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**University of Birmingham**



**Energy Efficiency for Diesel Passenger  
Trains**

by

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degree of Master of research

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# ABSTRACT

The Rail Technical Strategy intends to achieve 4Cs targets, which are reducing carbon emission, increasing rail capacity, decreasing rail cost, and improving customer satisfaction. Reducing fuel usage and cost in rail travel depend on the development of more efficient operation and management.

In a railway system, energy required for traction is predominantly provided by diesel, followed by 30% consumption of electricity. In UK, diesel traction is used for a substantial proportion of rail traffic and the annual diesel fuel bill is increasing significantly as well as carbon emission. Therefore, improving energy efficiency of diesel train has been promoted.

This thesis presents an investigation of different energy saving strategies for diesel passenger trains. Stabling and power control are the main parts of the research. In order to obtain and analysis the methods, the thesis explores, through a series of case studies, a number of suggestions for different operating companies.

The first case study relates to reducing stabling time or engine idling time and minimise fuel usage by selectively shutting down the running engines. The additional information such as improvement of engine performance from cooperation between TOCs and the Manufacturing industry has increased potential energy saving. The second case study mainly focuses on energy calculation and analysis about Class 221 locomotives, combined with discussing eco-driving. The data processing and data analysis as the main method of this study has been designed to demonstrate the energy consumption is highly affected by idling, Engine RPM and deceleration choice. The outputs illustrate that reducing idling time, developing lower Engine RPM, and more coasting and soft braking could save energy. The final part of thesis roughly introduces the traffic management system for assisting energy saving and introduce the new traffic control loop combined with advanced automatic system.

Overall, the thesis provides evidence that technology packages (shutting down engines and eco-driving, TMS) could reduce energy consumption, decrease green gas emission, and reduce rail cost.

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The research about energy saving strategies, in particular polices of shutting down engines and eco-driving, has been investigated, and this thesis is the result of the investigation and statistic data research. The research could have not been accomplished without support from several organisations and individuals.

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## List of Abbreviations

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<b>Term</b>	<b>Explanation / Meaning / Definition</b>
AC	Alternating Current
APU	Auxiliary Power Unit
ATW	Arriva Trains Wales
CO <sub>2</sub>	Carbon Dioxide
DAS	Driver Advisory System
DC	Direct Current
DEMU	Diesel Electric Multiple Unit
DfT	Department for Transport
DHMU	Diesel Hydraulic Multiple Unit
DMUs	Diesel Multiple Units
ECT	Electric Current Traction
EMS	Environmental Management System
GB	Great Britain (England, Scotland and Wales)
GHG	Greenhouse Gas
HVAC	Heating, Ventilation, and Air-conditioningConditioning
OEM	Original Equipment Manufacturer
OTMR	On-Train Monitoring and Recording
RPM	Revolutions Per Minute
RSSB	Rail Safety and Standards Board, Great Britain
RTS	Rail Technical Strategy
SLU	Semi-conductor Logic Unit
TMS	Traffic Management System
TOCs	Train Operating Companies
UK	United Kingdom (Great Britain and Northern Ireland)

# Chapter One

## 1 Introduction

It is recognised that rail operations already makes a comparatively efficient use of energy and fuel. Rail is a relatively low carbon dioxide emission and so called ‘green transport’ mode, compared with other means of transport (such as planes and cars / trucks) (Peckham, 2007). Government promotes modal shift of transport from roads to tracks; hence it will accelerate the growth of rail transport as well as cause pressure on railway capacity. Increasing capacity and development of rail traction and operation will aggravate the energy crisis and environmental pollution.

Most of counties over the world are trying to find a solution to reduce energy consumption and greenhouse gas (GHG) emission. In Britain, according to the RSSB report called ‘Meeting Rail’s Carbon Ambition’, which claims rail can reduce emissions by 38% per passenger per km and gives an absolute saving of 400,000 tons pa in five years’ time. It is recommended both from a carbon and cost saving perspective that the industry should satisfy four interventions: energy efficient driving, weight reduction for new trains, automatic shutdown of auxiliary loads and enabling re-generative braking. (RSSB, 2011)

On the other hand, the Rail Technical Strategy (RTS) intends to achieve 4C’s, which have been used to position technical thinking at a step change. The 4C’s objectives are: (Webb, 2013)

- Reduce carbon by 50%
- Increase capacity by 50%
- Decrease cost
- Improve customer satisfaction

Reducing fuel usage and cost in rail travel will depend on the development of more efficient rolling stock, modernising infrastructure and optimizing operations. Reducing GHG emissions will depend both on improving diesel train energy efficiency and the electrification of rail systems, which can ensure that rail achieves extremely low levels of CO2 emission (Peter, Lew, & Cazzola, 2009). Increasing the capacity of railways is expected to introduce intelligent traffic management system to optimise traffic flow, improve reliability, and reduce the overhaul periods.

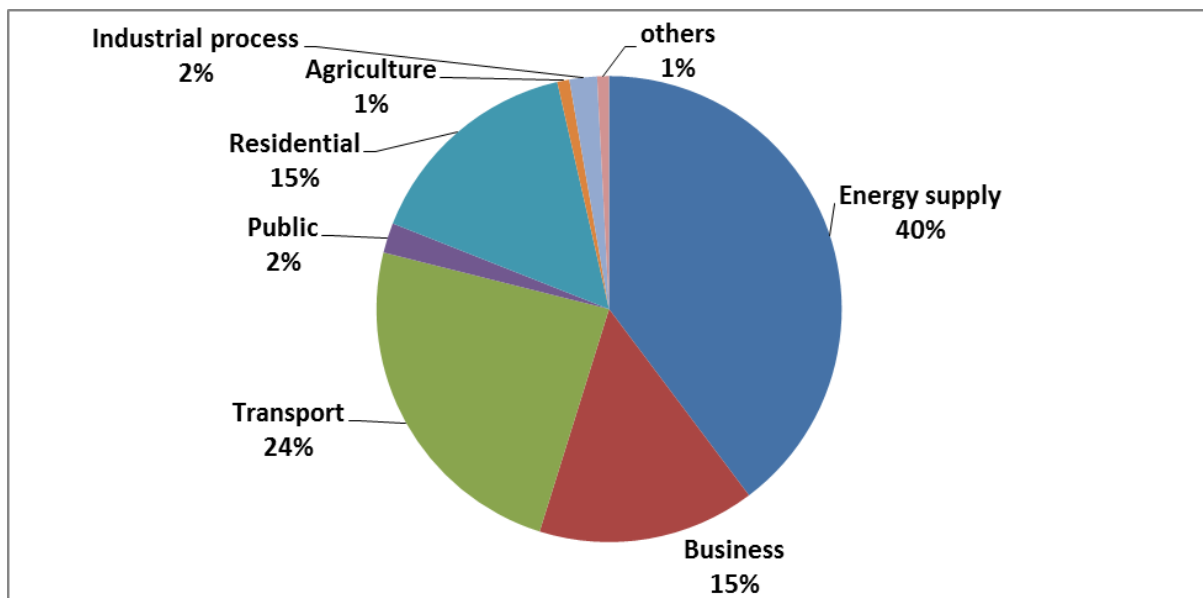
In summary, in order to combine economic competitiveness with environmental friendliness, railway systems must increase their energy efficiency. The reasons for improvement of energy efficiency could also be summarised in three parts: rising energy costs, energy security and independence, and climate change.

This thesis focuses on how to achieve the above aims by investigating and evaluating two methods – shutting down engines and energy efficient driving.

### 1.1 Energy and emission problem

In the past, in the 1950s and 1960s, the activities of the environmental movement was only focused on local effects, e.g. alleviating the worst effects of industrial discharges into rivers, remediating contaminated land, reducing atmospheric pollutants from domestic, industrial and traffic sources, and so on (Lesley & B.Hallberg, 2010). It is known that human activities put many species and the environment into a dangerous situation. The term ‘sustainable development’, first published in 1987, is a broad, dialectical concept that balances the need for economic growth with environmentally friendly and social equity (Wilson, 2003).

It is now accepted that the present global warming is related to emissions of GHG. Carbon-based fuels providing energy is one of the main sources of greenhouse gas. The report, called 2013 UK greenhouse gas emission by fuel type and end-user, shows ‘Transport’ accounting for about 25% of total UK GHG emissions (see Figure 1).



*Figure 1: Greenhouse gas emissions by end-user from 1990 to 2013 (estimates)*

*(source: DfT, 2014)*

In 2013, Network Rail shows, in Britain, road transport contributing 21% of carbon emissions, and 7% of this originating from road freight (Network Rail, 2013). Figure 2 shows railway is a low carbon mode transport, accounting for about 1~2% GHG emissions of total transport. However, as GHG emissions are tending to decrease in transport as a whole, they are increasing in the rail sector. It is proved that the policy about moving passengers and freight from road to track is effective but causes pressure on rail capacity, and increases its complexity and energy consumption. Thus, the accelerating increase of demand and capacity requires efficient railway operation and management.

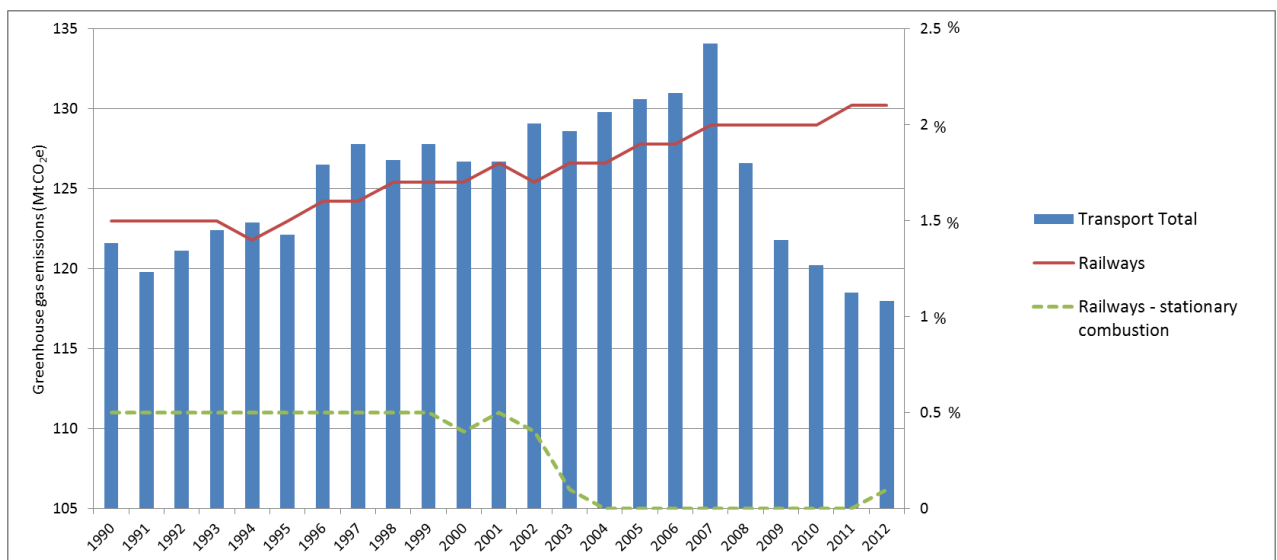


Figure 2: Transport GHG emissions, 1990-2012

(Sources: DfT, 2014)

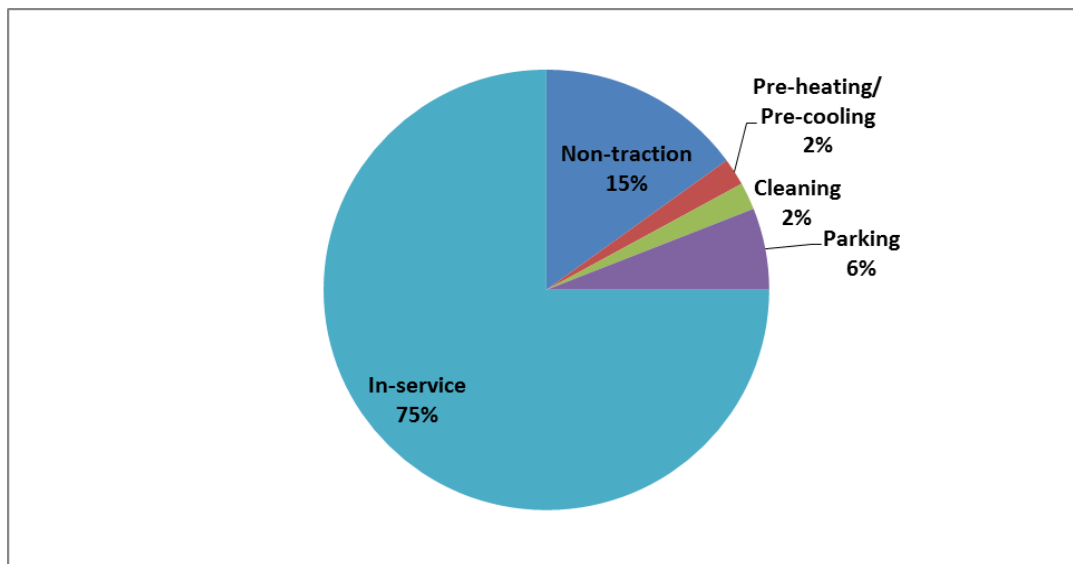
## 1.2 Energy consumption of railways

For the whole railway system, the energy consumption can be classified into traction and non-traction parts. The former comprises the power required to operate rolling stock across the system (including in-service and out-of-service), whereas the latter accounts for the energy utilised at stations, depots and other facilities in the system. Generally traction energy consumes about 85% in urban rail systems. (Powell, González-Gil, & Palacin, 2014).

Non-traction energy consumption for railways is divided into five main areas of activity: (IZT and Macroplan, 2012)

- Commercial activities: Stations and concessions
- Maintenance activities: Workshops, depots and service buildings

- Heating of switches
- Technical railway operation: Lighting of infrastructure, signalling, telecom, traffic control and data centres
- Administration and offices



*Figure 3: Energy consumption percentage of railway system*

*(Source: Railenergy final conference, 2010)*

For the energy consumption of rolling stock, two operation modes are considered: in-service and out-of-service. In service mode comprises the train operation with passengers, from origin to destination station including stand stills on the way. Out of service mode are periods (hours per day) where the train is stationary in depot areas, without passengers, pre-heating/pre-cooling, cleaning and parking (Eric & Maestrini, 2010). The energy consumption of a whole railway system can be seen in Figure 3.

In-service traction energy demand of a train stems from three areas: (Nolte, 2003)

- Train motion – Mechanical power at the wheel is needed to overcome the different types of resistance confronted by the train (running resistance on the one hand and inertia and grade resistance on the other hand).
- Losses in traction equipment – This mechanical power is provided by traction equipment at the expense of a certain amount of heat losses. This includes diesel engine, transmission, and auxiliaries such as motor ventilation.

- Passenger comfort – In the case of passenger service, an appreciable share of the overall energy consumption is needed for passenger comfort (heating, lighting, toilets etc.)

Table 1 shows an example of diesel motion energy losses. Diesel engine conversion from chemical energy to mechanical energy consumes main stored energy, accounts for about 68% total energy. Then the transmission system (e.g. mechanical, electric, hydraulic) would continue to lose a smaller part of the energy during conversion of engine RPM to vehicle speed. Running resistance and Inertia in different types of train show the different percentage of energy consumption. The situation is caused by speed and mass. Idling and Auxiliary usage is discussed in the following charts in detail.

