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FACULTY OF ENGINEERING AND THE ENVIRONMENT

Civil, Maritime and Environmental Engineering and Science
Transportation Research Group

Selection of Low Carbon Technologies for Heavy Goods Vehicles

by

Anthony Velazquez Abad

Thesis for the degree of Doctor of Engineering

May 2016

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF ENGINEERING AND THE ENVIRONMENT

TRANSPORTATION RESEARCH

Thesis for the degree of Doctor of Engineering

SELECTION OF LOW CARBON TECHNOLOGIES FOR HEAVY GOODS VEHICLES

Anthony Velazquez Abad

Profit margins in logistics are very tight and reducing fuel costs is critical to remain competitive. Customers and policy makers are becoming more sensitive towards climate change due to the links between fossil fuels and global warming. This research presents a framework to help decision makers to select the optimal heavy goods vehicles' specification that minimises their carbon emissions cost-efficiently given their aversion to risk.

The framework developed, uses a broad range of methodologies, techniques and tools including carbon emission lifecycle analysis; simulations; live trials; statistical analysis; metaheuristics and multicriteria decision analysis. An assessment of the waste-to-fuel opportunities of quick service restaurants showed that these could cover around 5% of the energy needs of UK commercial fleets and it was found that used cooking oil could reduce diesel emissions by over 85%. Among the range of scenarios built, the solution recommended by the framework indicated that all vehicles should fit spray reduction mudflaps, low rolling resistance tyres, automatic tyre monitoring systems and lightweight materials. While urban HGVs should also have automatic manual transmissions, regional and long-haul HGVs should include aerodynamic trailers and predictive cruise control instead. Compared to the do-nothing scenarios, the net present costs of urban, regional and long-haul vehicles can be reduced by 3%, 9.4% and 10.7% and their GHG emissions by 7%, 14.6% and 17.1%, respectively. This results in savings between £2.7M to £4.4M and 7,950 to 8,262 t CO_2 eq. for the whole fleet of the industrial sponsor over 5 years. The lowest cost solution could save £5.8M and 27,684 t CO_2 while carbon minimisation one could save over 30,000 tonnes and £2.9M, with current energy prices. The results suggest that diesel technology HGVs can still play a role in the decarbonisation of road haulage and that the uptake of low carbon technologies is highly influence by the risks aversion of the decision maker and duty cycle. The results demonstrate that the EU 2020 targets of delivering 10% savings from road transport by 2020 are perfectly feasible.

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LIST OF ACCOMPANYING MATERIALS

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DECLARATION OF AUTHORSHIP

I, Anthony Velazquez Abad

declare that the thesis entitled

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and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

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- where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
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- where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
- parts of this work have been published as: Journal and conference papers

Signed: ....

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EPSRC
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ABBREVIATIONS

3PL	Third-party Logistics Provider
AD	Anaerobic Digestion
AHP	Analytic Hierarchy Processes
AMT	Automated Manual Transmissions
APU	Auxiliary Power Unit
AQ	Air Quality
AT	Automated Transmissions
B100	Fuel with 100% Biodiesel
BEV	Battery Electric Vehicle
Bio	Biogenic
BTG	Biomass to Gas
BTL	Biomass-To-Liquid
CBG	Compress Biomethane Gas
CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power
CI	Compression Ignition
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CONCAWE	Conservation of Clean Air and Water in Europe
CSR	Corporate Social Responsibility
CVT	Continuous Variable Transmission
DC	Distribution Center
DD	Double Decker
DECC	Department of Energy and Climate Change
DEFRA	UK Department for Environment, Food and Rural Affairs
DERV	Fuel for diesel-engine road vehicles
DfT	UK Department for Transport
DME	Di-methyl Esther
DMFC	Direct Methanol Fuel Cells
DOE	US Department of Energy
DoE	US Department of Energy
EC	European Commission
EIA	Energy Information Administration
EPA	US Environmental Protection Agency
EPSRC	Engineering and Physical Sciences Research Council
ETC	European Transient Cycle
e-Trucks	Battery Electric Trucks
EU	European Union
FAME	Fatty Acid Methyl Esther
FAO	Food and Agriculture Organization of the United Nations
FCR	Fuel Consumption Reduction
FF	Fast Food
FFSC	Fast Food Supply Chain
FiTs	Feed-In-Tariffs
FSC	Food Supply Chain

FT	Fischer-Tropsch Process
GA	Genetic Algorithm
GDP	Gross Domestic Product
GHG	Green House Gases
GTL	Gas-to-Liquid
GVW	Gross Vehicle Weight
GWP	Global Warming Potential
HDV	Heavy Duty Vehicle
HEV	Hybrid-electric vehicles
HFC	Hydrofluorocarbons
HGV	Heavy Goods Vehicle
HVO	Hydrogenated Vegetable Oil
ICE	Internal Combustion Engine
IEA	International Energy Agency
IPCC	Intergovernmental Panel Climate Change
KERS	Kinetic Energy Recovery Systems
KPIs	Key Performance Indicators
LAIR	Liquid Air (cryogenic air gas)
LBG	Liquid Biomethane Gas
LCV	Long Combination Vehicles
LCVP	Low Carbon Vehicle Partnership
LDV	Light Duty Vehicles
LHV	Lower Heating Value
LIN	Liquid Nitrogen
LNG	Liquid Natural Gas
LPG	Liquid Petroleum Gas
LSFC	Load Specific Fuel Consumption
MARR	Minimum Acceptable Rate of Return
MB	Martin Brower UK
MCA	Multicriteria Decision Analysis
MDV	Medium Duty Vehicle
MeOH	Methanol
MOT	Ministry of Transport
NAEI	UK National Atmospheric Emissions Inventory
NG	Natural Gas
NO_x	Nitrogen oxides
NPC	Net Present Cost
NPV	Net Present Value
O_3	Ozone
OECD	Organisation for Economic Cooperation and Development
OEM	Original Equipment Manufacturers
OMCG	CNG from Municipal Waste
PaHs	Polycyclic aromatic hydrocarbon
Pb	Lead
PEMFC	Proton Exchange Fuel Cell
PHEV	Plug-in Hybrid-electric Vehicles
PM_x	Particulate Matter
QSR	Quick Service Restaurant
R+D	Research and Development

REGO	**Renewable Energy Guarantees of Origin**
RHIs	**Renewable Heat Incentives**
RTFC	**Renewable Transport Fuel Certificates**
RTFO	**Renewable Transport Fuel Obligations**
SAFED	**Safe and Fuel Efficient Driving**
SC	**Supply Chain**
SCET1	**Ethanol from Waste Wood pathway**
SCG	**Spent Coffee Grounds**
SI	**Spark Ignition**
SLA	**service level agreement**
SOFC	**Solid Oxide Fuel Cell**
SO_x	**Sulphur Oxides**
SS	**Scatter Search**
SWBT	**New Generation Single-wide Base Tyre**
TCO	**Total Cost of Ownership**
TPMS	**Tyre Pressure Monitoring System**
tkm	**Tonne x kilometres**
TOFA3a	**Tallow to FAME waste-to-fuel pathway**
TOHY1a	**Tallow to HVO waste-to-fuel pathway**
TRU	**Transport Refrigeration Unit**
TS	**Tabu Search**
TTW	**Tank-to-Wheel**
UCO	**Used Cooking Oil**
UK	**United Kingdom**
V2G	**Vehicle-to-Grid**
VED	**Vehicle Excise Duty**
VOC	**Volatile Organic Compounds**
WHDC	**World Harmonised Duty Cycle**
WHSC	**World Harmonized Steady Cycle**
WHTC	**World Harmonized Transient Cycle**
WOFA3a	**UCO to FAME waste-to-fuel pathway**
WOHY1a	**UCO to HVO waste-to-fuel pathway**
WTT	**Well-to-tank**
WTW	**Well-to-Wheel**
YIMBY	**Yes In My Back Yard**

1. INTRODUCTION

Chapter Aims:

To highlight the relevance of the research

To rationalise the research questions

To outline the thesis structure

This thesis is the outcome of a four-year research project supported by the Engineering and Physical Sciences Research Council (EPSRC), the University of Southampton and Martin Brower UK Ltd. (MB), a subsidiary of a global leading food distribution company. The industrial sponsor supplied operational data, qualitative feedback and testing vehicles, allowing the simulation and trial of technologies that helped to shape the development of the mathematical models included in the framework. Other companies have contributed with opinions, software licenses and technical support to this research including vehicle manufacturers, suppliers of low carbon technologies, vehicle workshops and commercial software developers. A list of the main companies contacted appears in Appendix 1, where details of the unstructured interviews are illustrated.

