifications to do with the task of erecting electrification masts and the necessary wiring have a significant effect on the overall costs. The assumptions can be improved by a more in-depth study into actual costs and trends in costs throughout the existing programme(s).

Energy consumption: The energy consumption values have been largely simplified and take no true account of the speed profiles of the units involved, other than in an aggregated manner. Train performance modelling would greatly improve the accuracy of these values. In particular, there is no facility to understand the increase in EC4T charges as a result of increases in mass. Therefore the IPEMU and FCEMU cases benefit unfairly from this aspect.

Auxiliary power: no separate account of power for auxiliaries has been made. Given the propensity for trains to need more 'hotel' power for facilities such as HVAC, WiFi and other modern technologies, and that the trains currently being replaced currently do not have such facilities it would be sensible to take some account of this in the overall energy consumption calculations.

Mass & effects: train masses have been averaged over several vehicles whereas individual vehicles can have very different masses depending on where key equipment is located. This effect may not be significant in term of business case value assumptions, however it should be explored to understand how critical it might be to individual axle loads. In addition, with the advent of new train designs for the likes Thameslink and CrossRail, it is anticipated that the overall mass of vehicles may reduce in the future. Given that the analysis is based on a comparison between similar train architectures, the overall effect of reducing the base vehicle mass may be negligible. However there may be nuances in how the track access charging changes in the future, and there may be non-linearities in the differences between lighter and heavier trains. In addition, VUC is a simplification of other valuing calculations such as VTISM. A sensitivity test should be conducted to establish how each of these factors may change the OPEX costs.

Battery sizing: The sizing of the batteries is simplified on several levels:

- The sizing has been carried out for each route. In reality a manufacturer would build for the worst-case, which would worsen the business case on routes where the battery requirement was small than that which was installed;
- Battery technology is constantly evolving, and the sizing assumed from studies today may be pessimistic compared with what might be available in 20 – 30 years;
- There is no consideration of the charge window within which the batteries are operating and no account taken of the reduction in battery charging effectiveness over time, other than through replacement.

A study in this area would assist the refinement of the battery assumptions.

7.5.2 Operational Concept Refinement

The operational concept within the study is highly simplified and takes no real account of through-working, ECS mileage (this is particularly important when considering fuel point locations), peak hour train lengthening and changes to the hourly timetable, or seasonal timetable changes. Use of a shadow operating timetable may provide more accuracy in terms of the fleet numbers required and annual mileages. However, this is a substantial task and a feasibility study into the overall benefit from this level of input work should be carried out in the first instance.

7.5.3 Strategic and Economic Business Case Considerations

The electrification case is weakened in contrast to the other options in the followings ways:

- As stated in section 1.4, the 'sparks effect' has not been considered, in that the additional revenues from passengers apparently attracted simply through the presence of electrification. Due to the lack of operational experience, it is not yet understood as to whether or not this effect could be conferred to the IPEMU and FCEMU solutions due to their 'part-electric' nature and the departure from noise and pollution aspects surrounding diesel traction;
- There is no EC4T disbenefit for heavier trains, as previously discussed, due to the aggregated nature of the values used;
- There is no consideration of the overall carbon efficiency of each process. Clearly, a fully electric train is the most efficient in this case, there being only two main energy conversion process: chemical (coal & gas) / mechanical (wind & wave) / nuclear → electricity → mechanical (traction). IPEMU has additional conversion processes to electro-chemical and back, whilst FCEMU has some other form of process to create and transport the stored hydrogen. The simplicity of power conversion in electrified train operation has an inherent carbon efficiency which should be monetised an input to the business case.

There are shortcomings in the assumptions around the FCEMU option, notably the simplification of the fuel-cell architecture which is considered as a single component for the sake of the analysis. In reality there are a number of key components such as batteries, hydrogen tanks, conduits and heat exchangers (Kent, Gunawardana, Chicken, & Ellis, 2016), each of which may require replacement or refurbishment at different points during the overall lifecycle to the fuel cells themselves. A detailed analysis of the relative lives and replacement costs of the different elements should be included in further versions of the analysis.