*Table 1: Energy losses in the diesel train (source: Peckham, 2007)*

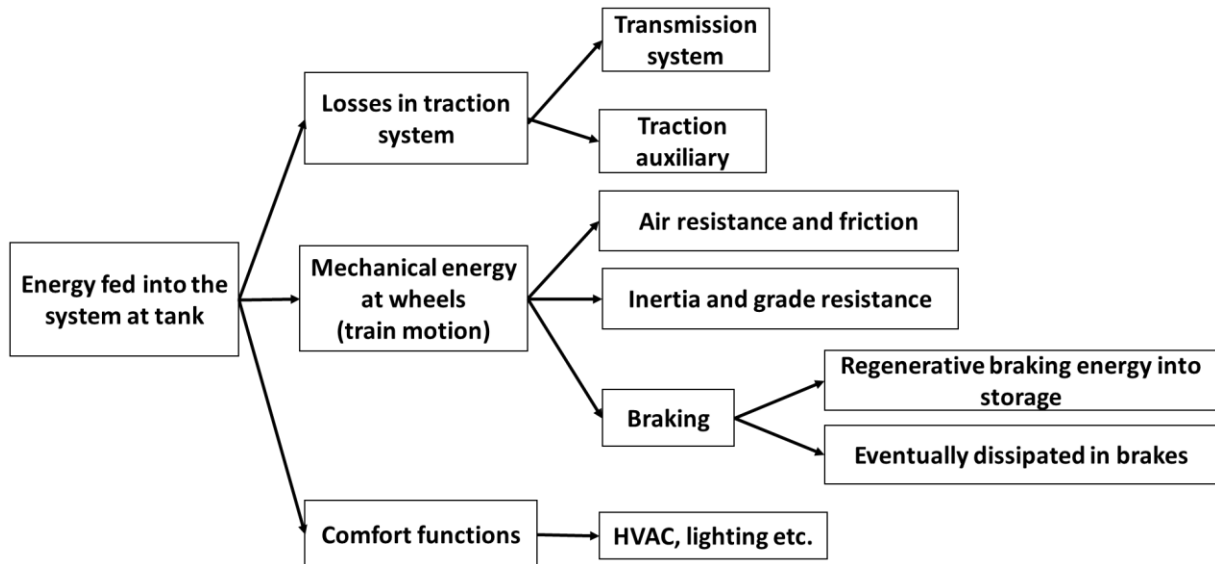
	<b>Intercity DEMU</b>	<b>Regional DHMU</b>
	Class 221	Class 170
<b>Engine Losses</b>	68%	68%
<b>Engine Idle</b>	5%	5%
<b>Auxiliary Use</b>	5%	5%
<b>Transmission Loss</b>	4%	3%
<b>Running resistance</b>	14%	6%
<b>Inertia</b>	4%	13%

It is also known that, different route circumstance, vehicle types and real situations could affect energy consumption. Acikbas etc. conclude the energy consumption depends on the following parameters (Acikbas, 2008):

- Line geometry: gradients, curves, stations, speed restrictions etc.
- Vehicle characteristics: control logic, acceleration, weight, motor, shape, auxiliary power system etc.
- Traction power system: diesel traction (diesel engine, transmission system, motor), electric traction (AC/DC suppliers, AC/DC motors)
- Operation conditions: headway time, dwell time, train configuration etc.

For diesel traction, the energy source is obviously the fuel in the tank. Figure 4 shows a diagram of energy consumption for a diesel passenger train. The chemical energy of the fuel is converted into mechanical energy by the combustion engine and this process has typically

an efficiency of around 40% (ratio between the mechanical output and the energy content of the fuel input) (Nolte, 2003).



*Figure 4: Energy flow diagram for a passenger diesel train with regenerative braking (author)*

### 1.3 Why focus on diesel trains?

In Britain, diesel traction is used for a substantial proportion of rail traffic and the annual diesel fuel bill will thus rise significantly. Diesel engine powered trains can also be damaging for the environment because of their relatively low efficiency and the carbon emission.

A key driver for the introduction of more fuel efficient technology is the rising rail traction energy bill. In the UK, as the cost of diesel continues to rise, a reduction in fuel costs will become very difficult to achieve for diesel-powered rail vehicles without new technology or operation to improve fuel efficiency. The number of litres of diesel used each year by GB rail has remained fairly constant over the past 5 years (see Figure 5). GB rail used 681 million litres of diesel in 2009-2010: passenger services used 482 million litres and freight services used 199 million litres. (Ed, Niki, Skipton-Carter, & Jim, 2012).

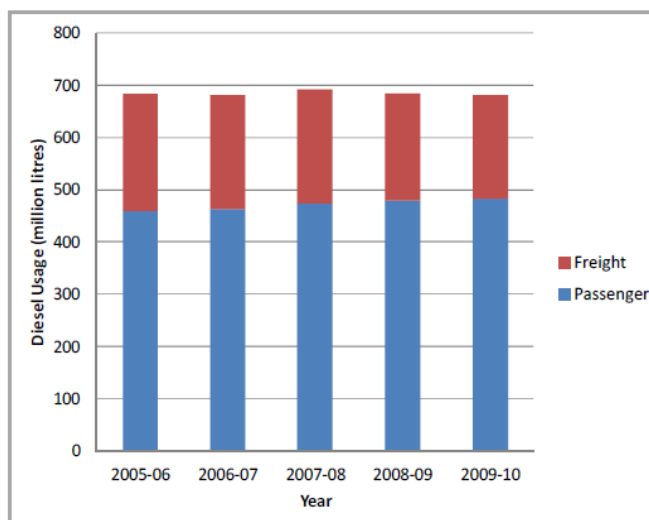


Figure 5: The number of litres of diesel used by GB rail for traction

(Source: National Rail Trends, 2010-2011)

Although the annual consumption of diesel is constant over the past 5 year, the annual traction fuel bill will rise significantly if the cost per litre continues to rise. It was estimated that Train Operating Companies (TOCs) would pay approximately £0.60/litre for diesel in 2012. If a 5% increase in fuel per year is assumed (see Figure 6), this cost could reach £0.98/litre in 2022. If the number of litres of diesel remains the same, this would equate to an increase in annual diesel fuel costs of £258m in 2022 (compared to 2012): (Ed, Niki, Skipton-Carter, & Jim, 2012)

- In 2012, 681m litres of diesel at £0.60/litre = £409m
- In 2022, 681m litres of diesel at £0.98/litre = £667m

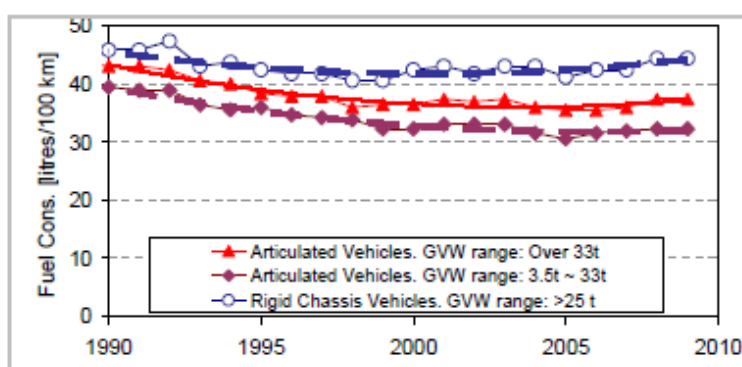


Figure 6: Fuel consumption statistics for the UK on-highway heavy duty automotive sector

(Source: Road Freight Statistics, 2009)

It is recognized that rail operations already make a comparatively efficient use of energy and are a relatively small contributor to carbon dioxide emissions. However, it is important that strategic plans are implemented to reduce cost and environmental impact. (Peckham, 2007)

#### 1.4 Energy saving strategies

The aim of energy saving is to increase energy and cost efficiency of integrated railway systems by investigating, certificating and validating methods or solutions ranging from the introduction of innovative traction technologies, components and layouts to the development of new rolling stocks, optimised operation and infrastructure management (Railenergy, 2013).

Having analysed different train operating companies' energy reduction and sustainability reports, commonly applied strategies of diesel passenger trains were summarised as: (Peckham, 2007) (IZT and Macroplan, 2012)

##### **Rolling stock:**

- Mass reduction. Component-based lightweight design: Aluminium car-body, Light coach interior equipment, Fibre reinforced polymers and Sandwich structures; System-based lightweight design: Jacob-type bogies, Single-axle bogies, and Mechatronic innovations.
- Aerodynamics and friction. Streamlining of head, tail, train sides and underfloor areas; Lubrication of wheels and tracks.
- Increase auxiliary engine on trains. A train with auxiliary power unit (APU) could supply power while the main traction engine is shut down.
- Hybrid technology. Energy storage technologies, including fly-wheels, batteries and super capacitors etc.
- Intelligent control of HVAC. Reducing heating and cooling load; Changes to interior temperature set point; Improve efficiency of lighting and selective lighting;
- Improving efficiency of traction drives and reducing energy conversion losses. Dispensing with the gearbox and providing direct drive from the motor to the wheel is possible. Smaller motors and greater distributed power.

##### **Operation optimisation:**

- Energy efficient driving. Energy optimisation of timetable; reduced standing time in stations, and Driver Advisory Systems.

- Reduce diesel engine idling. No idling at standstill, idling time limits, fit auxiliary power unit.
- Shutting down some engines on distributed power trains (intelligent engine control)

## 1.5 Aims & Objectives

This research aims to investigate and evaluate the current energy saving strategies in the railway. The research of the rail system to minimise energy consumption and better traffic management based on the development of innovative technologies and the optimisation of operation will enable energy savings and better efficiency of the railway system. Many operating companies have developed energy saving strategies, in-service during motoring or out-of-service in stations, terminals and depots. It is essential to investigate the process and results of these strategies implementation and try to achieve a technology package improvement.

In summary, the promotion and combination of the efficient methods is a key objective in this research.

## 1.6 Scope

Methods that are in the scope of this research include non-powertrain technologies (e.g. efficiency improvements from driver training, reducing stabling time, minimising empty running and efficient driving up to final drive). Topics that are out-of-scope of this study include technical parts - on-train systems that consume diesel fuel for traction purposes (i.e. engine and transmission systems), although some of them may briefly be discussed for completeness.

The research main focus is on improving diesel fuel efficiency as opposed to regulated emissions control and reduction. The trains of the study include:

- diesel-electric multiple units (class 221) running in service by Virgin trains,
- diesel-hydraulic multiple units, class 158 serviced by Arriva Trains Wales, class 170 serviced by London Midland and class 180 serviced by Grand Central Railway

## 1.7 General Methodology

The methods employed in the research can be split into three types:

- 1) Literature focused and
- 2) Interview focused

### 3) Experimental Analysis

Literature formed the basis for the introduction, background of diesel trains, and introduction and motivation for the case studies. These chapters consist primarily of a summary informed by literature.

The second part of the thesis consists of list of results and parallel comparison of current energy saving methods. Furthermore, it includes real-time data calculation and analysis by using Matlab programming and Excel statistics.

## 1.8 Thesis Structure

In this thesis, the author will consider the combination of the modern technologies in developing the packages of energy saving. The thesis will use two case studies and one introduction of traffic management system for a future railway.

### Chapter One: Introduction

The thesis begins with an introduction where the author briefly reviews the situation of energy crisis, energy consumption, especially for diesel trains, and the review of current energy saving strategies, followed by objectives and scope of the research. Finally, a short methodology section is included and the thesis structure is outlined.

### Chapter Two: Background of Diesel Train

In this background chapter the author describes the history of diesel trains and the principle of diesel traction, including 4-stroke ignition and transmission system. Also the classification of diesel train in UK is outlined.

### Chapter Three: Case study 1- shutting down the engines

In this first case study, the author lists several methods about shutting off policies – switch off saloon HVAC, auto shut down reduction and selective shut down engines. The work was undertaken by the author with the investigation from train operating companies.

### Chapter Four: Case study 2- energy efficient driving

In this case study, the author undertakes real-time data collection and data analysis. The specified outputs were proof of preferred driver behaviour resulting in efficient power control. The work was undertaken by the author involved in research placement in Virgin Trains.

### Chapter Five: Traffic Management System for energy saving

This chapter is an assumption and introduction. The author would like to investigate modern technologies and package them together with investigated methods to achieve a safe, economic and efficient railway.

#### Chapter Six: Conclusion

In the last chapter, the author summarises the work, reviews the barriers to implementation. The author also gives a general discussion about technology packages and stakeholder engagement, including the recommendations and further research areas.

# Chapter Two

## 2 Background of Diesel Train

### 2.1 Brief history of diesel train

From the 1830s through the 1940s, steam locomotives were the main power source for railways throughout the world (Churella, 1998). However, steam locomotives were inefficient and costly to maintain and operate. In 1876, Dr. N.A Otto developed a gas engine, and in 1884, Gottlieb Daimler produced the first petrol engine. In 1886-90 James Ackroyd Stuart developed the compression-ignition oil engine, and after several years' effort, Dr. Rudolf introduced an engine using oil only. Diesel's theoretical studies showed that compression-ignition engines could achieve thermal efficiencies as high as 73 percent compared to 6-10 percent for a steam engine and 18-22 percent for gasoline spark-ignition engines (Churella, 1998). The successful development of compression-ignition engine forms the name of Diesel. (The British Transport Commission, 1962). At that time, compared to steam locomotives, diesel trains had numerous advantages, listed as follows: (Churella, 1998)

- Efficient. Because of higher thermal efficiency, diesels required less fuel to do the same work.
- Economic. Steam locomotives had higher maintenance costs, because of its weight, high boiler pressures, numerous heat production and large numbers of loosely fitting moving parts.
- More tractive effort.
- Cleaner.
- Dynamic brakes, where equipped.

### 2.2 Diesel engine and transmission

The main breakthrough of diesel engine technology in fuel economy was brought about by injection technology improving the energy efficiency of diesel combustion engines by 15-20% (IZT and Macroplan, 2012). The main arrangement and flow of diesel traction is shown in Figure 7.

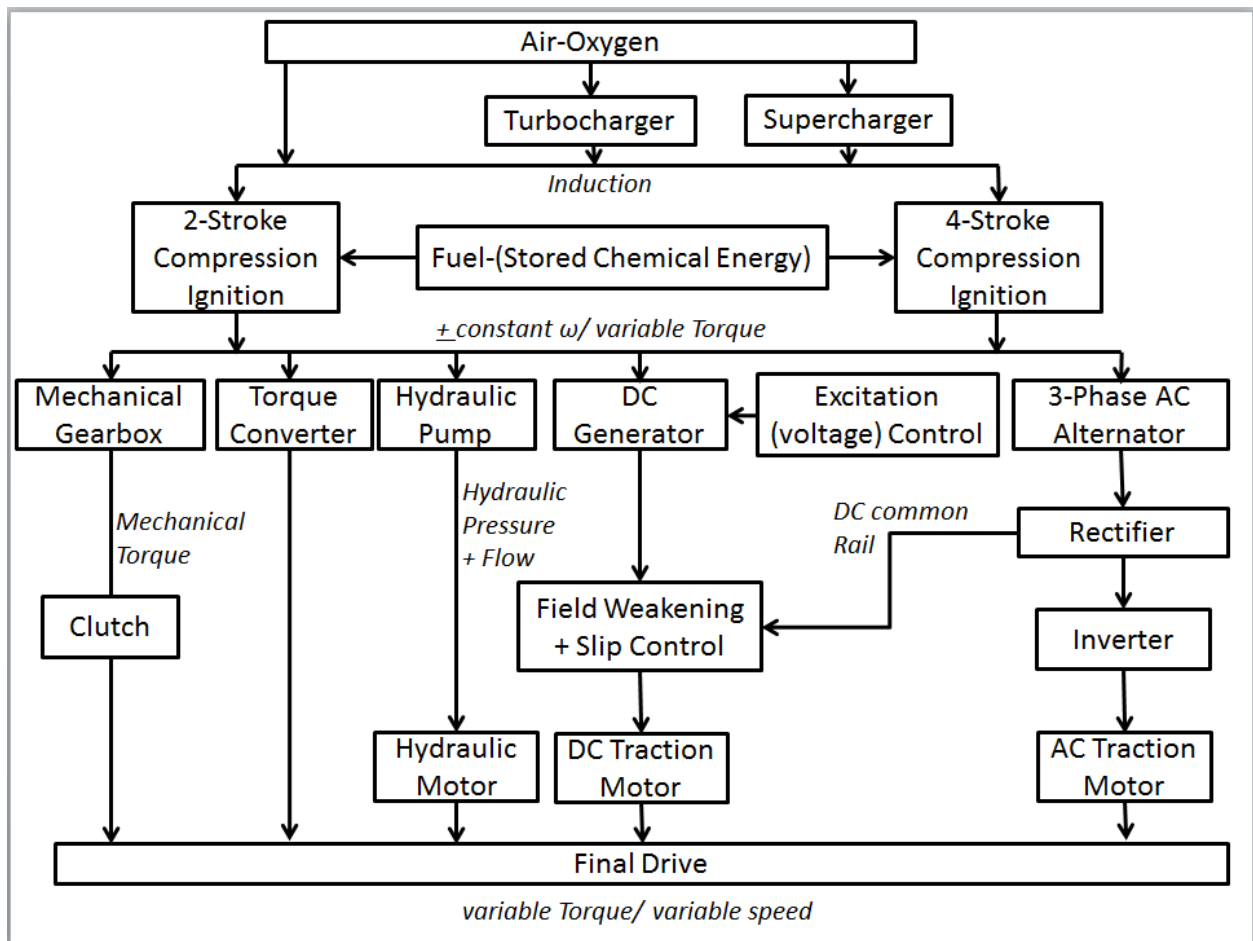


Figure 7: Transmission Arrangements of diesel trains (Author)