This thesis determines the realistic carbon savings that heavy goods vehicles (HGVs) can achieve under several scenarios in the short term and discusses policy actions that could help to promote more fuel-efficient vehicles in the medium and long-term. It does this by developing a decision making framework that can help logistics companies, but also vehicle manufacturers, leasing companies and policy makers to specify the right combination of energy efficient technologies that minimise GHG emissions cost-efficiently and with acceptable levels of risks, according to operational, financial, engineering and environmental factors as well as qualitative preferences. To determine the optimal combinations of technologies that maximise carbon savings, this research combines the findings of simulations and real world trials from primary and secondary sources and it uses a combinatorial metaheuristic approach and multicriteria decision analysis to yield a range of preferred solutions.

Based on financial, operational, environmental and engineering data, 45 scenarios based on rigid and semi-articulated HGVs have been built representing urban, regional and long-haul deliveries duty cycles. This includes three fuel price projections; one assuming the central DERV prices forecast by DECC (2014e) and the prices for B100 paid by the industrial sponsor; and the another two with prices 20% higher and lower than these. For each one, five objective functions were modelled. GHG emission prices were considered to be £0/tonne CO_2eq[1]., as in EU payment of these are only enforced to power stations, heavy energy use industrial plants and aircraft operators (European Commission, 2013b); however other carbon prices have been used to calculate sensitivity analysis. The different levels of GHG emissions have been qualitatively assessed in the multicriteria decision analysis model. The framework helps to investigate the impact of energy efficient technologies and how these can support the reduction of GHG emissions in the period 2015-2020[2]. The results are compared to future EU targets to evaluate if these can be realistically met with the current technology. A review of policy measures for the promotion of certain HDV energy efficient technologies is also put forward and the conflicts between air quality and GHG gases emissions are discussed.

This chapter is divided into five sections. Firstly, the general reasons for undertaking this research are explained. Secondly, the particular research questions are introduced. In the third section, the structure of the thesis is presented. After outlining the scope of the work, in the final section the contribution to knowledge is elucidated.

1.1 PROBLEM DESCRIPTION AND MOTIVATION

HGVs use mainly fossil fuels and there is a drive to decarbonise transport to reduce its impact on climate change. As reflected in European Commission (2011), to avoid having to limit transport demand it is necessary to reduce its dependency on oil without compromising its efficiency. The private sector may be interested in reducing GHG emissions when this does not influence negatively on profit margins. This is not always possible due to the high cost of some of the technologies that improve energy efficiency. Furthermore, evaluating the trade-offs between a large number of low carbon technologies is very difficult for logistics companies when fuel savings, costs, carbon emissions and technological risks are considered simultaneously. This thesis supports the decision making process by providing a robust framework that can yield solutions depending on multiple criteria, quickly and consistently.

Rising food costs and volatile fuel prices coupled to energy insecurity and environmental concerns have led to an increased interest in how to maximise the use of existing resources and particularly, exploring newer energy pathways such as waste-to-fuel opportunities from food supply chains. Reducing fuel consumption

[1] The heuristics model can also factor in different carbon prices; however, these are not currently being enforced to logistics operators.

[2] The heuristics model can optimise vehicle specifications for the year 2010, 2015 and 2020.

and using biofuels from waste streams can improve energy security; reduce fuel costs and landfill disposal fees, while strengthening the competitive position of the firm, overall in a sector where profit margins are very thin.

There is scientific consensus that anthropogenic GHG emissions, such as the ones produced by fossil fuels, lead to global warming and this is responsible for climate changes and extreme weather events across the planet (IPCC, 2014). It is assumed that if concentrations of CO_2 eq. in the atmosphere are kept under 550 ppm, the most dangerous consequences of climate change could be avoided (Renewable Fuels Agency, 2008). This equates to limiting temperature increases to 2°C and it implies 40-70% lower GHG emissions by 2050 (compared to 1990 levels) and near zero GHG emissions by 2100 (IPCC, 2014). If this is not achieved, it is considered that the impacts of global warming by the end of the 21^{st} century may become irreversible (IPCC, 2014). Achieving this goal will improve the adaptation prospects of societies to climate risks and it will reduce the mitigation costs and technological, economic, social and institutional challenges (IPCC, 2014). Adapting road haulage to climate change is critical to avoid disruptions in logistical flows due to damaged infrastructure and extreme weather events; however avoiding global warming all together seems cheaper than building more resilient infrastructure, vehicles and services to mitigate losses derived from operational disruptions. As a result, promoting sustainable development and combating climate change have become integral aspects of energy planning, analysis and policy making in many countries (IEA, 2010). Furthermore, even if climate benefits are put aside, actions that mitigate climate change favours the self-interest of countries by providing a national net economic benefit (Green, 2015).

1.2 RESEARCH QUESTIONS AND OBJECTIVES

The research questions seek to produce a new understanding of the complex relationships between duty cycles, operational parameters and technical and environmental characteristics of certain low carbon technologies and the trade-offs between quantitative and qualitative objectives.

The framework developed for this research contributes to the discussion in the area of energy efficient technologies for HGVs proposing optimal vehicle configurations using the fast food supply chain as a case study. The specific research questions addressed are:

Q1 – What are the vehicle, powertrain, fuel and refrigeration technologies that can yield the greatest GHG emissions savings cost-efficiently for specific duty cycles and vehicles between 2015-2020?

Q2 – What is the potential of the fast food supply chain to produce fuels from its own waste and what are the carbon intensities and GHG savings from each pathway?

Q3 – What methodology can be developed to assist decision makers to select the adequate combination of low carbon technologies when there are conflicting objectives?

Q4 – How accurately can simulations and real world trials predict fuel consumption reductions of HGVs' technologies?

Q5 – How should spending on low carbon innovation for HGVs be prioritised?

Q6 – What policy measures could steer the reduction of GHG emissions from HGVs technologies?

1.3 THESIS OUTLINE

This thesis consists of six main chapters that represent the chronologic evolution of the work undertaken (Figure 1).

Chapter 1 introduces the observed problem, outlines the gaps within the current literature, introduces the research questions, illustrates the structure of the thesis and highlights the contribution to human knowledge derived from this research.

Chapter 2 compares the industrial sponsor operations with UK national average fleets and discusses the relevance of this research in the wider context. The aim of this chapter is help readers to identify whether the results found are applicable to their organisations.

Chapter 3 reviews the evidence and previous literature research of the key areas that need to be considered to understand the background of the framework developed in this thesis. This includes the relationships between road haulage, GHG emissions and global warming. In this section, the equations underlying the principles of energy consumption of vehicles are described and the relevance of driving cycles illustrated. The results of low carbon technology experiments and vehicle trials developed by secondary sources are discussed as well as the technical and physical principles of some technologies and their performance in regards to carbon savings. As fuel technologies play a key role in the decarbonisation of road haulage in this section, the topic of biofuels from waste streams is described in detail. The main waste streams in the fast food supply chain and the carbon emissions savings of several of these waste-to-fuel

pathways are explored in detail. Finally, a review of simulation systems, decision making techniques and tools for low carbon technology selection are introduced.