A significant shortcoming in the IPEMU and FCEMU assumptions is the lack of operational experience for either option. All inputs are based on limited data and in some cases, unverified estimates. In the coming years there will be more trials from which information and data should be reviewed to refine the assumptions contained in the analysis.

There is no strategic case definition in respect to the analysis. The assumption of passenger growth is very simplistic and not related to other factors such as future fuel availability (including grid-supplied electricity) demographic and economic drivers. Projecting so far ahead is difficult to do with high levels of confidence, but a more thorough consideration of all of the factors would be appropriate to a wider industry analysis.

In some of the cases described above, it may be difficult to accurately or reliably estimate the associated costs or benefits. It may also be problematic in determining whether or not a cost or benefit can truly be gained or incurred. It is therefore important in the first instance to compile a matrix of all of the above parameters and consider the feasibility of pursuing a more refined value on a case by case basis.

8 Conclusions

8.1 Findings

The following findings have been made as a result of the work contained herein:

- State of network / fleet today: The electrification of railways is a preferred state of technology due to performance, whole life cost, and the environmental sustainability of the power usage at the point of use. A lack of consistent policy surrounding electrification and the capital expenditure required has resulted in only a third of the GB network being electrified to date. A recent recognition of the need to electrify more of the core routes has resulted in several large-scale programmes now in progress, although escalating costs have delayed the implementation of these schemes, and future schemes may be in doubt. The traffic density on the electrified routes means that by the completion of the schemes in progress, two-thirds of all passenger trains and three-quarters of all passenger vehicles will be electric-powered by the mid 2020s. This still leaves around 3,000 passenger vehicles requiring some form of self-power if GB services are to be maintained at present levels. The prime mover in all cases presently is diesel engines.
- Issues around diesel usage: recent research has laid the blame for increasing levels of pollution in busy conurbations with diesel emissions. Coupled with ever-tighter legislation around new diesel procurement, it is reasonable to assume that by 2040 – 2050 (a time by which the current fleets of vehicles being procured will be at or approaching end-of-life) it will be difficult to justify the use of diesel in urban and city areas. The imminent arrival of the bi-mode IEP will herald the arrival of a train which can operate electrically under the wires in and around London, and wherever the main electrification extends to, and then continue under diesel power in less built-up areas with no electrification. This model of bi-mode operation is considered to be a strong option in the bid to reduce diesel emissions whilst avoiding large capital expenditure;
- Output of franchise area analysis: the GB network has been reviewed by passenger rail franchise area in relation to the existing and planned extent of electrification. The output of the review has been to assess to what extent the particular area has a gap in electrification or rolling stock future options. The results show the following groupings:
  - Areas with no gap:
    - London and South Eastern
    - London, Tilbury and Southen
    - Merseyrail
    - London Overground

- Areas with minor gaps:
  - TSGN (Thameslink, Southern and Great Northern)
  - London and South Western
  - East Coast Main Line
  - West Coast Main Line
  - TransPennine
- Areas with moderate gaps:
  - Great Western
  - London Midland
  - Greater Anglia
  - Northern
- Areas with considerable gaps:
  - Chiltern
  - ScotRail
  - Wales
  - Cross Country

One franchise area – Midland Main Line and East Midland Regional – was considered as having a substantial gap, and this area was chosen for detailed analysis. The eight areas either with moderate or considerable gaps demonstrates the potential for disruption should the continuity of diesel traction be affected;

- <u>Power options</u>: alongside diesel, two other technologies have emerged which provide a realistic alternative for inclusion in bi-mode options:
  - Battery clusters which provide traction power when on non-electrified track and recharge when the unit is back under the wire. The Independent Powered Electric Multiple Unit (IPEMU) has recently been trialled with a Class 379 conversion;
  - Fuel cells which provide the traction power on non-electrified sections. The fuel is hydrogen (with clean emissions), and the projected range of the trains without refuelling is several hundreds of miles. Whilst the Fuel Cell Electric Multiple Unit (FCEMU) has not to date been used in main line operations in the UK, fuel cells have long been used for buses and upcoming projects such as that of the collaboration between Alstom and Hydrogenics (Hydrogenics, 2015) for regional commuter trains should be monitored and scrutinised in depth.
- <u>Business case outline</u>: the routes that make up the East Midlands franchise area have been reviewed in relation to the extent of electrification following the projected main line programme due to be complete sometime around 2023. Each service route has then been assessed for the length and proportion of electrified and self-powered