### 2.2.1 The principles of diesel engine – four-stroke

Most British railway diesel locomotives and diesel multiple-unit trains are fitted with four-stroke-cycle engines. In the four-stroke cycle, power is transmitted to the crankshaft during the power stroke. See Figure 8. (The British Transport Commission, 1962)

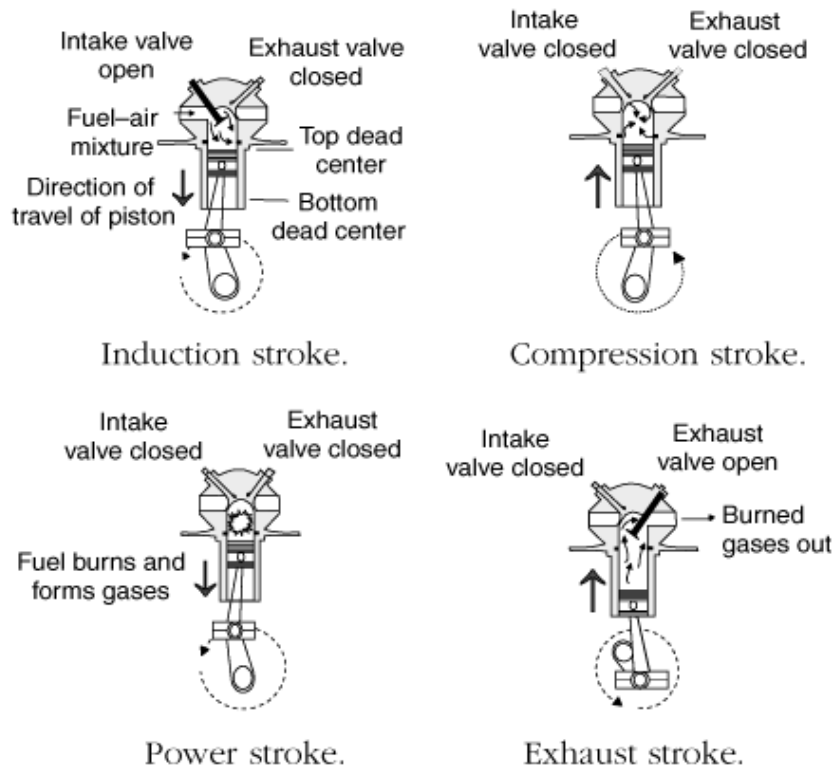


Figure 8: Four-Stroke Cycle (Source: Nipam Patel, 2014)

- First Stroke – Induction

Pure air accesses into the cylinder through an inlet valve with the movement of piston from top to bottom. (The British Transport Commission, 1962)

- Second Stroke – Compression

Then the inlet valve closes and the piston rise. As the piston rises further, the trapped air is compressed. During this period, the pressure goes up considerably, and this is accompanied by a temperature rise. Before completion of this compression, oil is sprayed into the cylinder. (Alcock, 1957)

- Third Stroke – Power

The fuel ignites immediately under high pressure. The mixture gas causes a rapid expansion which forces piston down on its power stroke, and so transmits power to the crankshaft. (Alcock, 1957)

- Fourth Stroke – Exhaust

With the exhaust value open, the waste gases are exhausted by the rising piston. (The British Transport Commission, 1962)

### 2.2.2 The principle of transmission system

The mechanical power produced from the combustion engine (2-stroke or 4-stroke) can be transmitted to the wheels in several ways. Generally, there are three types of transmission system in a diesel train. (The British Transport Commission, 1962)

- Electric transmission. DC-DC (Engine driven DC generator supplying DC motors); AC-DC (AC alternator and rectifier supplying DC motors); AC-DC-AC (AC alternator output rectified to DC and then inverted to 3-phase AC for the traction motors).
- Mechanical transmission. In a diesel-mechanical transmission, the main drive is by a fluid coupling. Fluid coupling is a hydraulic clutch equipped with a case filled with oil, a rotating disc with curved blades driven by the engine and another connected to the wheels.
- Hydraulic transmission. The same principle as the fluid coupling but it allows a wider range of “slip” between the engine and wheels. When the train speed has kept pace with engine speed, the fluid is drained out of the torque converter, so that the engine is virtually coupled directly to the wheels.

DSB said from an energy efficiency point of view, electric and mechanical transmission present some advantages over the hydraulic transmission as can be seen in Table 2.

*Table 2: Comparison of transmission systems in diesel traction (Source: IZT, 2012)*

	<b>Diesel-mechanic</b>	<b>Diesel-electric</b>	<b>Diesel-hydraulic</b>
<b>Engine efficiency</b>	equal	equal	equal
<b>Transmission efficiency (approximately)</b>	95%	85%	85%
<b>Possibility for optimum engine load</b>	high	high	low

### 2.3 Regenerative braking and energy storage

The term ‘regenerative braking’ is recycling energy from brake to motoring. Using braking energy in an electric train is widely used all over the world. For DC electrification, it is relatively straightforward to feed power from retardation back into the supply as this only requires the retardation voltage to exceed that of the supply. For AC electrification, regenerative braking requires the development of synchronise phase (David, 2014).

In contrast, regenerative braking in diesel trains is not widely implemented. As autonomous traction, there is no external power supply to accept the energy from braking. A high frequency, capacity and on-board storage system is required. On-board storage includes Battery (chemical energy), Supercapacitors (electric energy), and Flywheel (kinetic energy). The Energy Storage capacity can be seen in Table 3.

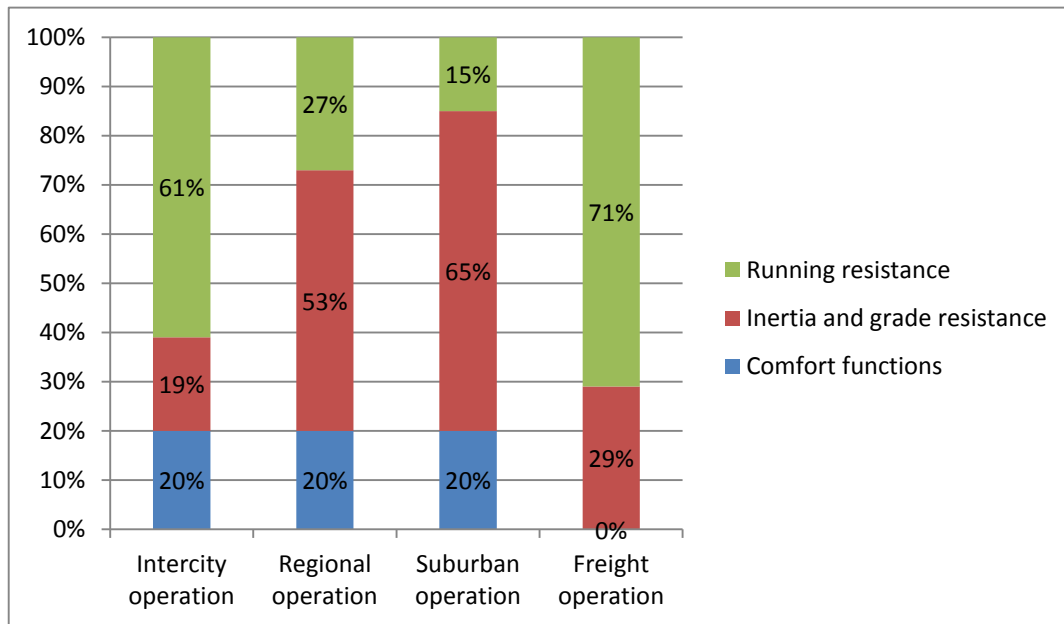
*Table 3: Typical properties of Energy Storage Technologies (Source: David, 2014)*

	<b>Energy Storage (Watt hours per kg)</b>	<b>Rate of energy transfer (Watt per kg)</b>
<b>Lithium Ion Battery</b>	175	300
<b>Nickel Metal Hydride Battery</b>	90	600
<b>Supercapacitor</b>	20	3500
<b>Flywheel</b>	120	5000

Batteries have high energy capacities compared to other storage devices, but charging time is relatively long which does not allow short-term storage of braking energy. It is ideal for a train with long stationary periods, like shunting locomotives (Peckham, 2007). In contrast, Supercapacitors can store energy at high rates but have a low energy capacity. Flywheels produce high capacity with high rate. But they are heavy and require substantial amounts of space that on trains proves challenging.

## 2.4 Classification of diesel trains

Figure 9 shows the typical consumption of energy demand for diesel train types. It is known that energy consumption or energy saving should be discussed from different parts – Intercity, regional, suburban and freight trains. Only passenger trains are considered here.



*Figure 9: Typical composition of energy demand for different operation/train classes*

*(Source: IZT, 2003)*

- Intercity trains (e.g. Class 221) could compete with air over medium distance, with the characteristic of long, potentially, high-speed journey with few stops.
- Regional trains (e.g. Class 170) operate between towns and cities. The characteristics of these trains are frequent stops and shorter distances than intercity trains.
- Suburban trains used for commuting into cities, with higher density passenger loading more stops than regional trains.

## Chapter Three

### 3 Case study 1- Smarter choices: shut down engine

#### 3.1 Introduction

This chapter presents a first study about an easier, short-term way to save fuel consumption called intelligent shutting down of engines. So far, operating companies played their part in reducing their carbon footprint. Since diverse franchising operating companies exist in the UK, they have been undertaking different routes and trains. There are varying amounts of energy saving strategies. However, fuel consumed in stabling hours has been traditionally overlooked. Shutting down engines and reducing idling is considered as a non-technical method, so it is easy to achieve in the short term. This project is based on interviewing the engineer from different train operating companies and the relevant benefits and drawbacks after shutting down the engines.

This chart includes different actions and feedbacks about shutting down policies from Train Operating Companies – London Midland, Grand Central Rail and Arriva Trains Wales. Two of them are members of the Green Transport Charter. A Green Transport Charter for the West Midlands (the Charter), is a pioneering partnership of transport sector organisations and bodies who are keen on reducing transport's contribution to GHG emissions, sharing good practice, supporting green innovation and promoting sustainable travel solutions. (Green Transport Charter, 2013). According to the 2011/2012 annual report, it shows Arriva Trains Wales have been introducing several policies to maintain their Environmental Management System (EMS) and reduce the impact of services on the environment; London Midland is another important energy saving contributor, which has reduced the mileage and number of empty trains that are required for a specific journey. On the other hand, Grand Central Rail is a new operating company which also focuses on energy saving and contributes to the green rail target.

The chapter starts by briefly stating the motivation of the research, continues by explaining the research methodologies and is followed by literature review and a list of current train operating companies' behaviours. Most importantly, the conclusion would give a diagram by efficiently combining three companies' strategies. This study proves useful guidance for a preliminary evaluation of further energy saving measures in this area.

### 3.2 Motivation

The motivation for this work is to improve the efficiency of fuel usage by turning off the engine or auxiliary facilities during stabling or out-of-service. According to rail corporations' assessment, trains are taken out of service and stabled when they are not required during off-peak times and overnight (Peter Symons, 2012). Those periods waste lots of fuel.

According to RSSB T618\_traction research report, modern distributed power diesel trains incorporate significant amounts of traction redundancy. Passenger loads are quite different between peak time and off-peak time. Some engines do not run efficiently at low load, so there is a potential to reduce power consumption by selectively shutting down some engines when the train is in traffic. (Peckham, 2007)

Typical running hours of some diesel trains are shown in Table 4, in which the data about Class 43 and Class 220/221/222 information depends on T618 – Improving the efficiency of traction energy use (Peckham, 2007 ), and the data of class 153 and 170 come from the calculations of period diagram supplied by London Midland staff. Typical Time Running in service and out of service is shown in Table 5. The data listed are calculated from sample 'typical' days in service and all data is per power car / motor car.

*Table 4: Typical Utilisation (Trains Working in service) (Author)*

Fleets	Typical average hours running per day per power car	Typical average miles run per day per power car
	hours	miles
Class 43 <sup>a</sup>	18.2	733
Class 220/221/222 <sup>a</sup>	15.1	640
Class 153 <sup>b</sup>	18.2	355.6
Class 170 <sup>b</sup>	19	499.14

(\*Source: a. Peckham, 2007; b. London Midland 2013)

*Table 5: Typical Time Running in service (including station turn-around times) and out of service (overnight) (Author)*

Fleets	Percentage of diagram time stood stationary in sidings and stations potentially idling	Time spent running between diagrammed destinations	Time spent idling during fuelling, serving and stabling in winter.
	-	hours	Hours
Class 43 <sup>a</sup>	12.60%	14.6	4.3
Class 220/221/222 <sup>a</sup>	38%	9.4	9.8
Class 153 <sup>b</sup>	45%	10.1	5.1
Class 170 <sup>b</sup>	34.20%	12.5	5.2

(\*Source: a. Peckham, 2007; b. London Midland 2013)

According to the above results, it shows that idling lasts a long time, for DMUs, it takes part of 35~45% of total running time. Even so, it shows a relative low percentage of High Speed Trains (class 43), idling which cannot be ignored. London Midland estimates idling consumes 4-5 litres per engine per hour, depending on the age of the engine and climatic conditions. So, the fuel usage during idling is approximately 20~45 litres per day per power car. In summation, reducing idling time shows a big potential. A slight time reduction of idling can reap huge rewards due to the multiplication and quantity factors. Therefore, a small percentage saving could result in hundreds of thousands of pounds saved across the fleet. As a result, it is something that is beginning to be taken more and more seriously.

On the other hand, in order to maintain cab and saloon comfort, drivers have to idle engine to obtain the required power for accessories, such as air conditioning, heating, television, refrigerator, and lighting (Rahman, et al., 2013). As shown in chapter 1, on-board auxiliaries – including heating, ventilation, and air-conditioning (HVAC), lighting and information systems – represent 20% of the total energy consumption, which is a potential to further reduce fuel consumption by shutting down the auxiliary facilities during out of service.

Therefore, the main purpose of this part is to develop a deeper understanding and promote awareness of energy consumed by rail vehicles while stabled. To achieve this, the outcomes of investigation from operating companies would inspire us.

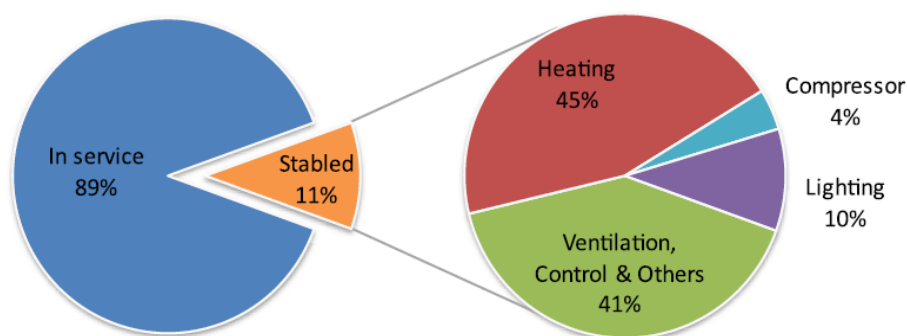
### 3.3 Methodology

The research project developed its work through a number of parallel activities. These include:

- Desk based literature review that records or researches train stabling or engine idling problems;
- Interview based research of different train operating companies about their energy efficiency policies including benefits and drawbacks.
- Comparison and calculations to estimate the potential magnitude of the benefits, the cost of implementing changes, and extension.