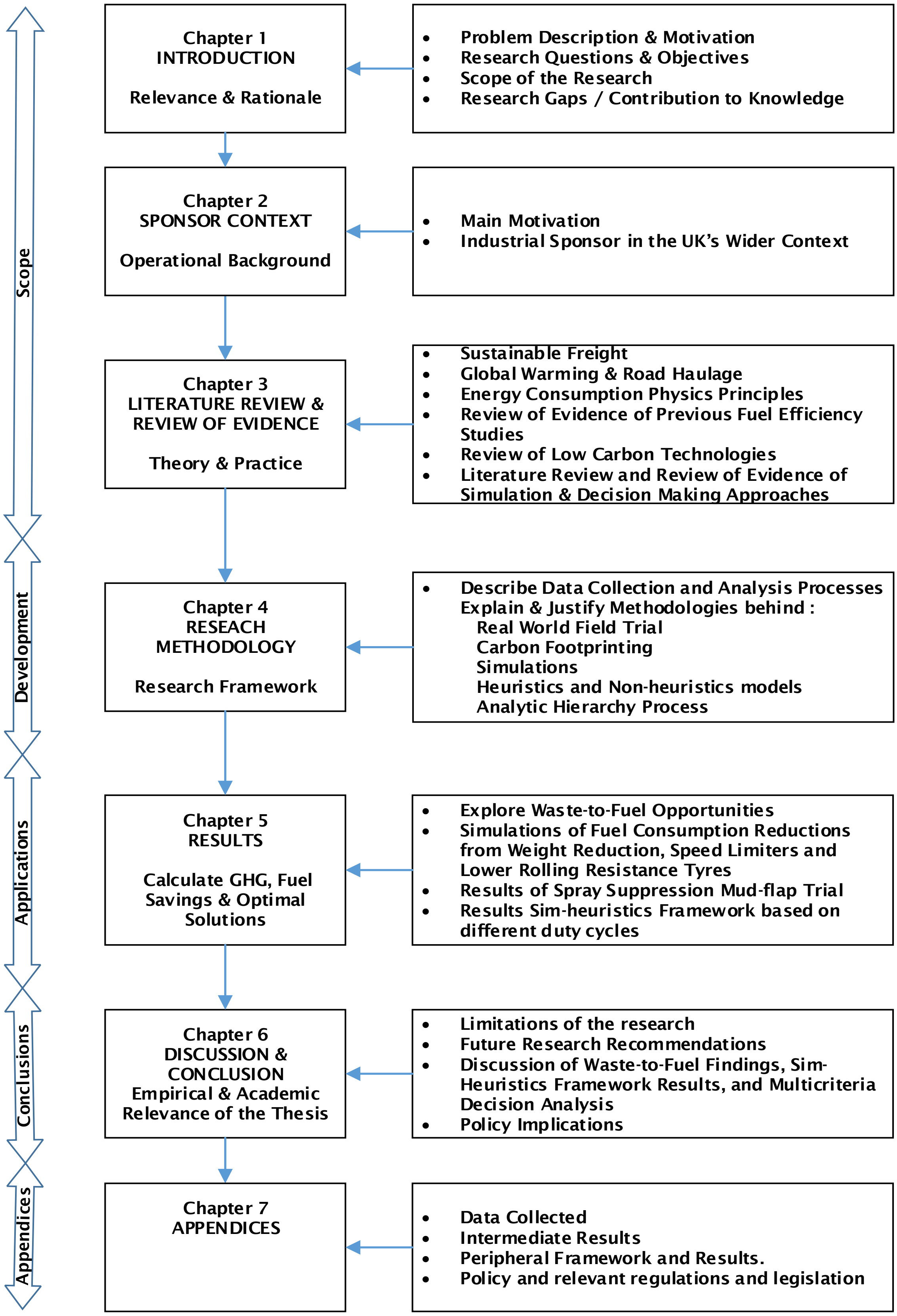


Figure 1. Thesis structure.

Chapter 4 develops and describes a framework linking the theoretical and empirical principles underlying this research, by using different data sources and techniques. In this section, the methodology followed for simulating and trialling technologies and vehicles is explained as well as the methodology conducted to audit waste-to-fuel prospects. Also, two bespoke quantitative models are explained and the selection of an evolutionary metaheuristics approach justified. Finally, the multicriteria decision analysis approach followed is described.

Chapter 5 presents the quantitative and qualitative results. Using primary data collected from field live trials with two vehicles provided by the industrial sponsor, the fuel consumption of spray suppression mudflaps was evaluated. Access to data from the telematics systems of the sponsor fleet from 123 vehicles was used to evaluate the fuel savings of a driving assistance device and to calculate operational parameters used in simulations and in the metaheuristics model. Further quantitative results were simulated with computer flow dynamics. The results were enriched with a literature review, review of evidence and commercial data to produce a financial analysis of the optimal combination of low carbon technologies following a metaheuristics model. Using secondary data captured for two years by the industrial sponsor regarding all its waste collections, in combination with primary data regarding their supply chain structure, allowed the calculation of carbon emission factors for several waste-to-fuel pathways. Qualitative assessments of pairwise comparisons of costs, GHG emissions and risks levels were provided by the industrial sponsor and used in an analytic hierarchy process. The outputs of the quantitative model were weighted against others, resulting in a ranking of preferred vehicle configurations, where quantitative and qualitative factors were assessed, according to the preferences of the decision maker.

Chapter 6 discusses the findings and their implications for logistics fleets, leasing operators, vehicle manufacturers and public policy makers and it finishes with concluding remarks. In this chapter, the methodological challenges found during this research were also discussed.

Chapter 7 presents appendices backing up assumptions and calculations and it provides methodological details and results of different analysis and strategies.

1.4 SCOPE OF THE RESEARCH

The DfT defines HGVs as vehicles over 3.5 tonnes; however, in this thesis the focus has been narrowed down to vehicles type N_3 BA (lorries) and N_3 BC (tractor units with semi-trailers); these are vehicles designed for the carriage of goods, having a maximum mass exceeding 12 tonnes and with a conditioned body with insulated walls and equipment to maintain the interior temperature as defined by the European Commission (2009a). These vehicles are similar to Class 8 vehicles, as classified in the USA. Due to the involvement of an industrial sponsor, the emphasis is on refrigerated rigid trucks (18 tonnes GVW) and semi-articulated trucks (33 tonnes GVW). These vehicles ship ambient, chilled and frozen food products under urban, regional and long-haul duty cycles.

The original aim of this research was to produce a framework that could assist the decision making process of procuring more energy efficient HGVs by reducing GHG emissions at the lowest net present cost of ownership. At the end, the initial aims were stretched to include other qualitative aspects that may be relevant to different stakeholders. The framework uses mainly secondary sources of information to obtain the fuel consumption reduction (FCR) of certain technologies but it also uses and explains how to simulate some of them; how to conduct live trials; how to calculate the carbon emission factors of several waste-to-fuel pathways according to the characteristics of the supply chain of the industrial sponsor; it puts forward a metaheuristics model that choses the optimal combination of low carbon technologies under certain scenarios; it develops a novel way of capturing vehicle CAN-bus data for posterior analysis of driving cycles; and finally, it suggests and applies a multicriteria decision analysis (MCA) approach to assist in the analysis of multiple and often conflicting criteria.

The framework is specific to the case study; the selection of energy efficient technologies for refrigerated road haulage vehicles based on the operational characteristics of Martin Brower UK Ltd., its financial particularities and the emissions of the waste-to-fuel opportunities of its supply chain. The framework can be adapted to different types of fleets, logistics organisations, vehicle manufacturers and leasing companies, and public policy making bodies by simply changing some parameters in the simulations, metaheuristics model and the scores in the analytic hierarchy process. The framework developed is compatible with other HGVs (bigger or smaller, with or without transport refrigeration units) as well as other types and categories of vehicles (e.g. urban buses, coaches, refuse trucks, military vehicles, off-road vehicles). However, the outcome of the metaheuristics method requires the input of the fuel consumption reduction achievable by each single technology or package of technologies according to specific duty cycles. Further simulations and tests are required for those cases. The flexibility of the framework makes possible the inclusion of air quality emission reduction technologies and other strategic objectives; however, these were beyond the scope of this research.

This research has quantified the WTW GHG emission factors for fuels produced from the waste generated by the industrial sponsor's supply chain. GHG emissions factors for other chains should consider the carbon reporting figures published by Governmental sources or conduct their own carbon audits.