operation. The fleet size for each route has been calculated and the CAPEX and OPEX costs have been estimated for each of a fully electrified baseline case, a diesel bi-mode case, a IPEMU case and a FCEMU case. The costs have been projected and discounted over a 60 year period to inform comparisons between the options, effectively producing benefit to cost ratios (BCRs) to inform the strength of each option;

- Business case results: the output of the business case analysis can be summarised as follows:
  - Electrification of the gaps is difficult to justify due to the CAPEX costs;
  - The diesel bi-mode option is sometimes weaker than and sometimes stronger than the electrification case, but the OPEX costs are high by comparison with any of the other options;
  - IPEMU wins out where the majority of the route is electrified;
  - FCEMU is the best option when there is a small amount of the route electrified;
  - The optimum solution for the East Midlands franchise therefore is a mixture of wholly-electrified units (where the full extent of the route is covered), IPEMU units and FCEMU units. However, operational efficiencies may lead to a more homogenous nature to the fleet, in which case FCEMU would be the preferred option.

The comparison model appears robust to sensitivity changes. However the simplifications in the assumptions and base costs have been indentified and present an opportunity to enhance the analysis prior to using this methodology on other franchise areas.

The key message however is that diesel is likely not to be the optimum solution in the future of the railway from a business case perspective and independently of the issues regarding pollution and environmental sustainability. The difference between full electrification and the FCEMU / IPEMU options is significant, but does not take into account demand change associated with the so-called 'sparks effect'.

The key finding of the work contained herein is that the analysis suggests that there are substantial whole life cost savings to be made by considering alternative power, including bi-mode battery and fuel cell options.

8.2 Recommendations

The key recommendation is that this initial study be developed into a full business case for consideration by the Department for Transport and other industry stakeholders for inclusion into policy and franchise scopes:

- The business case analysis should be refined in the following ways:

  - Use of 'bottom-up' electrification capital costs
  - Use of modelling to better inform the energy consumption of the different power options
  - Take account of auxiliary power and the increasing demands through the diversity of trains systems requiring electrical power
  - Better estimations of future train mass based on trends in recent and existing fleet designs. This can be used to better estimate power consumption and track access charge differences between the options
  - Investigation into the accuracy and sensitivities of VUC as the track access charging model in preference to VTISM or other models
  - More accurate battery sizing estimates
  - The operational concept could be modelled, using operating timetables and understanding seasonal changes, working efficiencies
  - The strategic and economic business cases in favour of electrification should be better studied to establish an input which is missing from the current analysis
  - The carbon efficiency of all options should be considered
- Any forthcoming trials using either IPEMU or FCEMU architectures should be closely monitored to determine improvements to the business case assumptions and the corresponding base values. Further, information should be gleaned from other applications which are using batteries and fuel cells. The FCEMU architecture should also be considered in more detail, given the simplifications contained in the analysis herein;
- Discussions should be held with the likes of DfT, NR, RSSB, ROSCOs, TOCs and train suppliers. The discussions should be allowed to test the understanding and the assumptions made in the analysis, whilst ascertaining if there are more accurate values to hand within any of the entities.
- Once refined, the analysis should be promulgated to the other franchise areas, particularly those considered to have a moderate or considerable energy and rolling stock gap in the future.
- Consideration should be given as to how the analysis could be used to assess the future of other GB rail users such as freight operators, open access operators and those currently excluded from the analysis.

The outcome of the wider analysis could then be used to inform future power strategy for all stakeholders in the GB railway industry.

8.3 Word Count

There are 23,340 words between sections 1 (Introduction) and 8 (Conclusions).