### 3.4 Literature based research

In the study of J.P Power, they showed the stabling problem is not negligible in comparison with energy consumed in service. According to their results, stabling of the Metrocar consumes approximately 11% yearly, which is accounted for by on-board auxiliary systems while the vehicle is stabled. Heating has been shown to be responsible for about 45% of this consumption, while the lighting and compressed air systems account for 10% and 4% respectively; other consumption included fans and control circuits representing 41% of the total stabled energy consumption. In summation, HVAC systems therefore play a key role in the auxiliary energy consumption of stabled Metrocars, with the ambient temperature being the main influencing factor in such consumption. Figure 10 gives a graphical summary of the approximate energy consumption breakdown of stabled Metrocars. (Powell, González-Gil, & Palacin, 2014)



*Figure 10: Breakdown of main auxiliaries' energy consumption in stabled Metrocars*

*(Source: Powell,2014)*

According to Rail Diesel Study WF2 Final Report (N Hill, 2005), the primary reasons to leave the engine's idling include:

- Pre-heating/keeping the engines warm, or at operating temperatures. This is necessary as a train leaving a station under high load conditions when the engine is cold can lead to engine damage/increased wear; (Certain locomotive engines are also sensitive to frequent stop-start cycles.)
- Providing power for the air compressors for the safety brakes;
- Providing power for heating/cooling of the driver's cabin and passenger carriages.

Secondary reasons include:

- Providing power for lights, on-board cleaning and other auxiliaries;
- The need to maintain power supply to the catering vehicle.

It was not possible to carry out detailed analysis to estimate the costs and benefits associated with strategies for reducing idling from busy terminal railway stations. There are a number of possible options suggested for reducing idling emissions at stations:

- No idling at standstill – Enforced engine switch-off at stations, shunting yards, and depots (“no-idling” policy);
- Idling time limits – Time limits on engine idling at stations (particularly important at rail termini);
- Fit auxiliary power unit (APU) – The traction engine can be shut down when the train is waiting at stations or stabled whilst the auxiliaries can be retained by running the smaller auxiliary engine (Peckham, 2007);
- Reduced DMU engine use - For DMUs, where engine idling is unavoidable, the number of train engines left in operation should be reduced, where possible.

### 3.5 Train Operating Companies' strategies

#### 3.5.1 London Midland – auto shut down

London Midland was the first train operating company to fit energy consumption meters to all their electric trains. London Midland had an objective to reduce Carbon Dioxide (CO<sub>2</sub>) emission per passenger journey by 5.75% in 2011/12, driven by a 4% reduction in Electric Current for Traction (EC4T) consumption and a 1% reduction in gas oil use. This target is reflected in the 2011-2013 Safety and Environment Plan and contributes towards the plan to achieve Go Ahead Group's ongoing Driving Energy Further Targets which aims to reduce carbon dioxide (CO<sub>2</sub>) emissions per passenger journey by 20% by 2015.

Their 'Traction Energy and Premises Environment Group' is focusing on a number of issues to reduce site energy use by investment and improved management, including: (Green Transport Charter, 2012)

- Introducing smart lighting on stations that dims automatically when daylight is bright and gets brighter on dull days.
- Waste from all London Midland stations and depot gets sent to a Materials Recycling Facility where it is sorted by hand and machine into different recyclable waste streams. These then go to be made into different products (e.g. plastic bottles, fleece clothing)

These methods helped London Midland reduce CO<sub>2</sub> emissions per passenger journey by 21% since the start of the franchise, and recycled 76% of their waste in 2010/11. (Green Transport Charter, 2012)

Shutting down policies in London Midland has two sections – switch off engines overnight and switch off saloon HVAC during stabling.

Firstly, shutting down engines overnight. In 2011, London Midland introduced a new engine 'shut down' policy at depots to ensure that they only run train engines for as a short a time as necessary. They did this via briefing and engagement with depot staff. Following the success of the initiative they extended it to drivers to encourage them to make sure train engines were turned off, when they are left for long periods during the day. The manual engine shut down policy resulted in significant fuel savings. Class 170s have reduced diesel consumption by 4.5% and Class 153s, have seen even greater reduction of 8%. Furthermore, shutting down engines overnight at depots has also allowed them to be a 'better neighbour' by reducing overnight noise levels for residents living close to their maintenance depots. (Green Transport Charter, 2013).

Another successful improvement is switching off saloon HVAC (also called sleep mode) during stabling. Sleep mode would be active to switch off the saloon HVAC when doors are closed and the cab is not active. Both conditions are to be satisfied for sleep mode. This method is specifically suited to the train fitted with a Train Management System, because it is only required to do modification of software. A review was conducted of all class 350 stabling (in-service and overnight). The potential stabling hours, which could be switched off, are shown in Table 6. SX defines from Monday to Friday. SO stands for Saturday only and SU means Sunday only.

*Table 6: Class 350 trains stabling hours (Source: London Midland Internal Documents)*

SX day time stabling per day	206.65 hours
SX overnight stabling per day	350.85 hours
SO day and overnight stabling per day	1079.18 hours
SU day and overnight stabling per day	719.75 hours

From the data, it shows that stabling length is significant. According to evaluating of the electricity consumed, all class 350 in London Midland would save a lot of costs. The following are the details of calculation in terms of net annual financial and carbon emissions savings.

*Table 7: Annual financial saving and carbon emissions' saving*

*(Source: London Midland Internal Documents)*

	Savings in kWh/day @23.5kW	Annual Savings in kWh	Annual savings @ 9p/kWh	Annual savings in kg of CO <sub>2</sub>
SX day time stabling	4814.945	962989	£86,669.01	469746.0342
SX over night stabling	8174.805	1634961	£147,146.49	797533.9758
SO day and overnight stabling	25144.894	1005795.76	£90,521.62	490627.1717
SU day and overnight stabling	16770.175	670807	£60,372.63	327219.6546
Total Annual Savings	54904.819	4274552.76	£384,709.75	2085126.836
Loss of savings due to ad-hoc repairs and cleaning inefficiencies @10%	5490.4819	427455.276	£38,470.97	208512.6836
<b>Annual savings minus losses</b>	<b>49414.3371</b>	<b>3847097.484</b>	<b>£346,238.77</b>	<b>1876614.153</b>

These savings consider the overnight cleaning, shunting, alighting/boarding of passengers and preparation of units by driver. However it will be deactivated during winter and it doesn't consider the fluctuation of the electricity bill. The investment of this method is modification and implementation cost. Siemens presented the cost to be about £94,848 for all implementation of class 350 operated by London Midland. So, this could benefit from year 2 approximately £300k as the modification would take several months to design and carry out. And then the year after would approximately save £346k.

The methods are summarised as Figure 11.

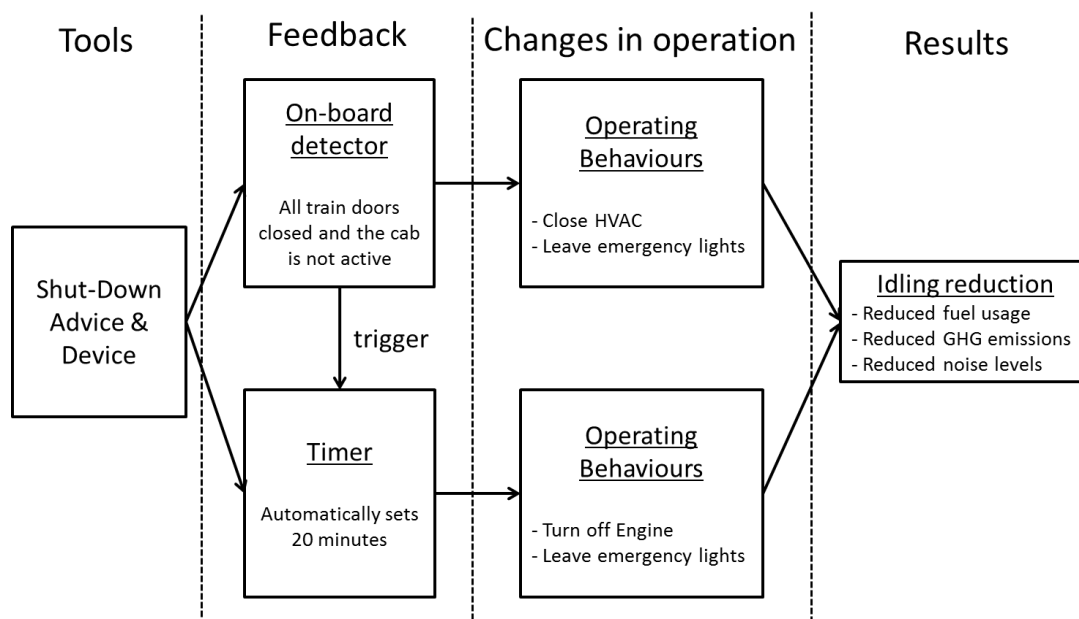


Figure 11: Shutting down through real-time feedback (Author)

The above results show a big energy and financial saving by introducing ‘switch off the engines’ policy. However, for Diesel Multiple Units (DMUs), like class 170 vehicles, because of a Semi-conductor Logic Unit (SLU), it has a delay timer that switches the engine off if the unit has been left running with no driver key in. The delay timer could minimise engine ‘sleep mode’ time and degrade benefits. The internal report shows all old class 170 vehicles have a delay timer that is set to 25 minutes through an SLU. The SLU is an electronic component which is also responsible for some transmission control, emergency lighting and traction WSP. As mentioned before, idling consumes 4-5 litres per engine per hour, depending on the age of the engine and climatic conditions. The long 25 minutes could consume 1 litre per engine.

London Midland cooperated with Porterbrook and has designed a modification to the circuit which will provide the desired outcome of a 10 minute engine shutdown delay. The outcome will save 15 minutes worth of engine idling during auto shut down situations. For class 170 fleets, there are 34 vehicles in the 2 car sets and 18 vehicles in the 3 car sets. At present, it is hard to check how often units auto shutdown. So there are some assumptions during calculation. The basic information shows in Table 8.

*Table 8: Class 170 vehicles basic data in auto shutdown*

*(Source: London Midland internal reports)*

	Pessimistic	Realistic	Optimistic
<b>Assuming shut down times per day</b>	2	4	6
Typical consumption per engines (in litres per hour)*	4.5	4.5	4.5
Number of 2 car units	17	17	17
Number of 3 car units	6	6	6
<b>Total number of engines</b>	52	52	52
Time saved by auto shutdown reduction (in minutes)	15	15	15
Time saved by auto shutdown reduction (in hours)	0.25	0.25	0.25

\*Data is used average value.

*Table 9: Modification financial saving (Source: London Midland internal reports)*

		Pessimistic	Realistic	Optimistic
<b>Fuel amount</b>	Total fuel consumption per day (in litres)	117	234	351
	Total fuel consumption per week (in litres)	819	1638	2457
	<b>Total fuel consumption per year (in litres)</b>	42588	85176	127764
<b>Financial saving</b>	Fuel cost in pounds per litre	£ 0.64	£ 0.64	£ 0.64
	<b>Amount of fuel saved per year (in pounds)</b>	£ 27,256.32	£ 54,512.64	£ 81,768.96

The financial benefits are evaluated in Table 9. The minimum amount of fuel saving is up to £ 27,256.32. The modifications fees are presented as about £18k, which include procure components, engineering design and labour costs etc. In sum, it would save approximately £20k in the second year as the modification would take several months to carry out and in third year it would gain whole benefits from the auto shut down reduction. Please note that the savings values will increase if the cost of diesel increases or during excessively cold environment.

### 3.5.2 Grand Central Rail – selective shut down

Grand Central is an open- access passenger train operator, which means they don't receive subsidy from, or pay any premium to the Department for Transport. They mainly carry passengers from London Kings Cross to York and the North East and to Doncaster and West Yorkshire. (Grand Central Rail, 2014)

The company considered shutting down the engines to save on using fuel and reduce the engine hours run, which in turn extend life time of the engine. Every engine should be replaced after servicing 20,000 hours. The engineer in Grand Central Rail introduced intelligent selective engine method for Class 180 (DMU) and Class 43 (locomotive).

Class 180s are 5-set Diesel Multiple Units with all vehicles powered, an engine under each coach, and the train also has the ability to share electrical power between cars if needed. So traction redundancies have the potential to run with isolated engine. With the distributed power and shared electrical power a class 180 can operate with up to three engines isolated and not lose a lot of time in service, as a result GC can keep a train in traffic with isolated engines, transmissions, battery chargers or cooler groups. The impact is the stress on the remaining running engines, transmissions, cooler groups, battery chargers which are worked harder putting extra stress on these items.

The good choice is that four of the five engines on the Class 180 are selectively shut down on appropriate routes and periods during the journey. The arrangement of the engines shows in Figure 12. Shutting down the middle diesel engine and power supplier for the coach is supposed to transfer the power from adjacent engines.

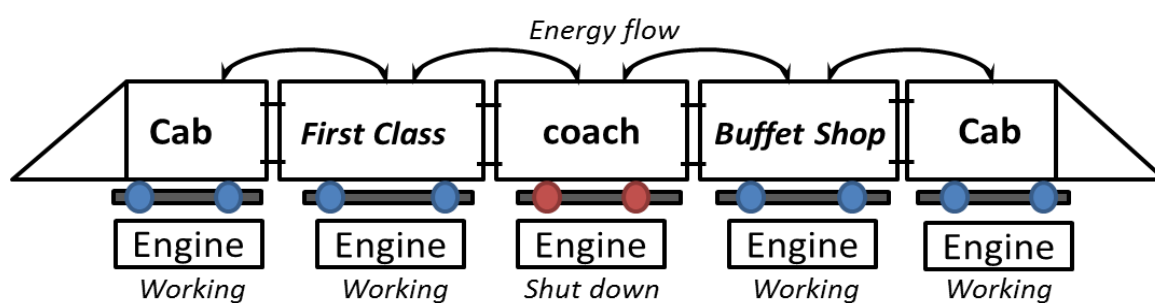


Figure 12: Class 180 selectively shutting down the engines (Author)

According to the specific day calculation, five engines running almost consume 3.92 (litres per mile), and selective running consumes 2.24 (litres per mile) see Table 10.

*Table 10: Class 180 fuel consumption in specific days (Source: Grand Central internal documents)*

<b>Date</b>	<b>Set HSTo.</b>	<b>DMU</b>	<b>Diagram</b>	<b>Service Mileage</b>	<b>Number of engine</b>	<b>Fuel consumption (litres)</b>
29-Jun	180101	DMU	GC181	1024	4	2632
06-Jul	180105	DMU	GC181	1024	4	2714
13-Jul	180101	DMU	GC181	1024	5	4017

For HSTs, like Class 43 diesel locomotive, the company shuts one engine down for running over the slow speed lines. The rough test about shutting one engine between York and Sunderland shows the fuel usage was 103.2 litres/ hr (2\*engines) and the fuel usage was 92.2 litres/hr (1\*engine).

### **3.5.3 Arriva Trains Wales – acceleration improvement**

Arriva Trains Wales is a member of the Green Transport Charter. The company is working constantly to improve the quality of the services they offer passengers. Shutting down engines has another problem, restarting and accelerating.

According to the traction diagram (Figure 7), accelerating time from 0 to normal speed is influenced by the diesel engines and transmission system. If we could improve transmission performance and minimise accelerating time, it could benefit not only increasing opportunities for shutting down, but also improve the energy efficiency, especially for Diesel Hydraulic Multiple Units (like, Class 170, Class 158 etc.). Table 1 shows transmission system losses about 5%. Current DMU transmissions have two-stages: a fluid flywheel which allows slippage as the engine accelerates, and a fluid coupling to provide a fixed drive. As a result, mean efficiency during acceleration to 20 mph is about 30%, see Figure 13 (David, 2014) and is considered efficient above the speed threshold (50 mph) at which the hydrodynamic coupling is locked up (Ed, Niki, Skipton-Carter, & Jim, 2012). Therefore it needs maximum acceleration rate to accelerate speed up to 50 mph.