This research focuses on the selection of low carbon technologies; however, further fuel and GHG emissions can be saved by complementing the results with other non-technological approaches for energy efficiency that are outside the scope of this research (e.g. driving behaviour training, demand reduction and hard and soft policy measures).

1.5 CONTRIBUTION OF THE RESEARCH

The approach undertaken in this research (sim-heuristics), combining simulations and operational research techniques (metaheuristics and multicriteria decision analysis) is novel and constitutes an innovative contribution to technology selection for HGVs. Previous literature calculated fuel savings from technologies chosen by the user; however, this research automatizes the selection process according to certain parameters and preferences.

The outcome of this research is a powerful framework that improves the quality of the decision making process for the procurement or specification of green HGVs and embraces most areas that can have an impact, providing a very descriptive methodological guideline. The metaheuristics approach creates insights into the relationships between financial factors (e.g. rates of return, costs), operating conditions (e.g. impacts of duty cycles on fuel consumption), vehicle energy efficiency technologies (e.g. low carbon technologies) and environmental aspects (e.g. GHG emissions). The MCA approach also provides interesting insights into the relative importance and trade-offs between different objectives. This research is also an interesting source of information for policy making as it discusses the conflicting objectives between the air quality and carbon emission reduction agendas, the impacts of discriminative subsidy structures of some biofuels and it provides guidelines of the most efficient low carbon technologies under different scenarios and policy measures to incentivise the uptake of these. Vehicle manufacturers and leasing organisations could also use the framework to provide more robust vehicle specification recommendations to their customers.

Also, as a co-product of this research, an innovative device for capturing can bus data has been developed. This SAE J1939 to OBD2 device allows the transmission of data wirelessly to a Tablet where dashboard and engine data can be captured and transferred into a file for further statistical analysis.

2. THE INDUSTRIAL SPONSOR

Martin Brower UK, Ltd. (MB) is a third party logistics supplier that manages the logistics of a world leading fast food chain. This includes managing distribution and contracts with other freight companies, warehousing and the provision of logistic IT services. MB has a fleet of over 150 vehicles around the UK, dedicated mainly to refrigerated food road haulage and the reverse logistics of quick service restaurant waste.

2.1 THE INDUSTRIAL SPONSOR AND ITS MOTIVATIONS

MB works mostly for a single customer in most of the markets where it operates worldwide. This position grants MB's client a strong bargaining buying power, allowing it to easily dictate contractual terms. MB's main customer is ISO 14,001 accredited and it enforces this environmental management system on its suppliers, including MB. This represents a strong driver for environmental excellence across the whole supply chain. This power, on the other hand, leads to some inefficiencies. As part of the customer branding strategy and due to safety concerns, MB vehicles are decorated with its main client corporative image and their vehicles are not allowed to increase loading factors by sharing empty trailer capacity. MB's HGVs have a loading factor over 90% in origin; however, back-hauling loading factors cannot be maximised for the aforementioned reason, and trailer loads consist mainly of reverse collections of separated waste fractions.

MB operates as the sole 3PL provider for its main customer in more than half of the worldwide markets where they operate. This one-to-one relationship does not mean that there is a monopoly in the service provision, as there are many 3PL companies servicing the food market. It is not a monopsony either, as MB could chose at any moment to tender to other logistics competitors. There is, nevertheless, a very close relationship between both parties with integrated IT systems and business processes as part of a long lasting partnership spanning several decades. Typically, logistics firms have many customers who make the relationship between MB and their main customer atypical among UK 3PLs. For example GIST is the sole distribution supplier for KFC, however GIST deals with many other customers. Having several customers reduces risk exposure to the business success of the single customer and it presents economies of scale, which facilitates capital intensive investments. On the plus side, the performance related long-term contracts that MB enjoys give the business enough stability and security to consider making capital investments (e.g. vehicles, trailers, warehouses, infrastructure) that have a life expectancy superior to the typical

length of a regular 3 or 5 years contract. Examples of potential investments that MB has considered during this research included the adaptation of the diesel fleet to biomethane and using cryogenic refrigeration instead of conventional transport refrigeration units; investments that both would require the deployment of infrastructure with a life expectancy of 15 years or longer.

Based on The Logistics Report 2015 (FTA, 2015), the typical average profit margin in logistics from 2008 to 2013 was 2.5%. With such small returns, keeping costs at a minimum is critical to remain competitive in the marketplace. Based on data from FTA (2014b), Table 1 indicates the relevance of fuel and labour costs in the total costs of HGVs. The percentage of fuel costs increases with vehicle GVW and number of axles. Fuel costs represent under a third of the total costs of rigid HGVs (18t 4x2 axles) and a third for artics (33t 4x2 axles); the main vehicle types used by MB. For this reason, focusing on fuel consumption reduction is a very important driver not only for MB but also for any other logistics companies running HGVs over 7.5t. Any improvement in this area may have a multiplicative effect on the profit margins and at the same time, it can help meet GHG emissions targets.

Table 1. Percentages that fuel, labour and other costs represent for different vehicle types. Adapted from FTA (2015).

Vehicle type	Fuel costs as a % of total costs	Labour costs as a % of total costs	Other Fix & Variable Costs (%)
3.5t van - diesel	16	63	22
7.5t rigid	21	45	35
10 - 12t rigid	26	36	38
12 - 14t rigid	22	39	39
16 - 18t rigid	29	39	33
26t rigid	30	35	36
32t rigid	30	32	38
33t (2+2) artic	33	30	36
32.5t drawbar	30	32	38
38t (2+3) artic	34	29	37
38t (3+2) artic	33	29	38
40t (2+3) artic	34	29	37
44t (3+3) artic	36	27	38

MB services are bound by service level agreements (SLA) combined with an open book cost disclosure approach to determine costs, service performance and quality levels, bonus' incentives and the recapture of excess profits. Every year, both parties agree on unit rates and other key performance indicators (KPIs) and after reviewing variances for the financial year, a profit margin percentage is paid on top of MB's costs. This reduces the risks for MB as profit margins in distribution are very sensitive towards fuel price increases. This also benefits the customer as they do not have to pay for the risk-premium that MB should otherwise charge to cover risks from potential fuel price increases. This has

proven especially beneficial for the client during the decrease in fuel prices between 2014 and 2015. As a profit margin is paid on top of the costs, one would assume that the higher the costs, the higher the profits for MB and the lesser the incentives for waste reduction and environmental performance. However, this is not the case for three main reasons i) the open book policy allows the client to review and control cost trends over time; ii) the efficient contract management framework currently in place establishes strict targets related to financial, operational and environmental performance; iii) there is an environmental mandate resulting from ISO 14,001 which both parties adhere to.

There is a considerable trust between both parties and a clear vision that they compete against rival supply chains and not between each other. When benefits can be obtained, they do not consider their relationship like a zero-sum game but like a win-win situation that will improve the efficiency of the chain benefiting all parties. For example, the “fee contract” facilitates that the customer enjoys free reverse logistics services while MB can get an additional stream of revenue from selling these arisings. This is evident when selling used cooking oil (UCO) and buying back biodiesel at a discounted market price. These lower fuel costs, at the same time, also benefit the main customer as transportation costs also decrease.

It seems evident that the survival of MB depends largely on the success of its main customer. Key factors in the strategy of the customer seem to be an increasing market share (quota) in its main markets, improving shareholder value, introducing innovation in technologies and menus, and achieving leaner operations and improving brand image and operations through excellent environmental practices.

Reducing GHG emissions supports the strategy of the whole supply chain in two different ways. Firstly, lowering emissions typically means lower energy consumption and therefore, cheaper fuel bills and transportation costs. This may lead to higher profit margins and lower total costs, which could improve shareholder value and a market share respectively. For example, better routing and scheduling and longer combination vehicles could improve fleet efficiency by reducing the total mileage travelled and the number of vehicles and drivers required. This typically could lead to cheaper costs, improving bottom line results even further. In addition, this also helps to reduce congestion levels which improves air quality and reduces noise pollution. Reducing nuisance and complaints from the local community may support the application to open new restaurants. Furthermore, intelligent transportation systems (ITS) technologies not only help to reduce emissions but they can also improve restaurants' performance. Geofencing for example, is used to accurately inform restaurant managers of the time of arrival of deliveries. This allows the effective organisation and scheduling of staff, reducing wasted waiting time. Secondly, there are benefits associated with promoting a greener image. A survey conducted by DHL found that within the next 10 years, 51% of their end consumers would be willing to favour a company with green transport/shipping solutions over a cheaper provider (DHL, 2010). This implies that sustainability can have a positive impact on operating cash flow by increasing sales and ultimately, benefitting shareholders' value.