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10 Appendix A – Existing GB Rolling Stock

Class / train formation	No of trains	No of vehicles	Train type	Operating type	Notes
121	Not considered				1st generation vehicles used for driver training
139	Not considered				Limited application - not influential
142	94	188	DMU	Suburban	
143	23	46	DMU	Suburban	
144	23	56	DMU	Suburban	
150	137	278	DMU	Suburban	
153	70	70	DMU	Mid-distance	
155	7	14	DMU	Mid-distance	
156	114	228	DMU	Mid-distance	
158	164	349	DMU	Mid-distance	
159	30	90	DMU	Mid-distance	
165	75	177	DMU	Suburban	
166	21	63	DMU	Mid-distance	
168	19	71	DMU	Mid-distance	
170	122	332	DMU	Mid-distance	
171	16	44	DMU	Mid-distance	
172	39	93	DMU	Suburban	
175	27	70	DMU	Mid-distance	
180	14	70	DMU	Intercity	
185	51	153	DMU	Mid-distance	
220	34	136	DEMU	Intercity	
221	43	214	DEMU	Intercity	
222	27	126	DEMU	Intercity	
313	63	189	EMU	Suburban	1 set in departmental use - not counted here
314	16	48	EMU	Suburban	
315	61	192	EMU	Suburban	
317	72	288	EMU	Mid-distance	
318	21	63	EMU	Mid-distance	
319	86	344	EMU	Mid-distance	
320	22	66	EMU	Mid-distance	
321	117	468	EMU	Mid-distance	
322	5	20	EMU	Mid-distance	
323	43	129	EMU	Suburban	
332	14	61	EMU	Mid-distance	
333	16	64	EMU	Mid-distance	
334	40	120	EMU	Mid-distance	
350	87	348	EMU	Mid-distance	Mixture of high a medium density seating
357	74	296	EMU	Mid-distance	
360	26	109	EMU	Mid-distance	

Class / train formation	**No of trains**	**No of vehicles**	**Train type**	**Operating type**	**Notes**
365	40	160	EMU	Mid-distance	
373	Not considered				Eurostar operations not considered in this study
374	Not considered				Eurostar operations not considered in this study
375	112	438	EMU	Mid-distance	Mixture of high a medium density seating
376	36	180	EMU	Suburban	
377	239	946	EMU	Mid-distance	Mixture of high a medium density seating
378	57	285	EMU	Suburban	
379	30	120	EMU	Mid-distance	
380	38	130	EMU	Mid-distance	
387	64	256	EMU	Mid-distance	Excludes C2C and speculative orders (20 units)
390	56	574	EMU	Intercity	
395	29	174	EMU	Intercity	Arguable classification, but high-speed, therefore Intercity
442	23	115	EMU	Mid-distance	
444	45	225	EMU	Mid-distance	
450	127	508	EMU	Mid-distance	1 unit off-lease - not counted
455	137	548	EMU	Suburban	
456	24	48	EMU	Suburban	
458	36	180	EMU	Mid-distance	
465	147	588	EMU	Suburban	
466	43	86	EMU	Suburban	
483	Not considered				
507	32	96	EMU	Suburban	1 set scrapped - not counted
508	28	84	EMU	Suburban	15 sets scrapped - not counted
HST	94	745	Diesel-hauled	Intercity	NMT not included
MkIII Loco-hauled (AGA)	15	130	Electric-hauled	Intercity	
MkIII Loco-hauled (Chiltern)	6	31	Diesel-hauled	Intercity	
MkIII Loco-hauled (ATW)	3	12	Diesel-hauled	Intercity	
Sleepers	Not considered				Can be both electric and diesel-hauled - not influential
IC225	31	302	Electric-hauled	Intercity	

11 Appendix B – Network Rail RUS Identified Electrification Gaps

Four types of gap were in the existing electrification network, refined down from the 60% of track miles currently non-electrified:

- Gaps which the filling of which would allow for more efficient passenger services:
  - Great Western Main Line;
  - Midland Main Line;
  - Transpennine routes, principally between Manchester and York;
  - North Manchester suburban routes;
  - Thirsk - Sunderland;
  - Leeds – Harrogate - York;
  - London and South Western mainline to Exeter / Weymouth via Salisbury (i.e. from Basingstoke);
  - The Cardiff Valley Lines to Rhymney, Merthyr Tydfil, Aberdare and Treherbert;
  - Chiltern Main Lines from Marylebone to Aylesbury and Birmingham Moor Street;
  - Welsh Marchers route from Newport to Crewe / Chester;
  - Cross Country in-fills: Derby – Birmingham, & Banbury to Birmingham;
  - Nottingham – Lincoln;
  - North Wales route from Crewe to Holyhead;
  - Glasgow – Kilmarnock;
  - Falkirk Circle from Edinburgh to Dundee and Perth;
  - Perth – Aberdeen and Inverness;
  - Ashford – Hastings;
  - Oxted – Uckfield;
  - Reading – Redhill;
  - Marks Tey – Sudbury;
  - Ely – Norwich;
  - East Suffolk / Norfolk lines from Norwich to Lowestoft and Great Yarmouth.
- Gaps which currently prevent more efficient freight services, or alternative routes to those currently operated:
  - Felixtowe – Birmingham ham via Peterborough & Leicester;
  - Peterborough – Doncaster via Lincoln;
  - Coventry – Nuneaton;
  - Nuneaton – Rugeley via Walsall;

  - Bedford – Oxford;
  - Nottingham – Stoke via Castle Donnington
- Diversionary capability for existing electrified routes, or those core routes which are anticipated to be electrified in the near future;
  - Newcastle – Carlisle (allows ECML – WCML interchange);
  - Stockton – Durham avoiding Darlington;
  - Chesterfield – Rotherham avoiding Sheffield;
  - Colton Jn – Moorthorpe;
  - Pontefract – Doncaster;
  - Leeds – Castleford – Woodford – Pontefract;
  - Toton & Erewash Valley;
  - Corby – Oakham;
  - Birmingham cross city line avoiding New Street;
  - Chippenham – Trowbridge;
  - Castle Cary - Yeovil
- Gaps which could be filled to provide new service capability, such as connecting diverse areas already electrified to enable a new through service:
  - Glasgow – Stirling;
  - Wolverhampton – Shrewsbury;
  - Preston – Ormskirk;
  - Southport – Wigan;
  - Wigan – Kirby;
  - Bidston – Wrexham

For each of the gaps identified, NR proposed options to complete the gap. Primarily the option was either to electrify or not, the decision on which form of electrification depending on the location of the gap – the perpetuation of 3rd rail being assumed therein.

The results of the analysis for passenger service efficiency showed the highest ranking options and the associated BCRs as follows:

- Midland Main Line: BCR not stated, although socio-economic BCR quoted as being **'infinite'**
- Great Western Main Line (to Bristol and Swansea only): **>2.0** variable depending on assumptions made due to IEP implementation
- Cross Country – assumes that the MML and GWML are already electrified. Electrified extent ends at Paignton: **3.4** (this increases to **5.1** if Leeds – Colton Junction is already electrified as part of the Trans-Pennine work)

- Basingstoke to Exeter St Davids: **3.1**
- Berkshire and Hampshire, GWML route to Taunton via Newbury, assuming diesel traction beyond Plymouth: BCR not specified, socio-economic benefit cited
- Manchester to Euxton Junction & Preston to Blackpool North & Oxenholme to Windermere: **2.3**
- North cross-Pennine, including Liverpool and Manchester airport to Newcastle, Middlesborough and Hull: **5.8** [note: this assumes that Leeds – Colton Junction is already electrified as part of the cross-country scheme. BCR drops to **1.2** if this is not the case]