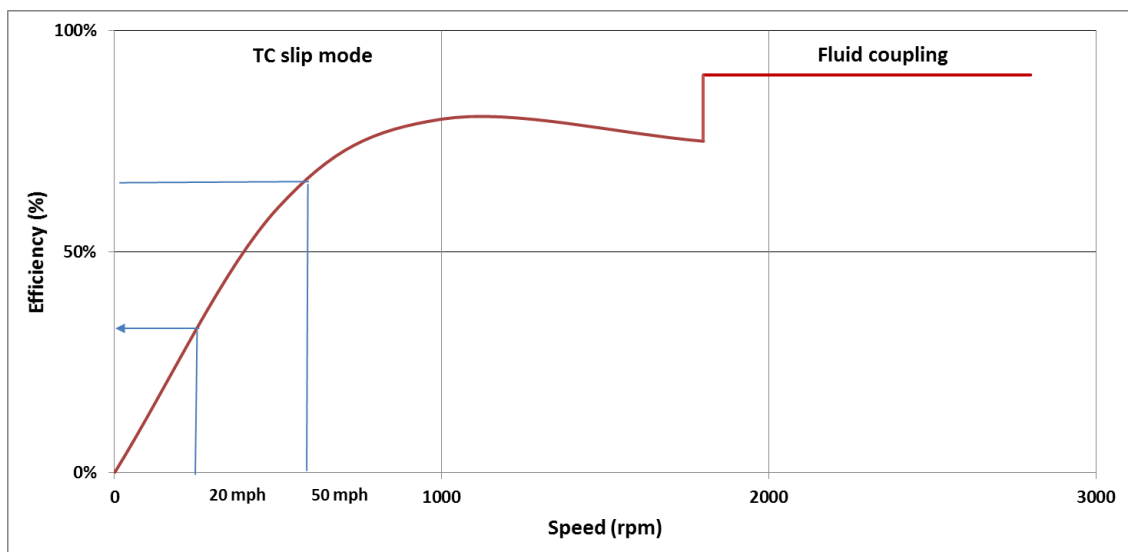


Figure 13: Class 170 transmission efficiency (Source: David, 2014)

In 2013, ATW, in conjunction with Angel trains, tried to test the modernisation of class 158 by fitting a new Voith DIWARail gearbox. It could improve engine power ramp (50 rpm/s) to upshifting of notches. Starting up behaviour has significant influence on fuel consumption and saving potentials, and the advanced Voith DIWARail shows big potential for this.

Fitting a new Voith DIWARail gearbox could improve engine power. Trials using the new gearbox were tested on Class 158 running between Cardiff and Crewe. The results include the comparison with old Voith T211, see Figure 14.

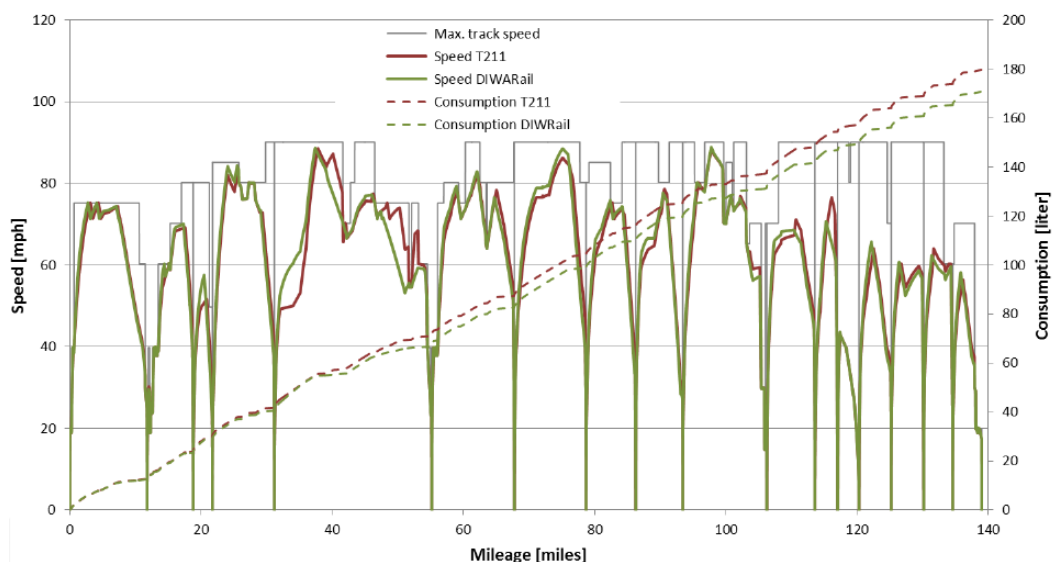


Figure 14: Fuel consumption comparison between T211 and DIWARail

(Source: ATW internal reports)

The conclusion is as follows:

- DIWARail reduced travel time running at the same speed limit.
- DIWARail reduced traction, braking, and idling percentage, combined with increasing coasting.
- Reduction of fuel consumption resulting from power ramp (50 rpm/s) shows approximately 4-5% lower fuel consumption of T211, DIWARail could save about 7-8% fuel consumption overall.
- DIWARail offers improved reliability compared with an old T211.

In principle DIWARail shows under all circumstances fuel saving potentials and benefits for the shutting down policies.

## 3.6 Risk assessment

### 3.6.1 Switch off saloon HVAC

#### Technical Risks

- Cleaning of Units with emergency lighting: The cleaning of units is carried out with the cab doors open and hence sleep mode will not be active.
- Freezing of internal pipes during winter: The sleep mode will not be active during winter. As part of the winterization plan, a task will be added to the existing list of procedures to de-activate sleep mode.

#### Operational Risks

- Complaints from drivers of cold cabs: The HVAC in the cab is not switched off when sleep mode is activated. Only the saloon HVAC's are switched off.

#### Commercial risks

- Complaints from passengers: A test was conducted at Camden depot by the Traction Energy manager to review the impact of sleep mode on the internal environment of the unit after sleep mode has been activated for more than 4 hours. The time taken to get to the required temperature was 10 min and this was considered acceptable as the time taken to get to Euston from Camden was well in excess of 10 min.

### 3.6.2 Intelligent selective engines

#### Technical Risks

- Class 180, selecting four of five engines proving traction and electrical load to the saloon: increasing pressure for running engines. For the remaining engines, alternators, and transmission working harder producing more stress and heat and increase the probability of failure.
- HST, one power car had problems: causing wheel/rail adhesion stress on traction motors and damaging wheel sets.

#### Operational Risks

- Lower speed for HST: the selective running could decrease average speed and it might cause delay on some routes, and increase pressure on the timetable.

#### Commercial risks

- Degrades customer experience: costing delay as well as losing time in service

### 3.7 Conclusion

According to the investigation from different operating companies, it shows reducing engine idling/ stabling time could reduce amounts of fuel usage further to gain financial saving. The methods include switching off the saloon HVAC on short-term stop (like, intermediate stations), or shutting the engines down on long-term stops (like, terminal stations and depots), auto shut down delay reduction and intelligent selection of running engines. In addition, these shutting down strategies could be optimised by shortening the restart time and developing accelerating performance.

Figure 15 shows rough ideas of shutting down methods for future railway choice. Start and stop of train is based on timetable. It requires communication between controller and train. Controlling shutting down behaviour includes auto and manual. Auto shut down requires the software modification of Traffic and Train Management System; Manual shut down is a mechanical process. Auto shut down could achieve a railway automatic level. The task of smart choice about shutting down is to assist the railway system achieving safe, economic and efficient goals.

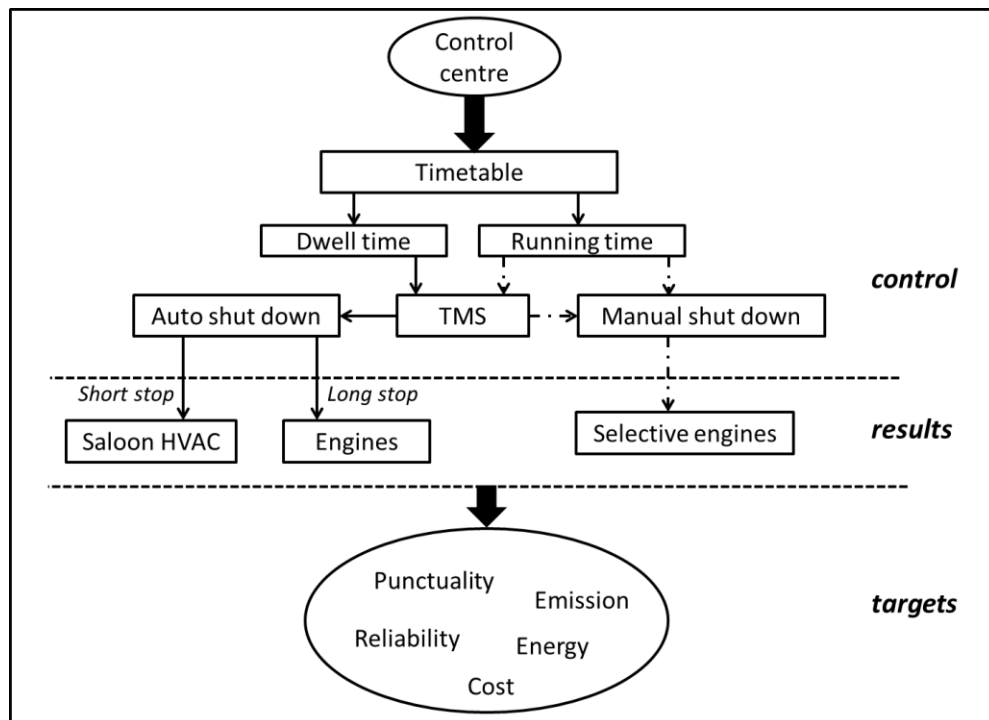


Figure 15: The diagram of shutting down behaviours for modern train (Author)

# Chapter Four

## 4 Case study 2- energy efficient driving

### 4.1 Introduction

This chapter presents a second study in optimum Diesel Multiple Unit (DMU) driving. The definition of optimum driving practice is to utilize minimum traction energy to achieve a run between two stations within the defined time period (Chui, Li, & Lau, 1993). Chapter 3 introduces a fuel reduction method, and this chapter would like to analyse how to use the limited fuel to achieve maximum driving, which is so called eco-driving.

Energy efficient driving, is one of the most important approaches to reduce energy consumption. It is focusing on setting guidelines for individual drivers. It is considered as an easier, cheaper and cost efficient method.

A train can be driven in three different modes: accelerating, coasting, and braking (Yong, Yun, Fang-ming, & Bao-hua, 2011). Literature on energy-efficient operation of trains goes back to the late 1960s, when the optimal control problem for a simplified linear train model was solved analytically by applying Pontryagin's Maximum principle, and the resulting optimal driving style consists of four sections: maximum acceleration, cruising at constant speed, coasting, and maximum deceleration (Rudiger, Peter, & Markus, 2000).

Virgin Super Voyager trains, Class 221, as experimental samples are investigated in this chapter. According to calculations of the energy consumption of different driving styles, analysing the related factors, like acceleration, coasting, and braking, would influence the energy efficiency.

The key point about efficient driving is when and how to apply each one in a suitable way which is limited by speed, timetable and the least amount of energy consumption. Eco-driving aims to change the driving behaviour through simple advice, like maintain a steady speed, accelerate moderately, follow speed limits, and brake accurately (Karsten, Mouritsen, & Kristian, 2013).

The author not only focused on the Virgin trains Class 221 which operates on the London Euston and Chester line in UK, but also gave some successful cases running in specific routes to support eco-driving. Also, the author roughly state the current hot technology, DAS. The chapter firstly describes the motivation of this research, followed by investigating current research. Then it shows the basic information of the Virgin Voyager routes and train

information, and explains the research methodology. Then, the author will show relevant calculating results and conclude eco-driving. Finally, the chapter roughly compares DAS with eco-driving based on specific routes. Although this research mainly focuses on Virgin Voyager trains on certain routes as specific case research, it is intended that the conclusion could be applied to all rail systems.

## 4.2 Motivation

Intelligent selectively shutting down the engines is a good solution to reduce fuel usage during stabling hours or running in specific routes. However, in fact, the biggest fuel consumption originally comes from motoring. It is necessary to optimise fuel usage by improving energy efficiency. The motivation of this work was also concerned with the short-term and easier energy saving methods.

A train travels from one station to another station with variable gradients, curve and speed limits etc. The journey must be completed within a given time to achieve punctuality, and it is desirable to minimise energy consumption. Although the optimal control suggested obeys four rules: maximum acceleration and braking, cruising at constant speed, and coasting. However this rule may not be suitable for current trains.

Currently, Driver Advisory Systems are commonly considered an appropriate means to reduce energy consumption of trains. It has first been developed for regional or suburban trains with relatively short interstation distances and only simple constraints which have to be considered. (Albrecht, Gassel, Binder, & Luipen, 2010). However, this system requires precise train models and calculation of trajectory using a discrete search space and a numerical solver, such as a rescheduling, generic algorithm and real-time communication. For example, the constraints of DAS is frequently rescheduling on some routes, which causes frequently varying advice and might confuse the driver. So DAS is quite complicated and not cost-efficient to refurbish old trains on some routes. In contrast, eco-driving just focuses on power control by training drivers.

Current British rolling stock is faced with a huge number of old trains which are not fitted with TMS or DAS or hybrid technology. These trains include Intercity and Suburban and are servicing main routes. Driving technique can greatly impact on energy consumption and environment. Adjusting driving behaviours can help to reduce energy consumption and CO<sub>2</sub> emissions.

Class 221s, intercity trains, are diesel multiple unites without DAS and regenerative braking. Energy consumption control purely depends on individual drivers. Drivers' driving style is

quite different and contributes to different energy consumption. Coasting and braking points selection are possible approach to accomplish energy saving within a specific run-time. That means drivers are supposed to turn off the traction motors at a certain point and operate deceleration by soft braking.

The main purpose of this work is therefore to develop a deeper understanding and promote awareness of energy efficient driving by analysing the factors of energy consumption. To demonstrate this, the outcomes of an experimental calculation aimed at assessing the energy use of different drivers' behaviours in the Virgin Super Voyager trains are presented.

### 4.3 Literature based investigation

Eco-driving is used to obey the Maximum principle and construct the trajectory based on four optimal regimes, in particular: Full power (limited by the maximal permitted acceleration of the train), cruising at constant speed (by applying partial power or partial braking, depending on the prevailing track and running resistance), coasting (Inertia motion), and braking with full power (limited by the maximal permitted deceleration of the train). (Albrecht, Gassel, Binder, & Luipen, 2010).


Karsten etc. suggested eco-driving for cars should follow below several separate sections. (Karsten, Mouritsen, & Kristian, 2013)

- Driving in the highest possible gear at lowest possible revolutions per minute (RPM).  
Fuel consumption is supposed to lower at low RPM due to friction.
- Maintain a constant speed.
- Anticipate traffic flow and avoid frequent starts and stops.
- Decelerate smoothly.
- Accelerate moderately.
- Eliminate idling. It is more efficient to switch off the engine than leaving the engine running, as mentioned in case study 1.
- Drive at or below the speed limit
- Do not press the accelerator when switching on the engine.
- Approach curves at correct speed and in the highest possible gear.
- Minimise extra weight and air resistance

- Maintain correct tyre pressure
- Avoid fuel consuming accessories.