Reducing GHG emissions is key to MB community involvement, benefitting society as a whole by mitigating some of the externalities of freight transport. The reason for MB getting involved in this research was a long-term strategy focusing on sustainability leadership. MB has undertaken many environmental initiatives, including an environmental award winning program for collecting and processing UCO from restaurants into biofuel for HGVs. The company is very proactive and pursues initiatives aiming at reducing landfill contributions, more efficient energy use and process improvements for waste minimisation.

Decision making process innovation in the selection of low carbon technologies and vehicle specification helps MB to reduce its carbon footprint cost-efficiently (hence improving profitability), at an acceptable risk and at the same time this is aligned with its strong corporate social responsibility strategic goals and the ones of its partner. This also helps MB to obtain reputational gains that benefits the whole supply chain.

2.2 INDUSTRIAL SPONSOR OPERATIONS IN THE UK CONTEXT

MB operations differ from the average national fleet statistics. The reasons are multiple and include the appearance of the load, the type of commodity moved and differences on duty cycles. Looking at the type of commodity moved, Figure 2 shows that food represented over a quarter of the total billion tonne-km moved in the UK in 2013 (DfT, 2015b), whilst for MB, this is its main type of commodity, with the exception of marginal waste collections and non-food promotional products.

The MB fleet consists of 18 tonne rigid lorries and 36 tonne semi-articulated trailers (down plated to 33 tonnes). According to DfT (2015c) these types of vehicles and weight represent 80% of the UK HGVs fleet (Figure 3). From that perspective, it seems that this case study could be applied to a broad vehicle population.

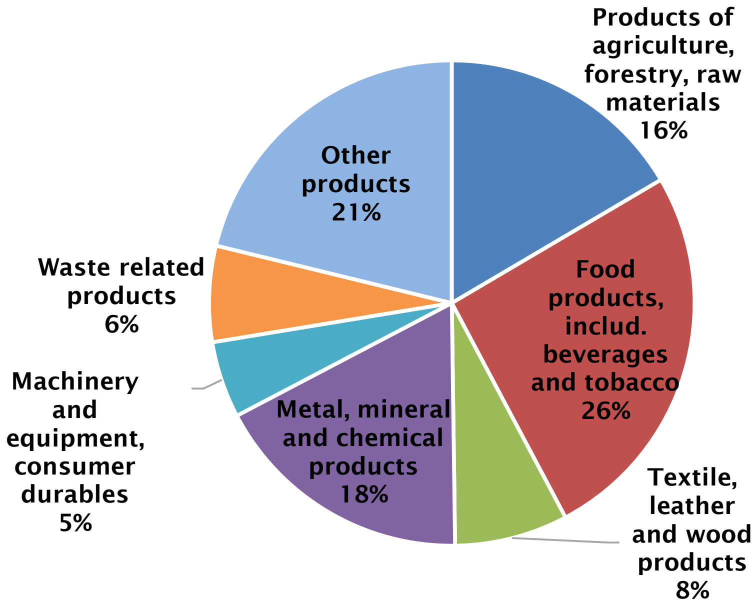


Figure 2. Goods moved by commodity group in the UK (2013).

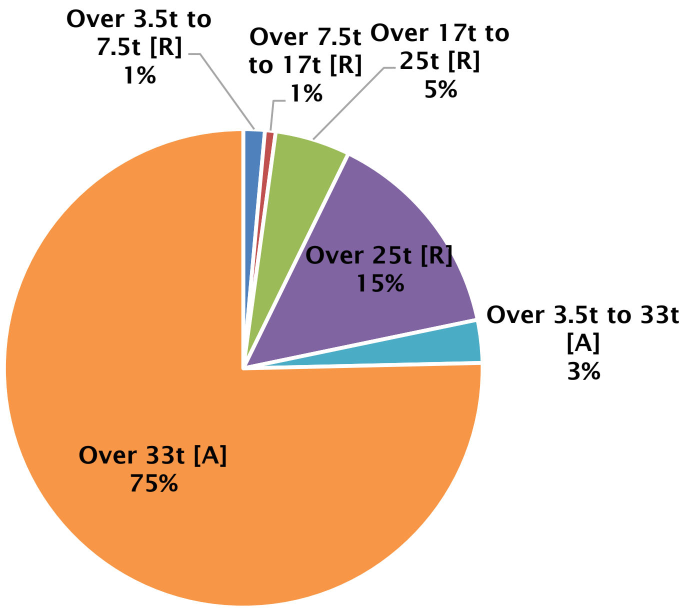


Figure 3. Marketshare of HGVs in the UK by type of vehicle (R=rigid, A=articulated) and gross vehicle weight (2013).

MB freight loads are delivered in roll cages. According to DfT (2015g), this represents just 7% of the UK mode of appearance of load (Figure 4). In the UK, most goods are delivered palletised (32%) which raises the business case for longer and heavier trailers to be used. Double decker trailers (DDT) are designed to carry loads over two floors; however, this is not possible when carrying multi-temperature rolling cages as there is not enough space to fit the cargo, evaporators and seal the different temperature compartments inside the trailer. For this reason, DDT trailers have not been considered in the metaheuristic model developed for this research, as these were not feasible for the industrial sponsor operations. Appearance of load also has an implication on the metrics of GHG emissions. Typically, most 3PL report these in t CO_2/tkm. MB invoices its customer by the number of cases carried, rather than weight or pure volumetric capacity. This means that the ideal KPI for measuring MB GHG emissions is kg CO_2eq. /case-km. However, as this makes comparisons with other fleets very difficult, an average weight per case was used as a proxy.

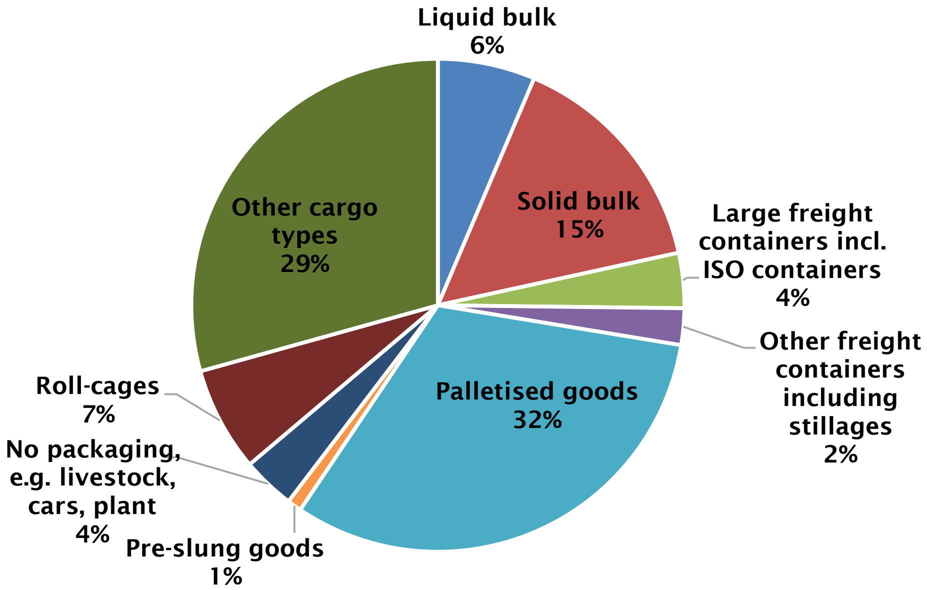


Figure 4. Tonnes-kilometer (tkm) transported in the UK by mode of appearance of load (2013).