12 Appendix C – Sample Options Cost Comparison, St Pancras to Scarborough

	Electrification		Diesel Bi-mode		IPEMU		Fuel Cell Bi-mode	
Year								
0	1st year wiring	63.09	1st purchase	39.87	Initial purchase	3.50	Initial purchase	37.54
1	2nd year wiring	63.09	operating	3.87	operating	1.84	operating	0.84
2	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
3	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
4	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
5	EC4T	1.32	operating	3.87	5-year replace	3.50	5-year stack/batt.	1.24
6	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
7	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
8	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
9	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
10	EC4T	1.32	operating	3.87	5-year replace	3.50	5-year stack/batt.	1.24
11	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
12	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
13	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
14	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
15	EC4T	1.32	operating	3.87	5-year replace	3.50	5-year stack/batt.	1.24
16	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
17	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
18	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
19	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
20	EC4T	1.32	operating	3.87	5-year replace	3.50	5-year stack/batt.	1.24
21	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
22	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
23	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
24	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
25	EC4T	1.32	operating	3.87	5-year replace	3.50	5-year stack/batt.	1.24
26	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
27	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
28	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
29	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
30	EC4T	1.32	operating	3.87	5-year replace	3.50	5-year stack/batt.	1.24

Continued overleaf

	Electrification		Diesel Bi-mode		IPEMU		Fuel Cell Bi-mode	
Year								
31	EC4T	1.32	replacement	43.73	operating	1.84	Replacement	0.35
32	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
33	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
34	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
35	EC4T	1.32	operating	3.87	5-year replace	3.50	5-year stack/batt.	1.24
36	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
37	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
38	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
39	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
40	EC4T	1.32	operating	3.87	5-year replace	3.50	5-year stack/batt.	1.24
41	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
42	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
43	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
44	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
45	EC4T	1.32	operating	3.87	5-year replace	3.50	5-year stack/batt.	1.24
46	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
47	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
48	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
49	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
50	EC4T	1.32	operating	3.87	5-year replace	3.50	5-year stack/batt.	1.24
51	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
52	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
53	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
54	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
55	EC4T	1.32	operating	3.87	5-year replace	3.50	5-year stack/batt.	1.24
56	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
57	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
58	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
59	EC4T	1.32	operating	3.87	operating	1.84	operating	0.84
60	EC4T	1.32	operating	3.87	5-year replace	3.50	5-year stack/batt.	1.24

13 Appendix D – Sample BCR Calculation Sheet: Electrification vs. Diesel, St Pancras to Scarborough

	Discount	Benefit	Cost	Net cash flow	Discounted cash flow	Cumulative		Discounted Benefit	Discounted Cost
Year	3.5%								
0	1.00	63.09	39.87	23.22	23.22	23.22		63.09	39.87
1	0.97	63.09	3.87	59.22	57.22	80.45		60.96	3.73
2	0.93	1.32	3.87	-2.55	-2.38	78.07		1.23	3.61
3	0.90	1.32	3.87	-2.55	-2.30	75.77		1.19	3.49
4	0.87	1.32	3.87	-2.55	-2.22	73.55		1.15	3.37
5	0.84	1.32	3.87	-2.55	-2.14	71.41		1.11	3.25
6	0.81	1.32	3.87	-2.55	-2.07	69.34		1.07	3.14
7	0.79	1.32	3.87	-2.55	-2.00	67.34		1.04	3.04
8	0.76	1.32	3.87	-2.55	-1.93	65.40		1.00	2.94
9	0.73	1.32	3.87	-2.55	-1.87	63.54		0.97	2.84
10	0.71	1.32	3.87	-2.55	-1.81	61.73		0.94	2.74
11	0.68	1.32	3.87	-2.55	-1.74	59.99		0.90	2.65
12	0.66	1.32	3.87	-2.55	-1.69	58.30		0.87	2.56
13	0.64	1.32	3.87	-2.55	-1.63	56.67		0.84	2.47
14	0.62	1.32	3.87	-2.55	-1.57	55.10		0.81	2.39
15	0.60	1.32	3.87	-2.55	-1.52	53.58		0.79	2.31
16	0.58	1.32	3.87	-2.55	-1.47	52.11		0.76	2.23
17	0.56	1.32	3.87	-2.55	-1.42	50.69		0.74	2.15
18	0.54	1.32	3.87	-2.55	-1.37	49.32		0.71	2.08
19	0.52	1.32	3.87	-2.55	-1.32	48.00		0.69	2.01
20	0.50	1.32	3.87	-2.55	-1.28	46.72		0.66	1.94
21	0.49	1.32	3.87	-2.55	-1.24	45.48		0.64	1.88
22	0.47	1.32	3.87	-2.55	-1.19	44.29		0.62	1.81
23	0.45	1.32	3.87	-2.55	-1.15	43.13		0.60	1.75
24	0.44	1.32	3.87	-2.55	-1.12	42.02		0.58	1.69
25	0.42	1.32	3.87	-2.55	-1.08	40.94		0.56	1.64
26	0.41	1.32	3.87	-2.55	-1.04	39.90		0.54	1.58
27	0.40	1.32	3.87	-2.55	-1.01	38.89		0.52	1.53
28	0.38	1.32	3.87	-2.55	-0.97	37.92		0.50	1.48
29	0.37	1.32	3.87	-2.55	-0.94	36.98		0.49	1.43
30	0.36	1.32	3.87	-2.55	-0.91	36.08		0.47	1.38