Matthew Barth and Kanok Boriboonsomsin, in 2009, suggested the concept of dynamic Eco-driving. Their advice is real-time communication between driver and operation centre. The advice is given in real-time to drivers changing traffic sensing and telematics, allowing for a traffic management system to monitor traffic speed, density, and flow, and then communicates advice in real-time back to the vehicles. This method could save approximately 10-20% under free flow conditions. However, compared to less congested condition, it shows higher percentage reductions in fuel consumption and CO<sub>2</sub> emission occur during severe traffic conditions. (Matthew Barth, 2009). In 2010 August, they did eco-driving research in U.S car drivers. The results from 20 samples of drivers in Southern California show that on average the energy consumption on city streets improves by 6% while the energy consumption on highways improves by 1%. According to responses from drivers, most of them were willing to adopt parts of the eco-driving advice after the training. (Kanok, Alexander, & Matthew, 2010)

#### 4.4 Virgin Super Voyager

<i>Class 221</i>		
<ul style="list-style-type: none"> <li>• Vehicle Type: DEMU</li> <li>• Application: Intercity Passenger Vehicles</li> <li>• Engine: Cummins QSK19</li> <li>• Transmission: Electric transmission</li> </ul> 	Combustion Cycle	4-stroke
	Maximum Speed	125 mph
	Average Car Weight	54 Tonnes
	Maximum Acceleration	0-60 in 70 seconds
	Full Service Deceleration	60-0 in 400 metres
	Peak Power	522 kW at 1800 rpm
	Peak Torque	2769 Nm at 1800 rpm
	Number of seats (5 car)	250
	Fuel range (miles)	1200
	Turbocharged	Yes
	Aftercooled	Yes

#### 4.4.1 General description and routes conditions

Class 221 is one of the Super Voyagers operated by Virgin trains. They are diesel-electric multiple units (DEMU's) built between 1999 and 2002. They differ from the Class 220 'Voyagers' in that the 221s are equipped with tilting equipment offering up to six degrees of tilt to allow them to take curves faster without affecting passenger comfort. Each coach of a 221 has a number of which the last two digits are the last two of the unit number plus 50, e.g. coach 60360 is part of 221 110. The 221 fleet is owned by Halifax Asset Finance, managed by Angel Trains, and leased to the operators. (Hulme, 2014).

There are 20 class 221 trains operated by Virgin, numbered 221 101 to 221 118, together with 221 142 and 221 143. 101 to 140 are five- car trains, and 142 to 143 are four-car sets. All coaches are equipped with a Cummins QSK19 diesel engine of 522kW (700hp) at 1800rpm per car, powering a generator which supplies current to motors driving two axles per coach. The Maximum speed is 125 mph (200 kph), and 1200 miles can be travelled between refuellings. A five car set provides 26 seats in First class and 224 in standard. All vehicles are incorporated with the latest techniques, including computer fault diagnostics (Train Management System), air-conditioning and fitted with at-seat audio entertainment systems and power sockets for laptop computers and mobile phone charging. (Hulme, 2014). The braking system of Class 221 is air and EP rheostatic. The output power and engine RPM are shown in Figure 16. Braking power is 45 kW and traction power ranges from 45~522 kW.

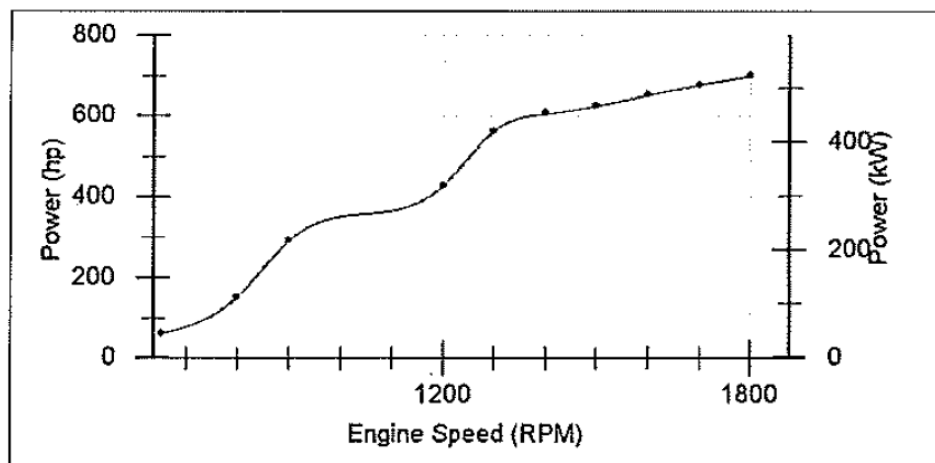


Figure 16: Power output curve (Source: OEM information)

Super Voyagers travel from Euston to Chester and North Wales, and from Birmingham to Edinburgh and Glasgow. In this chart, the specific route is between London Euston and Chester. It is about 179 miles, normally including 2 intermediate stations – Milton Keynes Central Rail Station and Crewe Rail Station.

## 4.5 Methodology

For the purpose of analysing efficient driving style, the research project developed its work through a number of parallel activities. These include:

- Desk based investigation of energy efficient driving strategies.
- Specific data collection, reduction, calculation and analysis
- Comparison and contrasting the potential magnitude of the benefits and the cost of implementing changes

The analysis is based on a pair of trains (outbound and return) operated by different drivers on an inter-city route with 3 – 5 public stops in each direction.

### 4.5.1 Basic Equations of Analysis

The heart of all train performance is based on Newton's Second Law:

$$\text{Force} = \text{Mass} \times \text{Acceleration};$$

$$\text{Acceleration} = \text{Force} / \text{Mass}.$$

The basic equations are:

*Equation 1: Instantaneous acceleration  $m/s^2$*

$$a = \frac{dv}{dt} = \frac{(T.E) - (Frictional\ drag) - (gradient\ force) - (curve\ drag)}{(effective\ mass)}$$

Where a = acceleration; v = speed; t = time; T.E = traction effort.

*Equation 2: Energy consumption: kWh.*

$$E = P \times T$$

Where E = energy; P = power; T = time.

### 4.5.2 Data collection

A number of data sources are available with information for vehicle energy consumption calculation. In the research, the data is based on OTMR, OEM and Allocations.

Data collected between 1st April 2014 and 27th April 2014 from the trains' "black box" On-Train Monitoring and Recording (OTMR) fitted to Class 221 forms the basis for the analysis in this chapter. OTMR records time, speed, power and brake setting, and odometer reading, in addition to other important data items about the train. And all of the parameters were

recorded every event. These data were downloaded in .xpt format to computers in Virgin trains offices, which include 20 trains running on about 30 routes.

Another important data is from OEM information or Engine Performance Data, which shows the relationship between gear speeds, which is defined as RPM (revolutions per minutes), and Torque/Power/Fuel Consumption output of the diesel engine. All data in OEM is based on the engine operating with fuel system, water pump, and inlet air restriction and exhaust restriction; not included are alternator, fan, optional equipment and driven components. Coolant flows and heat rejection data based on coolants as 50% ethylene glycol/50% water.

Allocations are the operational arrangement, which shows train timetable, mileage, headcodes. Those data are essential to classify the train and compare them on the specific route.

#### 4.5.3 Data reduction and selection

Since the data is sampled by OTMR during real operation there were some unavoidable discontinuities or noise in the recording periods, so it is necessary to select the useful data from the resources to reduce experimental measurements for further calculation.

Driving style varies from different routes. In order to analyse the different driving style in the same route, selecting every driver's data is an important thing. Finally, traction and brake setting, and driver number must be identified.

The researched route is from Euston to Chester and return from Chester to Euston. According to Allocations information, I sampled 18 journeys in this research. The details are shown in Table 11, and Table 12.

*Table 11: Euston to Chester Allocations (Source: Virgin Trains)*

Vehicles ID	Date	From	Depart	Arrive	To	Headcode	Mileage
1	03/04/2014	EUSTON	07:10:00	09:11:00	CHST	1D81FW	179.16
2	03/04/2014	EUSTON	12:10:00	14:10:00	CHST	1D86FW	179.16
3	03/04/2014	EUSTON	17:10:00	19:16:00	CHST	1D91FW	179.16
4	04/04/2014	EUSTON	10:10:00	12:11:00	CHST	1D84FW	179.16
5	04/04/2014	EUSTON	15:10:00	17:11:00	CHST	1D89FW	179.16
6	04/04/2014	EUSTON	20:10:00	22:13:00	CHST	1D94FW	179.16
7	06/04/2014	EUSTON	19:08:00	21:14:00	CHST	1D93FW	179.16
8	14/04/2014	EUSTON	11:10:00	13:11:00	CHST	1D85FW	179.16
9	14/04/2014	EUSTON	17:10:00	19:16:00	CHST	1D91FW	179.16

Table 12: Chester to Euston Allocations (Source: Virgin Trains)

Vehicles ID	Date	From	Depart	Arrive	To	Headcode	Mileage
10	03/04/2014	CHST	09:35:00	11:36:00	EUSTON	1A18EW	179.16
11	03/04/2014	CHST	14:35:00	16:37:00	EUSTON	1A43EW	179.16
12	04/04/2014	CHST	07:35:00	09:41:00	EUSTON	1R24EA	179.16
13	04/04/2014	CHST	12:35:00	14:38:00	EUSTON	1A33EW	179.16
14	04/04/2014	CHST	17:35:00	19:38:00	EUSTON	1A58EW	179.16
15	06/04/2014	CHST	15:33:00	17:41:00	EUSTON	1A51EW	179.16
16	14/04/2014	CHST	07:35:00	09:41:00	EUSTON	1R24EA	179.16
17	14/04/2014	CHST	14:35:00	16:37:00	EUSTON	1A43EW	179.16
18	14/04/2014	CHST	19:35:00	21:40:00	EUSTON	1A68EW	179.16

#### 4.5.4 Data calculation

The main tool used to calculate is Matlab simulation and Excel statistics.

From the OTMR data, it was possible to estimate the energy consumption of the trains, combined with standard technical parameters from OEM. There are a number of traction power settings in OEM, ranging from idling to full power. For each traction setting, the power output in kW is known. Total energy consumption is calculated by adding up time-step in each setting. The details are shown as follows:

---

#### Algorithm 1. Batching input files

---

```

1: getfilename=Is('file location*.xlsx*');
2: filename= cellstr(getfilename);
3: num_of_files= length(filename);
4: for j=1:num_of_files
5:   database(j,1)= struct('Name',filename(j),'Data',xlsread(filename{j},'sheet1'));
6:   database(j,2)= struct('Name',filename(j),'Data',xlsread(filename{j},'sheet2'));
7:   database(j,3)= struct('Name',filename(j),'Data',xlsread(filename{j},'sheet3'));
8:   traction= database(j,1).Data;           %traction/braking percentage
9:   time=database(j,2).Data;               %Date and time
10:  brake= database(j,3).Data;             %braking selection
11:

```

---

Algorithm 1 shows how to batch input OTMR files into Matlab. In Lines 8-10 I begin to select and classify the useful data. Line 12-13 in algorithm 2 is to transfer the traction/braking percentage to Engine RPM. From line 14 to line 24, it uses *similar function 1-5* calculating the power output based on engine RPM. In Lines 25-26 uses looping over all records to modify braking power to 45 kW.

**Algorithm 2. Power calculation**


---

```

12: for i=1:length(traction)
13:     rpm(i,j)=115/8*traction(i,j)+650-1150/8;
14:     if rpm(i,j)>=650 && rpm(i,j)<800
15:         Power=Function 1 (rpm(i,j));
16:         elseif rpm(i,j)>=800 && rpm(i,j)<900
17:             Power=Function 2 (rpm(i,j));
18:             elseif rpm(i,j)>=900 && rpm(i,j)<1200
19:                 Power=Function 3 (rpm(i,j));
20:                 elseif rpm(i,j)>=1200 && rpm(i,j)<1300
21:                     Power=Function 4 (rpm(i,j));
22:                     elseif rpm(i,j)>=1300 && rpm(i,j)<=1800
23:                         Power=Function 5 (rpm(i,j));
24:                     end
25:                 if brake(i,j)==1
26:                     Power(i,j)=45;
27:                 end
28:             end

```

---

Class 221 is fitted with a time correction system, which is used to check the time on the train matching the time in the control centre. Line 33-34 in algorithm 3 checks the records and sets `delt_t` to 3s.

**Algorithm 3. Time gap calculation**


---

```

29: for i=1:length(time)
30:     delt_t(i,1)=t(i+1,1)-t(i,1);
31:     if delt_t(i,1)<-85000
32:         delt_t(i,1)=delt_t(i,1)+86400;
33:     elseif delt_t(i,1)<0 && delt_t(i,1)>-85000;
34:         delt_t(i,1)=3;
35:     end
36: end

```

---

Energy calculation is based on equation 2. Algorithm 4 performs a simple loop to add-up energy consumption in delta time. Finally, in line 39, time units are updated from seconds to hours by dividing by 3600.

**Algorithm 4. Energy calculation**


---

```

37: Energy(1,j)=0
38: for i=1:length(time)
39:     delt_E(i+1,j)=delt_t(i,1)*power(i,1)/3600
40:     Energy(i+1,j)=delt_E(i+1,j)+Energy(i,j)
41: end

```

---

#### 4.5.5 Data analysis

The data analysis methodology can be summarised as follows:

- 1) Calculating the total energy consumption of each driver in the same route.
- 2) Comparing different drivers' energy consumption in the same route.
- 3) Investigating stabling, engine rpm and braking selection for energy consumption.
- 4) Power control suggestion.

#### 4.6 Experimental results and discussion

Energy consumption is a measure of effectiveness, and how many kWh per mile a train drives will indicate how energy efficient the train is. According to calculation, the energy consumption of different vehicles is shown in Table 13 and Table 14.

*Table 13: Energy consumption from Euston to Chester (Author)*

Trains ID	From	Depart	Arrive	To	Mileage	Energy consumption (KWh/mile)
1	EUSTON	07:10:00	09:11:00	CHST	179.16	16.987
2	EUSTON	12:10:00	14:10:00	CHST	179.16	16.219
3	EUSTON	17:10:00	19:16:00	CHST	179.16	15.782
4	EUSTON	10:10:00	12:11:00	CHST	179.16	19.732
5	EUSTON	15:10:00	17:11:00	CHST	179.16	19.460
6	EUSTON	20:10:00	22:13:00	CHST	179.16	18.658
7	EUSTON	19:08:00	21:14:00	CHST	179.16	16.983
8	EUSTON	11:10:00	13:11:00	CHST	179.16	17.129
9	EUSTON	17:10:00	19:16:00	CHST	179.16	18.524

*Table 14: Energy consumption from Chester to Euston (Author)*

Trains ID	From	Depart	Arrive	To	Mileage	Energy consumption (KWh/mile)
10	CHST	09:35:00	11:36:00	EUSTON	179.16	16.421
11	CHST	14:35:00	16:37:00	EUSTON	179.16	14.733
12	CHST	07:35:00	09:41:00	EUSTON	179.16	17.081
13	CHST	12:35:00	14:38:00	EUSTON	179.16	20.478
14	CHST	17:35:00	19:38:00	EUSTON	179.16	19.970
15	CHST	15:33:00	17:41:00	EUSTON	179.16	16.706
16	CHST	07:35:00	09:41:00	EUSTON	179.16	16.609
17	CHST	14:35:00	16:37:00	EUSTON	179.16	16.977
18	CHST	19:35:00	21:40:00	EUSTON	179.16	16.889

From Euston to Chester, the average energy consumption is 3174.72 (*kWh* per journey). The maximum value is train 4, 19.732 (*kWh/mile*), and minimum value is train 3, 15.782 (*kWh/mile*). So train 3 could save approximately 707.64 (*kWh*) per journey, compared to train 4.

On the other hand, trains from Chester to Euston, the mean energy consumption are 3102.7 (*kWh per journey*). Train 13 is the maximum energy usage, about 20.478 (*kWh/mile*), compared to the minimum energy consumption train 11, which is 14.733 (*kWh/mile*). The energy saving of train 11 is up to 938.2 (*kWh*).

In summation, the good performance of driving styles could save about 15~20% energy per journey. This shows big potential to save energy. In addition, the difference comes from the driver when and how to apply power control during the journey.

In order to further research the factors affect energy consumption, vehicle 1 to 4 were selected running from Euston to Chester as an example, and because vehicle 3 has the minimum energy consumption and vehicle 4 has the maximum energy consumption. Energy and Distance curve of these four vehicles are seen in Figure 17.