Considering that food transport represents 28% of the UK fleet; and rigid lorries and semi-articulated trucks constitute 80% of the national stock; and rolling-cages are used by 7% of the fleets; we could extrapolate that this case study represents more accurately around 1.56% of UK HGVs (this excludes duty cycles and the percentage of refrigerated fleets). The percentage that quick service restaurants' fleets specifically represents is unknown; however, it is reasonable to consider that it may be less than half.

MB routing policy allocates different vehicles considering the fleet mix as a whole. Typically rigid HGVs (18 tonnes) deal with urban duty cycles but can also be routed to regional destinations. Heavier HGVs (36t down plated to 33t) are likely to run long-haul duty cycles; however, whenever parking space is available in urban areas, semi-articulated lorries are also used. Regional duty cycles are serviced with a combination of rigid and semi-articulated HGVs. For the purpose of this research, it has been assumed that MB operations can be classified into three main duty cycles (urban, regional and long haul) whose characteristics have been statistically analysed (Table 2). Trips under 10km have been excluded as those are assumed to be yard trunking movements. Also, trips with unrealistic fuel consumptions (e.g. less than 15l/100km or more than 50 l/100 km) have been eliminated, as these are considered to be errors of the can bus. Some of these characteristics are compared with typical UK HGV fleets for similar duty operations (Table 3). A comparison of averages of length of haul between MB (Table 2) and UK national averages (Table 3) show that despite making shorter trips, MB total average annual vkm and goods moved (tkm) are much higher than the average UK fleet. MB average vkm for CF85 and XF105 (artics over 33t) were 66% and 87% higher than UK national averages respectively. The difference is even larger when comparing rigids (18t), as MB vehicles run 3 times more vkm per year. However, when comparing MB vkm (vehicle kilometres) with the findings of the FTA (2014a) survey for average values, these differences decrease to 25.5% and 41.2% for each artic model and 16.8% for rigids. In the FTA (2014a) study, high mileage fleets reported average vkm of 112,654 km for rigids 16-18t, this is in line with MB rigids and the 136,794 km for artics 33t representing 20% lower vkm than MB artics. Tonne-kilometers transported by artics were also superior by 37% and 81% when comparing the DAF CF85 and XF105 respectively. A possible explanation for this, is that MB vehicles can potentially operate 24h/day, an option not possible for all companies, especially sole traders operating their own vehicles, as the European Working Time directive limits drivers' driving time to 9 hours per day on average (European Parliament and the Council, 2006).

MB average length of haul for urban vehicles was 58.17 km and between 75 km and 83 km for regional (rigid vehicles) and long-haul (artic lorries); while national averages were 70 km and 126 respectively. The reason for such short trips may be the fact that there are 3 DCs strategically located near areas with high concentrations of restaurants. DfT (2015d) statistics show that the amount of vehicle-kilometres (vkm) run each year in the UK has decreased since 2000 (Figure 5). Average vkm may have decreased for several reasons such as the impact of the EU Working Time Directive. As drivers are not allowed to drive more than 56 hrs. per week (or 90 hrs. in a 2 week period), sole traders are likely to do less distance per year. More efficient routing and scheduling management may also contribute to reduce distances travelled and help to improve loading factors, which lead to fewer vkm. Another potential reason to explain the downwards trend from 2005 until 2013 may be related to the reduction in demand resulting from the economic crisis.

Table 2. Average typical operational values for MB in 2014.

MB Operations	Urban	Regional	Long-haul
Tractor Unit Make / Model	DAF CF65 4x2 Rigid	DAF CF85 4x2 Semi-articulated	DAF XF105 4x2 Semi-articulated
GVW (tonnes)	18	33 (plated) (Max 36t)	33t (plated) (Max 36t)
Power	210/250 hp (156/186 kW)	410 hp (300kW)	460 hp (340 kW)
Emission Standard	Euro V	Euro V	Euro V
Trailer Volume	Rigid Lorry 10.4m/61.1m^3	Semi-Trailer 13.61/76.62 m^3	Semi-Trailer 13.61/76.62 m^3
Average Annual veh km	112,776	151,468.7	170,405.9
Daily Mileage (km)	284.23	443.46	471.16
Mean Length of Haul (km)	58.17	75.75	83.0
Number of Drops	3.7	3.7	3.7
Max. Capacity Rolling cages/trailer (depending num. of lanes)	24	36/42	36/42
Max average tkm / year (93.3% loading factor)	571,325	1,303,757/ 1,521,049	1,481,483 / 1,728,396
Average Speed (km/h)	57.68	64.17	66.32

Table 3. Average operational values for UK road haulage vehicles in 2013. Adapted from: DfT (2015f).

Typical Duty Cycle	Urban/ Regional	Long-haul
Vehicle Type	Rigid Over 17-25t	Over 33t
Average Annual veh km	38,000	91,000
Average Length of Haul (kms)	70	126
Tkm/year	128,000	1,038,000

In the UK, 139 billion tonne-km of goods were moved in 2013 (DfT, 2015f) and as it can be seen in orange in Figure 6, the largest fraction of these were moved by artics (over 33t), except in trips up to 25 km, where rigids (over 25 t) dominated. The sum of all tkm moved by rigids were superior to the one of artics for lengths of haul up to 50 km, which is consistent with the idea that rigid (smaller) HGVs are used for city logistics. For an average length of haul over 300 km, rigids represent just 6.6% of all goods moved.

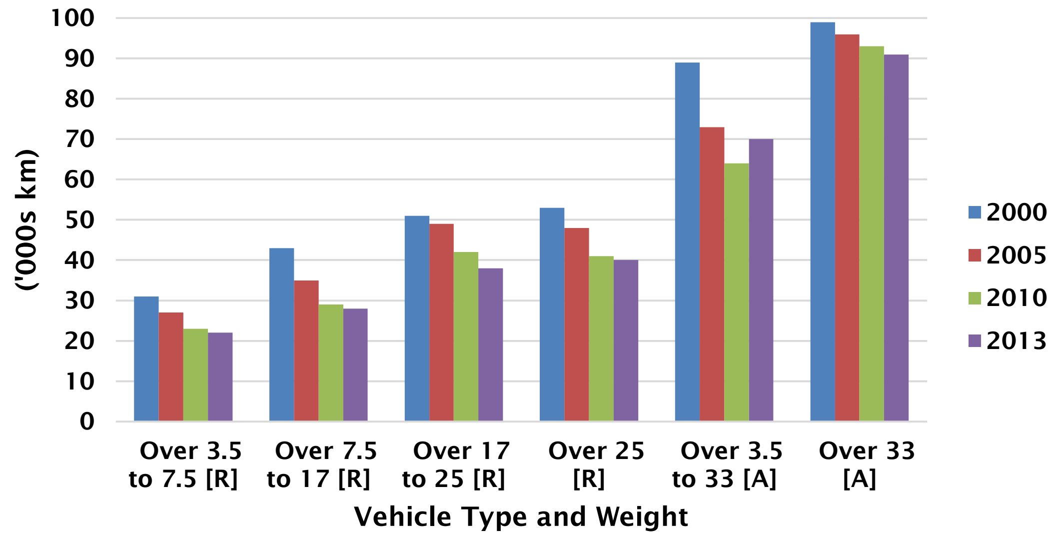


Figure 5. Average annual vkm for different vehicle types. 'R' means Rigid and 'A' articulated.