Continued overleaf...

	Discount	Benefit	Cost	Net cash flow	Discounted cash flow	Cumulative		Discounted Benefit	Discounted Cost
Year	3.5%								
31	0.34	1.32	43.73	-42.41	-14.60	21.48		0.45	15.05
32	0.33	1.32	3.87	-2.55	-0.85	20.63		0.44	1.29
33	0.32	1.32	3.87	-2.55	-0.82	19.81		0.42	1.24
34	0.31	1.32	3.87	-2.55	-0.79	19.02		0.41	1.20
35	0.30	1.32	3.87	-2.55	-0.76	18.26		0.40	1.16
36	0.29	1.32	3.87	-2.55	-0.74	17.52		0.38	1.12
37	0.28	1.32	3.87	-2.55	-0.71	16.81		0.37	1.08
38	0.27	1.32	3.87	-2.55	-0.69	16.12		0.36	1.05
39	0.26	1.32	3.87	-2.55	-0.67	15.45		0.34	1.01
40	0.25	1.32	3.87	-2.55	-0.64	14.81		0.33	0.98
41	0.24	1.32	3.87	-2.55	-0.62	14.19		0.32	0.94
42	0.24	1.32	3.87	-2.55	-0.60	13.59		0.31	0.91
43	0.23	1.32	3.87	-2.55	-0.58	13.01		0.30	0.88
44	0.22	1.32	3.87	-2.55	-0.56	12.45		0.29	0.85
45	0.21	1.32	3.87	-2.55	-0.54	11.90		0.28	0.82
46	0.21	1.32	3.87	-2.55	-0.52	11.38		0.27	0.79
47	0.20	1.32	3.87	-2.55	-0.51	10.88		0.26	0.77
48	0.19	1.32	3.87	-2.55	-0.49	10.39		0.25	0.74
49	0.19	1.32	3.87	-2.55	-0.47	9.92		0.24	0.72
50	0.18	1.32	3.87	-2.55	-0.46	9.46		0.24	0.69
51	0.17	1.32	3.87	-2.55	-0.44	9.02		0.23	0.67
52	0.17	1.32	3.87	-2.55	-0.43	8.59		0.22	0.65
53	0.16	1.32	3.87	-2.55	-0.41	8.18		0.21	0.62
54	0.16	1.32	3.87	-2.55	-0.40	7.79		0.21	0.60
55	0.15	1.32	3.87	-2.55	-0.38	7.40		0.20	0.58
56	0.15	1.32	3.87	-2.55	-0.37	7.03		0.19	0.56
57	0.14	1.32	3.87	-2.55	-0.36	6.67		0.19	0.54
58	0.14	1.32	3.87	-2.55	-0.35	6.33		0.18	0.53
59	0.13	1.32	3.87	-2.55	-0.33	5.99		0.17	0.51
60	0.13	1.32	3.87	-2.55	-0.32	**5.67**		0.17	0.49
							Total	**155.68**	**150.01**
							Discounted B/C		**1.04**