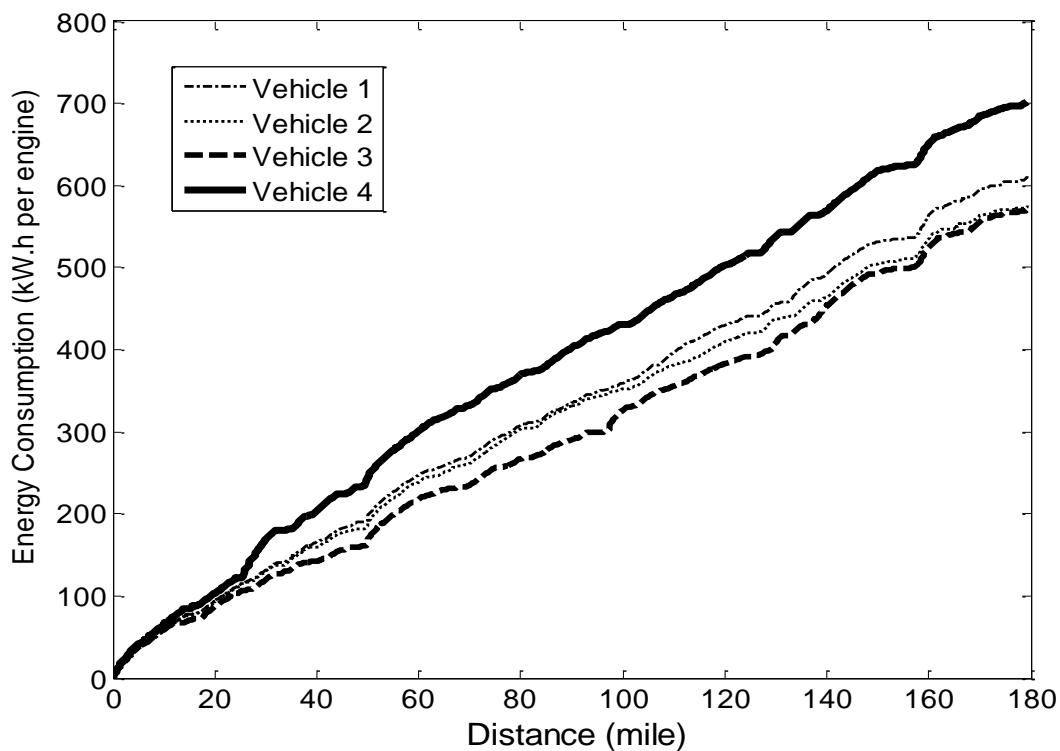


Figure 17: Energy Consumption vs. Distance (Author)

The above figure shows vehicle 4 is the highest energy consumption along the route. On the other hand, vehicle 3 comparatively has the lowest energy consumption during this journey.

The details of the four vehicles' performance from Euston to Chester can be seen in Speed and Time curves (Figure 18) or Speed and Distance curves (Figure 19). It shows vehicle 1 and vehicle 2 have two intermediate stops, while vehicle 3 and vehicle 4 have three stops but they separately stopped in different stations combined with different stopping time. Finally, vehicle 4 had 20 minutes delay and vehicle 3 had 8 minutes delay.

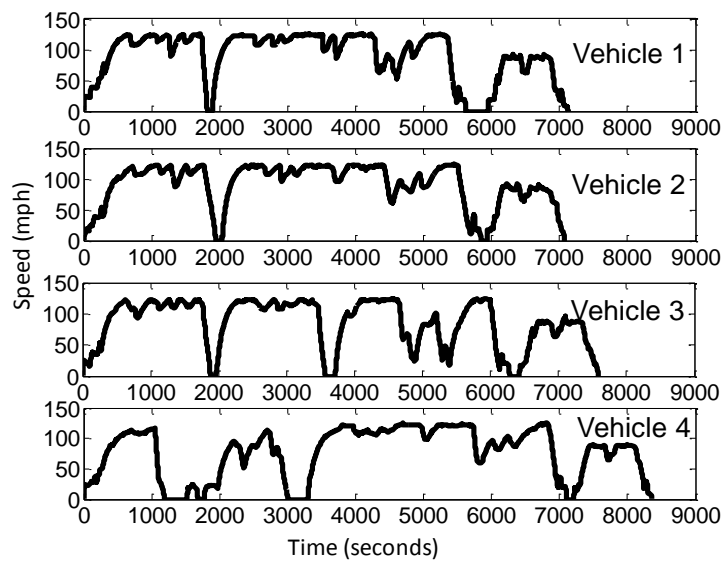


Figure 18: Comparison of speed variation in time (Author)

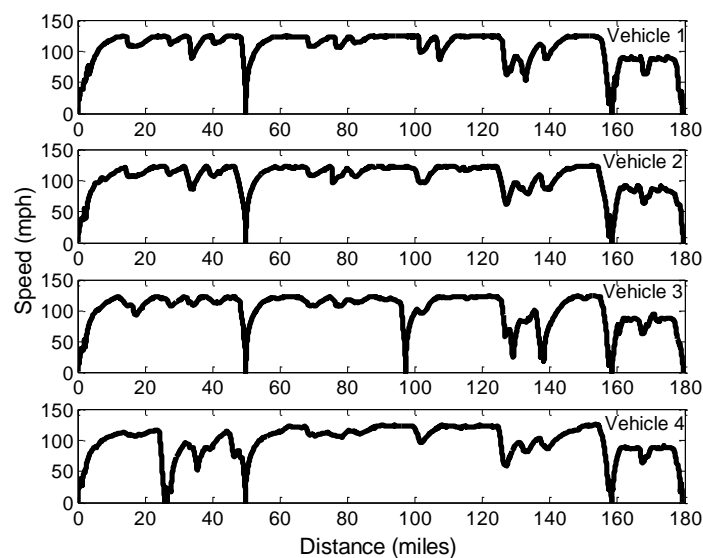


Figure 19: Comparison of speed variation in distance (Author)

#### 4.6.1 Stabling periods

According to the stopping time, the first thing is analysing stabling time. In eco-driving, avoiding idling or minimising stabling time is a key method. Since it still consumed fuel when the engine is running whilst the vehicle is stopping. The driver is hence consuming unnecessary energy when idling. The definition of idling is when engine RPM is above zero and the vehicle speed is zero for at least 2 continuous recordings. The details of calculation can be seen in Algorithm 5.

---

**Algorithm 5. Stabling hours calculation**

---

```
1: for i=1:length(time)
2:     if rpm(i)>0 && rpm(i+1)>0
3:         && speed(i)==0 && speed(i+1)==0
4:         t.idl(:,1)=time(i);
5:     end
6: end
```

---

In common, trains stop when waiting at a red signalling, in a queue or park at the station with engine turned on. But when considering idling, short stops near signalling lights does not belong to idling or short stops at station are neither. The records of these four vehicles stopping periods are show in Table 15. Only vehicle 1 and vehicle 4 have idling period. Specially, Vehicle 4 has a long stop in stop 1, about 10 minutes which is expected to consume about 75 kW.h, accounting for 2% of total energy consumption. Idling of vehicle 4 in stop one wastes energy compared with the other three vehicles.

*Table 15: Stopping periods during the route (Author)*

	<b>Vehicle 1</b>	<b>Vehicle 2</b>	<b>Vehicle 3</b>	<b>Vehicle 4</b>
Stop 1(minutes)	1.2	1.6	1.5	10
Stop 2(minutes)	5.8	1.4	2.25	5
Stop 3(minutes)	-	-	2.25	2
Total Stopping (minutes)	7	3	6	17

#### 4.6.2 Engine RPM analysis

The second analysis is Engine RPM. The specific power control is dependent on Engine RPM. So judging energy consumption should consider Engine RPM status.

Table 16 shows the rule of classification for Engine RPM, and it is based on data from OEM. The previous results show that energy consumption is supposed to be lower at low RPM, due to the friction resistance and thermal loss.

Table 16: Classification of Engine RPM (Author)

RPM	Type
650<=RPM<800	Very Low RPM
800<=RPM<900	Low RPM
900<=RPM<1200	Moderate RPM
1200<=RPM<1300	High RPM
1300<=RPM<1800	Very High RPM

Statistic data of Engine RPM selection per second are showed in Figure 20. The number of data points could also stand for controlling time (second). The results illustrate Engine RPM are distributed on very high level and very low level (including braking, idling and motoring). However, it is obviously that vehicle 4 has longer period for high RPM, about 1296 seconds, and it might also explain the reason why vehicle 4 is the highest energy consumption.

For vehicle 1 and vehicle 2, vehicle 2 has more low RPM combined with less high RPM. The lower energy consumption results of vehicle 2 also reflected the benefits of lower RPM.

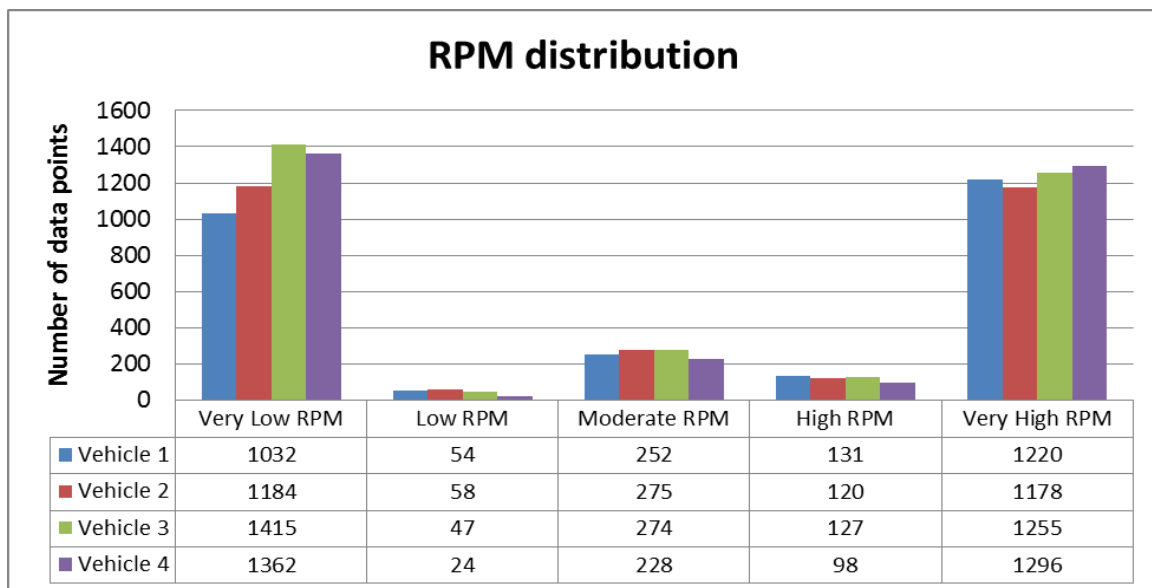


Figure 20: Engine RPM choice of four vehicles.(Author)

### 4.6.3 Deceleration analysis

Acceleration or deceleration is calculated in the standard equation as mentioned above Equation 1. I define the period of acceleration and deceleration is at least 3 seconds long. The minimum time span is used to prevent imprecise measurements. Because previous research has already proved maximum acceleration is good for energy efficiency, so the research only focuses on deceleration. Table 17 shows the results of deceleration value and its statistic data.

*Table 17: Statistic data of deceleration selection (Author)*

Deceleration (m/s <sup>2</sup> )	Number of data points			
	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4
0.298	68	186	126	116
0.447	56	32	73	67
0.596	38	7	48	18
0.745	23	3	10	15
0.894	11	0	0	1
1.043	1	3	0	1
Total	197	231	257	218

In fact, deceleration is controlled by braking or coasting. Braking is divided into hard braking and soft braking. The high deceleration value is hard braking, while the lower deceleration value could be coasting or soft braking. This research has not separate braking and coasting, due to the same power output. However, the above results reflect that the longer deceleration show the lower energy consumption.

In order to analyse the influence between coasting/soft-braking and hard braking, vehicle 1 and vehicle 2 are selected to do comparison. Figure 21 illustrates the comparisons of energy consumption and decelerating distribution of the two vehicles. Based on the figure, it shows higher energy consumption is due to hard braking. More soft-braking and coasting of vehicle 2 shows the better energy consumption.

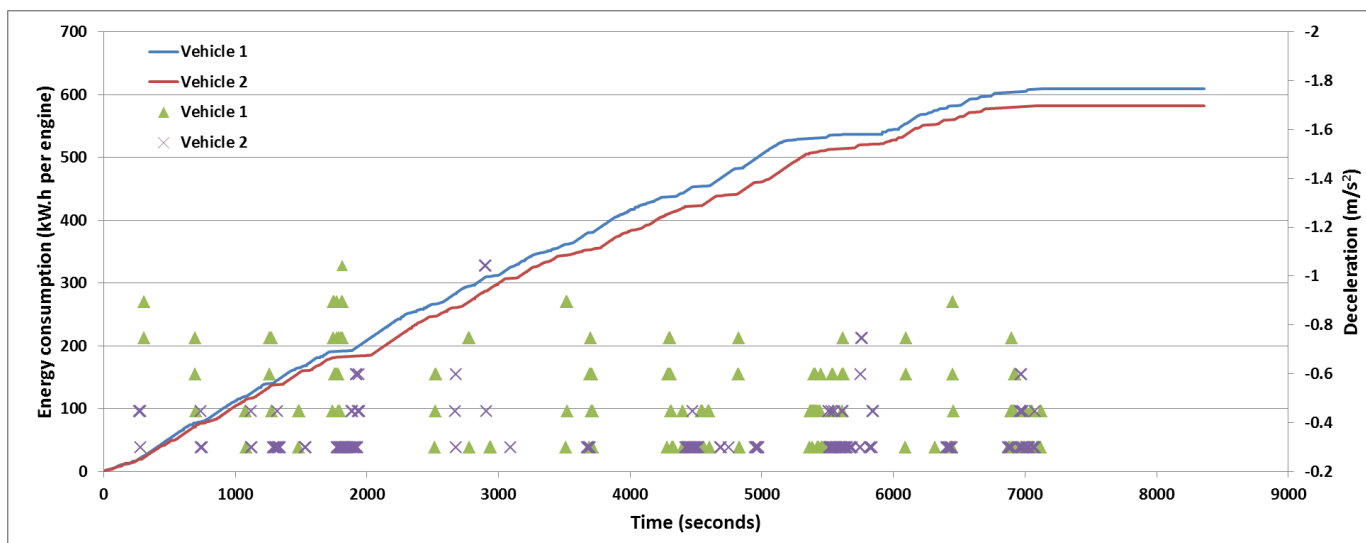


Figure 21: Comparison of energy consumption and deceleration selection (Author)

#### 4.7 Successful case study - Eco-driving implementation in Northern Rail

Northern Rail has implemented eco-driving by using the power controller. The use of the power controller becomes a balance between maintaining performance and driving as economically as possible. The details of their power controller show as Table 18.

Table 18: Power control strategy in Northern Rail (Source: Internal Documents)

0 – 5 mph	6 – 10 mph	11 mph +
Throttle Position	Throttle Position	Throttle Position
Notch's 0-3	Notch's 0-5	Notch's 0-7

The Notch control is actually engine RPM control. Tests have shown that starting a diesel in this way doesn't adversely affect performance and also acts to save fuel. Maintaining a lower power setting, for example notch 5, allows the transmission to change up at an earlier speed from torque converter to fluid flywheel (28 – 35mph).

#### 4.8 Technique support: engine performance improvement in Northern Rail

Eco-driving depends on engine RPM, which links to the fuel usage. So if we could improve the diesel engine's fuel efficiency, it could produce more power with lower engine RPM. LH has been investigating ways of improving the fuel efficiency of the range of engines it overhauls. This project has been focused on the Cummins NTA 855 R5 engine, currently being widely used in the passenger railway sector. The modification is changing the R5

Turbocharger change to fit a R1 turbocharger to an R5 engine. The Cummins NTA 855 R1 engine has a power output of 350 bhp whereas the Cummins NTA 855 R5 has 285 bhp.

The R1 turbocharger, like the engines, has many common components, most importantly: oil drain pipe, oil feed pipe, exhaust and intake connections and all respective gaskets. The other major feature is the envelope and packaging of the R1 turbocharger. The R5 turbocharger weighs in at 23.75kg whereas the R1 turbo is 21.45kg, a 2.3kg weight saving. As a result, the mounting points are under less stress due to the decrease in weight.

The results show it is possible to save the fuel from this modification through the acceleration stage and also at line speed in the 1800rpm-2100rpm range in notch 7. The use of the generic route provides a greater insight into how much fuel can realistically be saved. The route has been created and agreed between all participants, acting as an average route that the units are likely to cover with regards to time spent in each notch. From this we have seen a saving of 4.6% fuel by the modified engine over the standard set up. Although this is not definitive, it does put the testing into context of how the engine is likely to perform whilst in-service on a standard route, using a realistic operation of the notches.