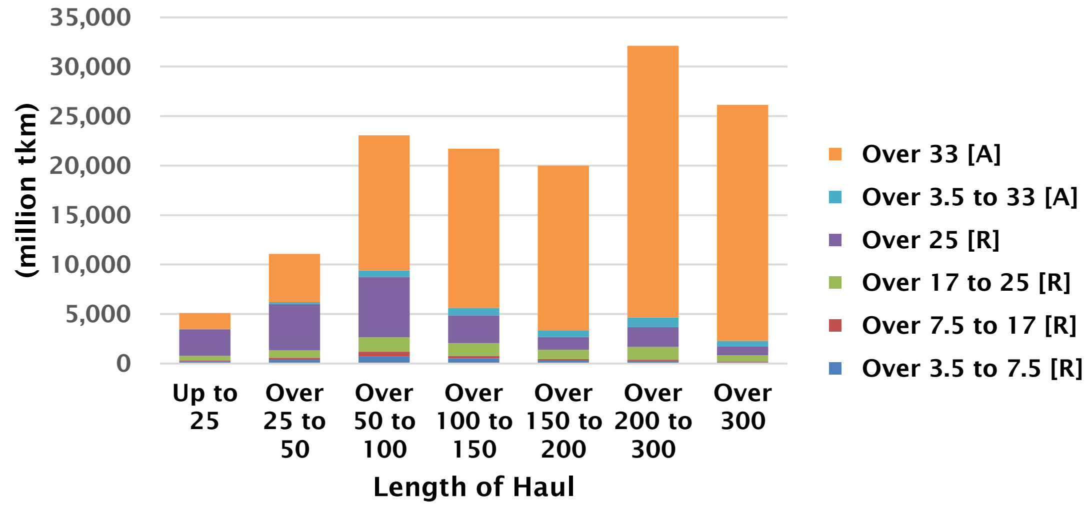


Figure 6. Average length of haul moved by vehicle type in the UK (2013).

MB presents a different profile to UK national fleets when looking at the goods moved (tkm) according to length of haul (Figures 7 and 8). Analysing DfT (2015f) data (Figure 6) it can be seen that while trips between 50 and 100 km still represent the highest fraction of goods moved by 17-25t rigids (Figure 7) and also for MB (Figure 8), UK fleets have also a considerable amount of goods moved for trips up to 300 km. In contrast, the goods moved by MB are carried over much shorter haul lengths. Assessing articulated HGVs, it can be seen that while UK fleets present a skew towards longer lengths of haul, MB shows a central tendency around trips over 100 to 150 km. The reason for this is that MB distribution centres (DCs) are optimally located to supply the demand of the network of Quick Service Restaurants (QSRs), mainly near densely populated urban areas which reduces average trip lengths.

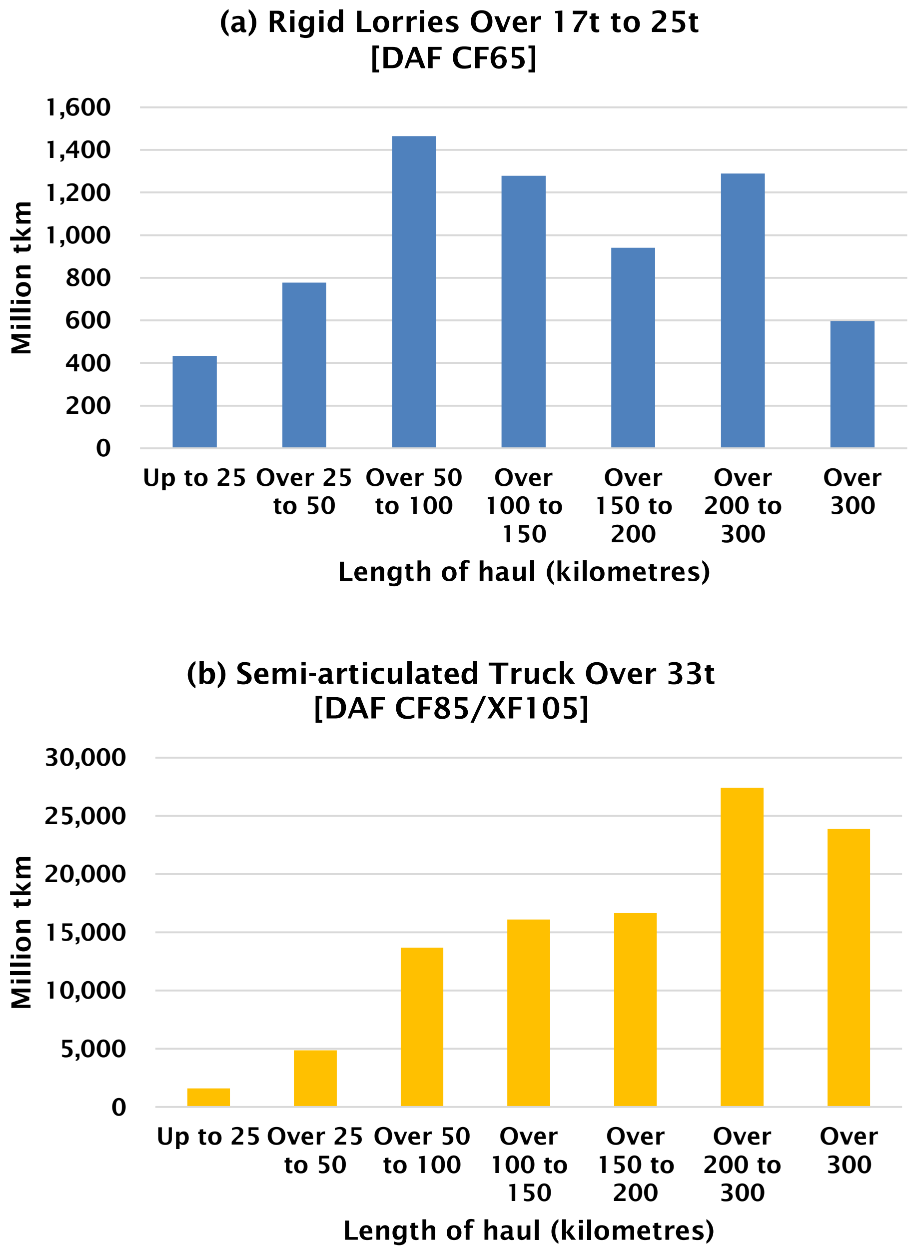


Figure 7. Total goods moved in 2013 by UK fleets of (a) rigid lorries and (b) semi-articulated trailers over 33t according to their length of haul in 2013.

The loading factor represents the ratio of the actual goods moved to the maximum achievable if the vehicles, whenever loaded, were loaded to their maximum carrying capacity. Empty running is defined as carrying zero tonnes. MB has zero empty running as back haul trips always carry waste products back to the DC (Figure 9). The average loading factor for the whole MB fleet is between the UK averages for rigid and artic HGVs as reported by DfT (2015e). The loading factor over one-way trips is exceptionally high (93%); however, this decreases on the return leg as vehicles cannot be shared with other customers and only carry waste fractions (used cooking oil, paper, cardboard, plastics, etc.).