#### 4.9 Other factors

It is important to recognize that there are a number of factors that could affect fuel consumption in the real world. Stabling, Engine RPM, braking and coasting selection, as discussed above, is one of them. Some of the other factors are showed below: (Kanok, Alexander, & Matthew, 2010)

- Rolling stock weight: it is affected by passenger load, if it carries more passengers on the same route, it would consume more energy to run.
- Road gradient: up and down is another factor which could affect fuel consumption. Going up requires more energy to overcome the added additional force and going down requires less energy.
- Weather condition: weather conditions affect train fuel consumption, both directly and indirectly, such as headwind increasing resistance, hot weather induces a higher usage of air conditioning.
- Peak time: during the peak-time, because of the tight timetable, it is easy to cause emergency brake. Frequent acceleration and deceleration could consume more fuel. So efficient driving could degrade significantly under terrible traffic condition.

#### 4.10 Conclusion

The energy consumption of train movement is related to train formation, running time, stop times and driver skill. Statistic and calculated data of energy consumption illustrate the control scheme. Consequently, the specific routes selected evaluate the control scheme. Energy efficient train control strategies have been summarized as beginning with a maximum acceleration, less idling periods, following with phase of partial traction and partial coasting, ending with a semi-final coast and a final soft braking.

There are many advantages of lower engine RPM, coasting and soft braking. It can reduce engine friction, wheel and rail wear, extend engines' life cycle and reduce the maintenance cost of traction equipment.

In fact, eco-driving is a simple driver advisory system, and the difference is that eco-driving is not equipped with an on-board device, which requires real-time timetable and update space conditions to continuously guide the driver on which notch position to use and achieving the most efficient driving. So, eco-driving is easier and cheaper, not requiring software or device implementation and rolling stock refurbishment. It could benefit for refit or disposing the amount of old trains in UK.

## **5 Traffic management system for future railway energy saving**

A railway is a complicated and integrated system. Energy saving strategies mentioned above could improve its performance and efficiency by introducing modern traffic management system. The intelligent traffic management system automates route setting, and provides an improved capability for predicting and managing disruptions in conjunction with operator organisations. It enables better informed real-time traffic regulation and more effective recovery plans, as well as assisting in the provision of consistent and more accurate information to the travelling public. It could benefit for saving time to shut down the engines during stopping or guide the driver to select running engines or fitted with DAS achieving eco-driving.

Today, the railway traffic system is mainly managed by dispatchers through a closed control loop, shown in Figure 22.

In the infrastructure layer, detection systems collect information of train movements. This information is processed by the interlocking and signalling system in order to provide information to the operational information layer, including the position and velocity of trains, the clearance of track block sections between signals, as well as the status of switches and signals (Fuchsberger, 2012). So this layer will confirm the track is safe and ready to pass.

The operational information layer maintains a forecast of the train movements. This forecast must be updated based on the dynamic changes taking place in the infrastructure layer and static data, such as timetable information, network infrastructure data or characteristics of train dynamics (Fuchsberger, 2012). This layer collect the information together and calculate the different available routes.

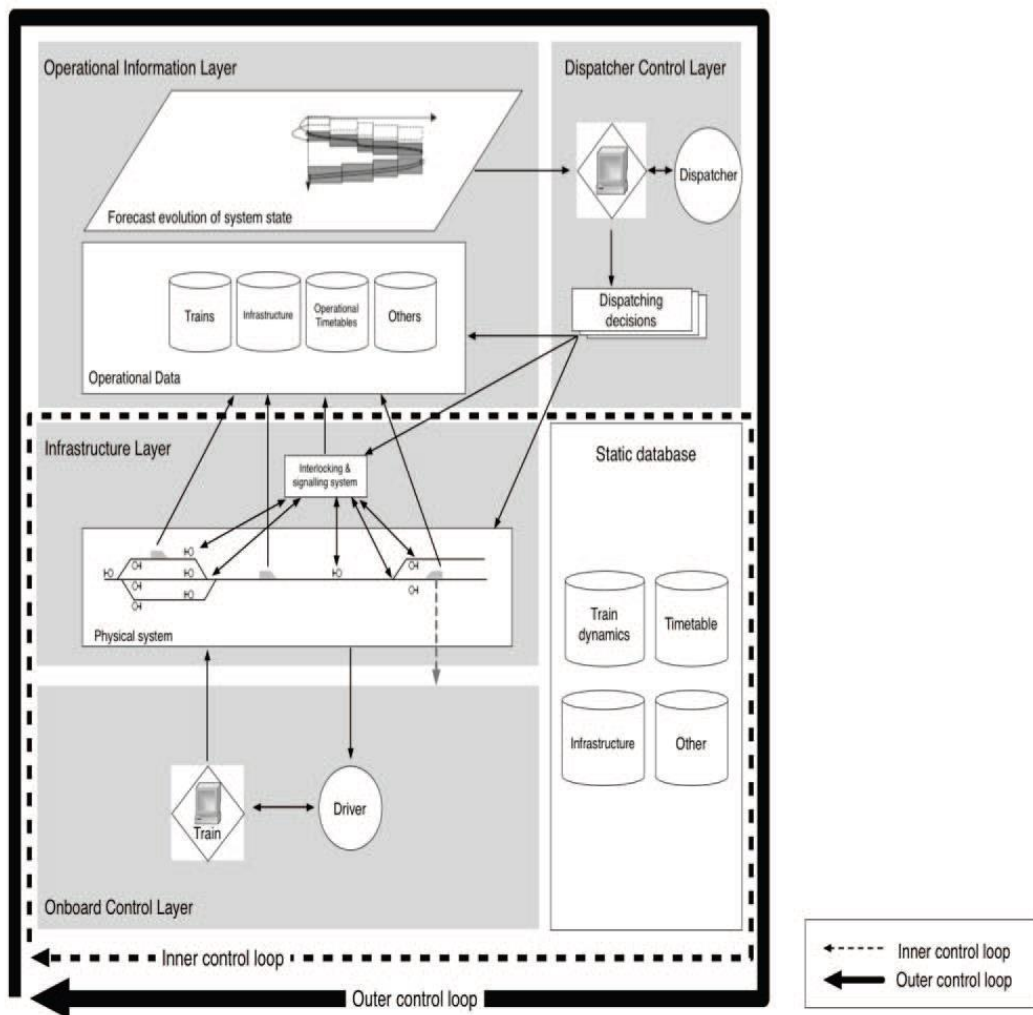


Figure 22: A dispatcher controls trains through dispatching decisions based on a forecast of train movements in form of a closed control loop (outer feedback control loop); A driver controls train based on signal commands and train dynamics in form of a separate closed control loop (inner feedback control loop). (Source: Xiaolu Rao, 2013)

In the dispatcher control layer, the dispatcher observes at his workstation, and forecasts trains' movement based on his expertise. These dispatching decisions need then to be translated into control actions such as switching commands for signals and switches or movement commands for the control of speeds of trains. If a dispatching decision affects the timetable, the operational timetable has to be updated accordingly. Therefore the three layers – the infrastructure layer, the operational information layer, and the dispatcher control layer – could be described as an outer feedback control loop. (Fuchsberger, 2012) (Rao, Montigel, Rao, & Weidmann, 2013).

Finally, in the on-board control layer the train driver could control the train according to lineside signal commands or driver advisory system (DAS). Drivers often use the information of the static schedule irrespective of the state of other trains. Therefore, another data flow is initiated between the infrastructure layer and the on-board layer as an inner feedback control loop (Rao, Montigel, Rao, & Weidmann, 2013)

However, current train management systems still have some challenges: neither in increasing capacity, such as adding more trains or coaches, nor in improving punctuality and reducing energy consumption and cost (Rao, Montigel, Rao, & Weidmann, 2013). In order to tackle these challenges, railway optimization is supposed to develop a degree of automation, namely Traffic Management System (TMS) in the outer feedback and Automatic Train Operation (ATO) in the inner feedback.

In summary, the future railway for diesel train in my research area should be like Figure 23.

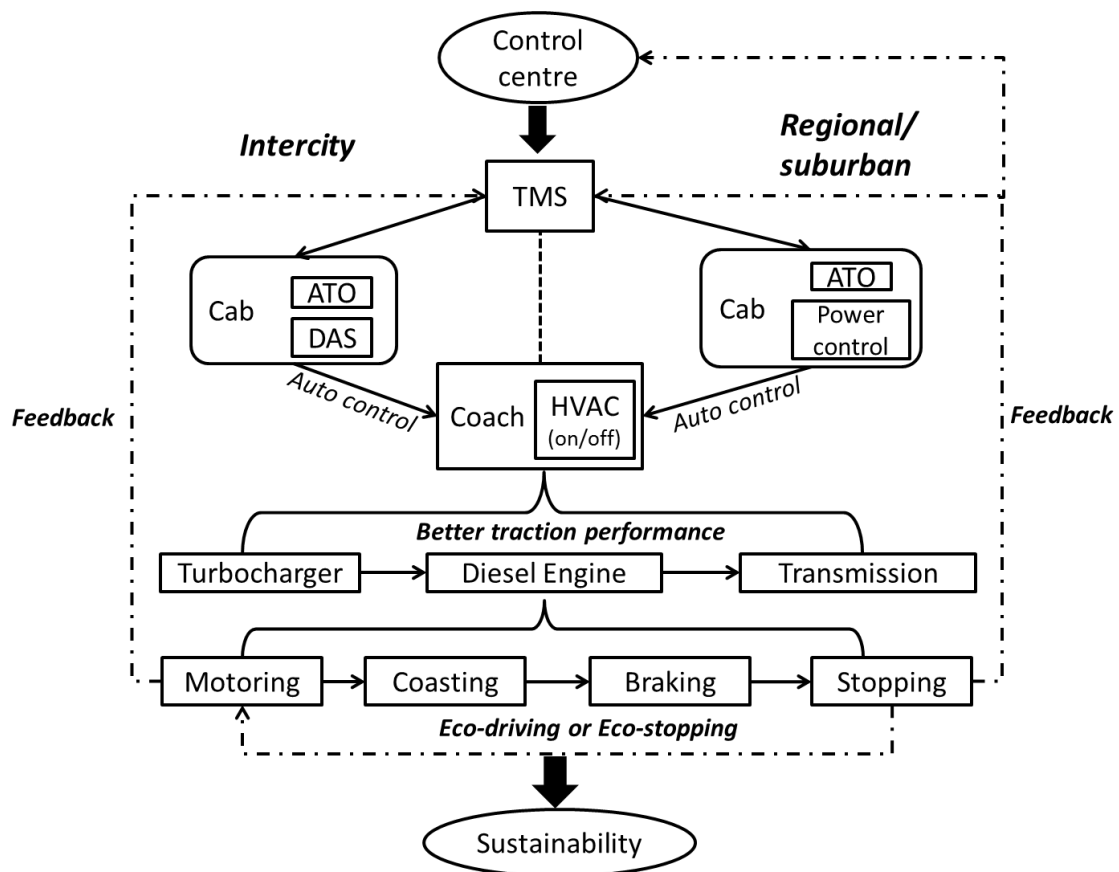


Figure 23: The diagram of future railway energy saving (Author)

# Chapter Six

## 6 Final Conclusions

In this thesis the author has considered the energy saving strategies for diesel passenger trains. The process has been extracting information from the literature based review, investigation and analysis of the data from several train operating companies. At present, the decisions are based on the specific data, however, these strategies could extend to the whole railway system. This thesis has shown that by intelligent shutting down of the engines, energy efficient driving, and the combination of advanced technologies, railway systems could reduce GHG emission, improve fuel efficiency, and achieve sustainable development.

### 6.1 Findings from case studies

A series of case studies have been undertaken and outlined. Each of these case studies demonstrates some aspect of energy saving methods or relevant technical development or analysis of data based on a range of available data. Lessons from each case study have been shown to be combined into the development of a complex and completion framework that allows developing an integrated approach or technology package to do data analysis, information extraction and system optimisation that would benefit for better future thinking and decision making.

The first case study presented was concerned with the fuel consumed by stabling. The investigation results show that the average stabling hours accounts for 40% of total running hours. For specified electric trains in the research, it could save £300K per year. Furthermore, some auto shut down trains have a delay timer of about 25 minutes. Since idling consumes 4-5 litres per engine per hour, reducing the delay timer to 10 minutes could save at least £27K per year. As an extension of the research, selectively shutting down the specified engines and improving torque converter also show big potential for energy saving.

The second case study presented was eco-driving and driver advisory systems as a means of improving energy efficiency. It is mainly based on specified energy consumption calculation of Class 221. The data processing and data analysis as a main method of this study has been designed to demonstrate the energy consumption is affected by idling, Engine RPM and deceleration choice. The outputs illustrate that reducing idling time, developing lower Engine RPM, and more coasting and soft braking could save energy. What's more, as a simple driver advisory guidance, eco-driving could be widely used in regional and suburban routes, with

low capital cost and short-term benefits. In contrast, current DAS is widely used in intercity routes with stable advice to optimise running trajectory.

The research has also, beyond the original scope, introduced a modern traffic management system. The increase in traffic capacity and complexity of the railway system demands real-time traffic control. A traffic management system is able to optimise traffic fluency and show energy saving potentials. The performance of ‘Eco-driving’ and ‘Intelligent Shutting Down’ can be improved by optimising traffic fluency and real-time communication by intelligent TMS.

The thesis also shows the benefits of collaborative research between rail industries. The ROSCOs, TOCs, and manufacturing industries have worked in partnership showing the efficiency of energy saving by improving the technologies. The successful cooperation of TOCs and manufacturing industries include updating software for ‘sleep mode’, SLU improvement for ‘auto shut down reduction’, and engine modernisation etc.

## 6.2 Barriers and Recommendations

The research was heavily supported by TOCs, so the results are tightly specified. The barriers to adoption of more efficient diesel powertrain systems identified include:

- Specific limitation – The fuel saving and financial saving were conducted in a specific situation, with limited academic input into the routing simulation.
- Route variation – for eco-driving, it is seriously influenced by gradient, uphill and downhill could show the different performance.
- Customer satisfaction – some energy saving methods might conflict with customer experience.
- Payback period- some technology implementation was limited by payback period. ROSCOs need payback over the remaining life of the assets and TOCs require payback within the franchising period.
- Reliability – Some strategies like selectively shutting down might cause running engines’ unexpected failures.
- Overhaul – Maintenance and overhaul of trains is an issue. Some diesel train modifications can change maintenance requirements with associated cost implications. Approval of overhaul organisation is required for most modifications.

- Limited cooperation between rail industries – Lack of information and technology communication with rail industries would limit resources constraints. This is due to the competition between TOCs.
- Weather conditions – Shutting down policies show limitation of weather. For example, on cold days we need to retain train heating or on hot days we need to consider retaining air-conditioning.
- Fuel measurement – Accurate and precise on board measurement of real-time fuel consumption could improve investigating efficiency. Existing fuel measurement and monitoring is based on dispensed fuel and mileage or modelled from train data.

In order to improve the energy efficiency of GB rail that focus on the actions and efficiency, it could consider installing precise fuel metering, temperature detection, improved automatic level for train monitoring and control, classify routes with fleets, and enhance stakeholders' engagement, further to achieve package improvement.

### 6.3 Further Research

The Railway system is a rapidly developing complex and integrated system. The future railway would be smarter and faster, fitted with automatic train control and on advanced telecommunication system. As complexity of the system increases, it is necessary to understand and update information and technologies better and faster, thus better energy saving advice and smarter energy control decisions within the railway is enhanced. This thesis has presented the idea about package in the diagram showing the future for 'shutting down' and 'eco-driving'. The integration and combination of multiple technologies in different rail industries shows much potential for technical cooperation and academic communication.

The focus of future work is to build a series of energy saving models which could promote technology packages. A number of technology packages could be applied to existing and new rolling stock to improve GB fleet diesel fuel consumption as a whole. Payback periods can be reduced by joining forces and applying improvements across as much of fleets as possible. In addition, the author would like to engage in building information modelling, doing simulation experiments, which could promote the collaboration between rail industries. By working together, the GB rail industry can improve the commercial viability of more fuel efficient technologies and implement better long-term solutions.

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