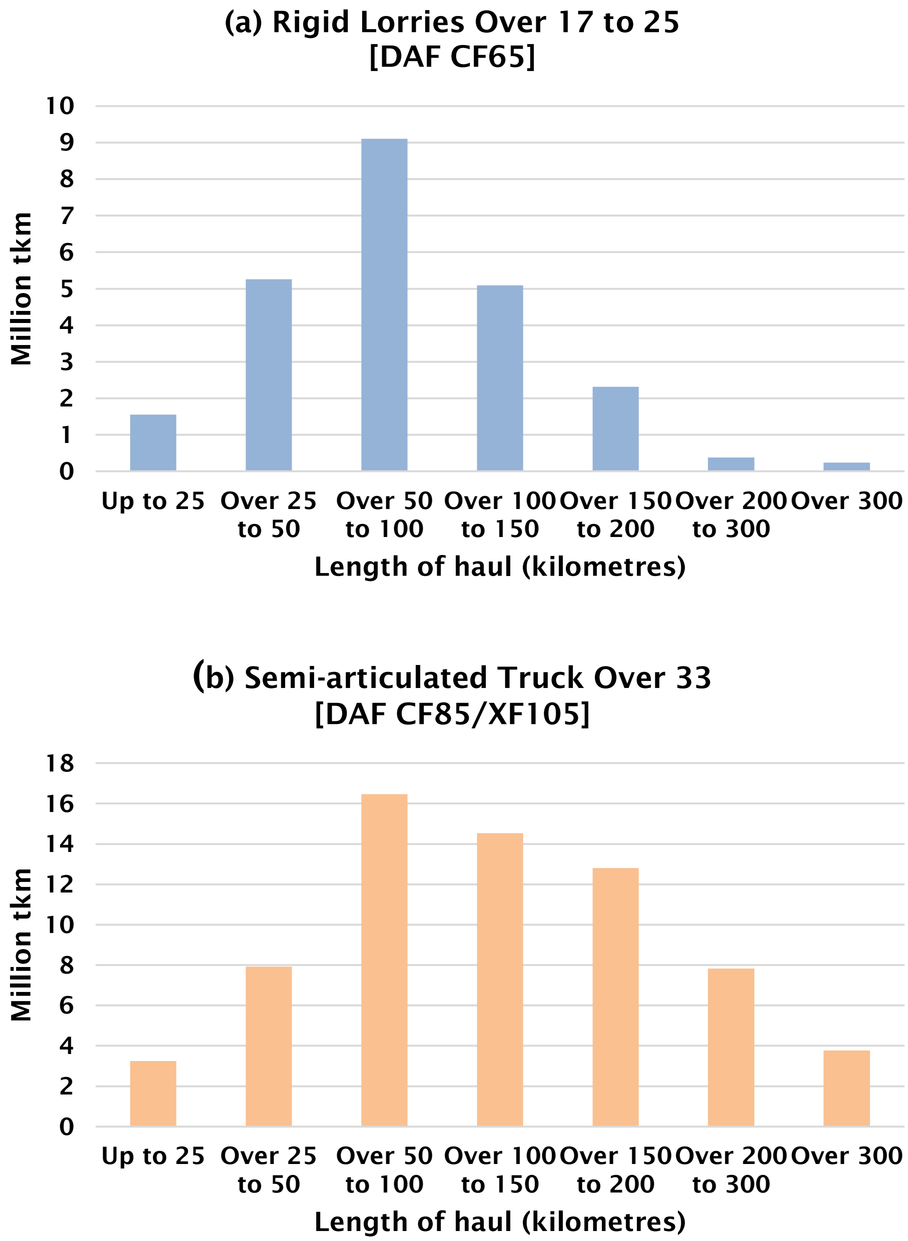


Figure 8. Total goods moved by MB in 2014 by (a) lorries and (b) semi-articulated trucks according to their average length of haul.

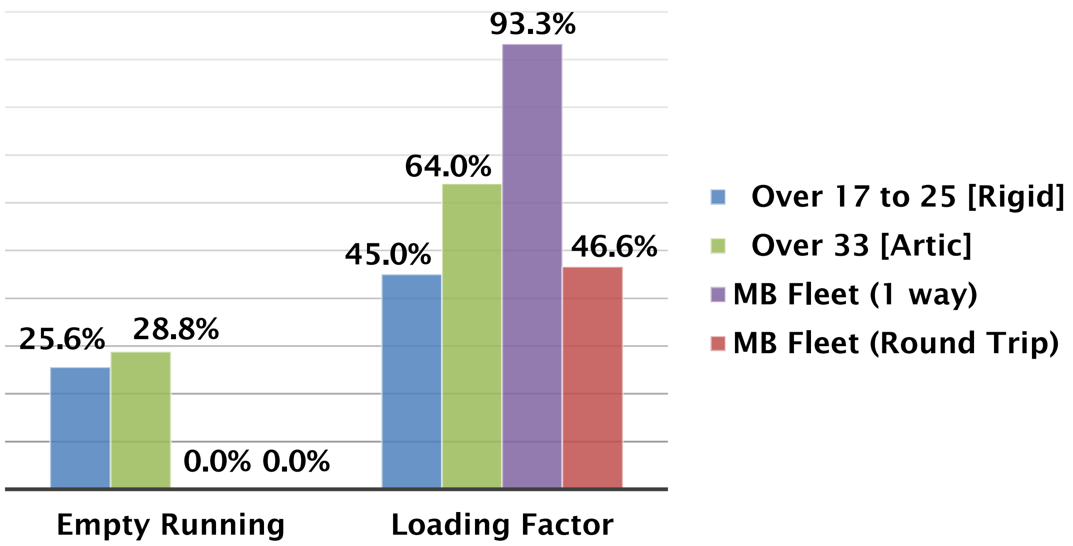


Figure 9. Comparison of empty running and loading factors between average UK and MB fleets.

MB already uses many low carbon technologies in their vehicles. This is evident when comparing the fuel economy (FE) of MB fleet with the aggregated British fleet as reported by DfT (2015h). This is illustrated in Figure 10, where the first two columns on the left represent British fleets and the three columns on the right represent DAF CF65, artics DAF CF85 and DAF XF105 HGVs. Their respective fuel economy (FE) is 16.7%, 20.3% and 21.5% better than the average national fleet. This suggests that as we are not comparing the same exact type of vehicle (GVW, loading factor, etc.) the application of the framework developed in this research has greater potential for improving the fuel efficiency of national fleets as these are less efficient than the one of MB.

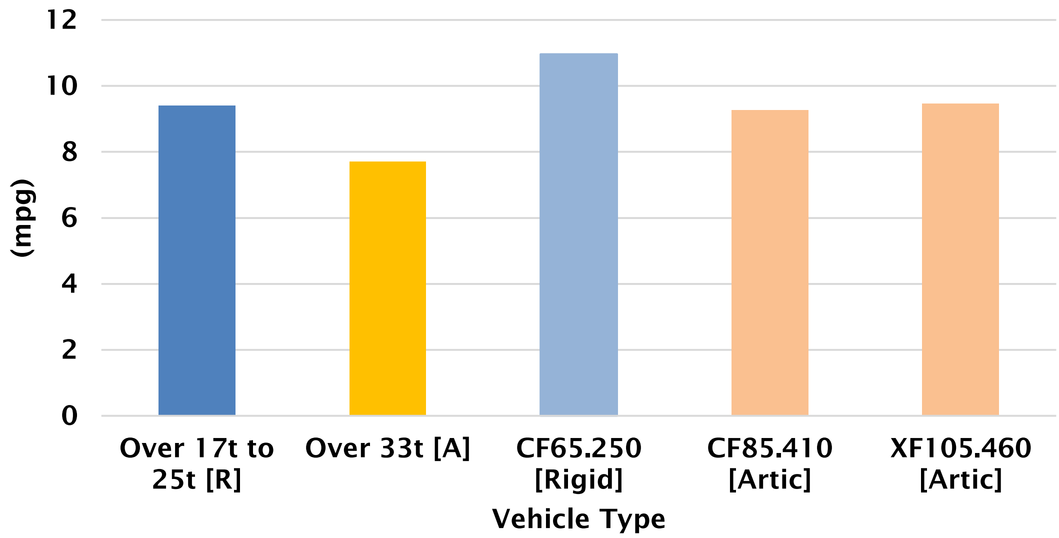


Figure 10. Fuel Economy MB fleet in 2014 compared to UK national averages for similar vehicles in 2013.

An additional factor that explains differences on FE between fleets is the duty cycle which is represented by a statistically representative driving cycle. A driving cycle represents the driving pattern of a vehicle or engine. There are legislative cycles that are used for vehicle type approval while others are used to match more closely real driving conditions. Driving cycles can also be divided between transient and steady (or modal). A transient driving cycle can be illustrated as a series of points representing velocity over time; they are typical of on-road driving and tested on chassis dynamometers. In contrast, steady (modal) cycles are test specific engine torque points over time; typically in an engine bench. The statistical analysis of driving cycles indicates average speeds, acceleration, number of stops, etc. This can give a very broad notion of the type of duty that the cycle represents and how this could compare with a different one. As the official driving cycles used for vehicle approval and air quality emissions analysis are used by all road HDV including waste refuse trucks, buses and coaches they are not ideal for representing how logistics fleets operate. Taking as an example the European Transient Driving cycle (ETC) (Figure 11), the official one to test Euro V HDVs, the cycle has zero stops and it is split into three segments. In the urban segment, the average speed is 23.3 km/h, much lower than MB average speeds whilst the rural and motorway driving average speeds are 69.3 km/h and 84.4 km/h respectively (Barlow et al., 2009). These speeds are considerably higher than the 64 km/h and 66 km/h reported in Table 2 for MB. As regulatory driving cycles do not include delivery drops they are not representative of how logistics firms use their vehicles. Some characteristics of official and bespoke driving cycles are illustrated in Appendix 2.

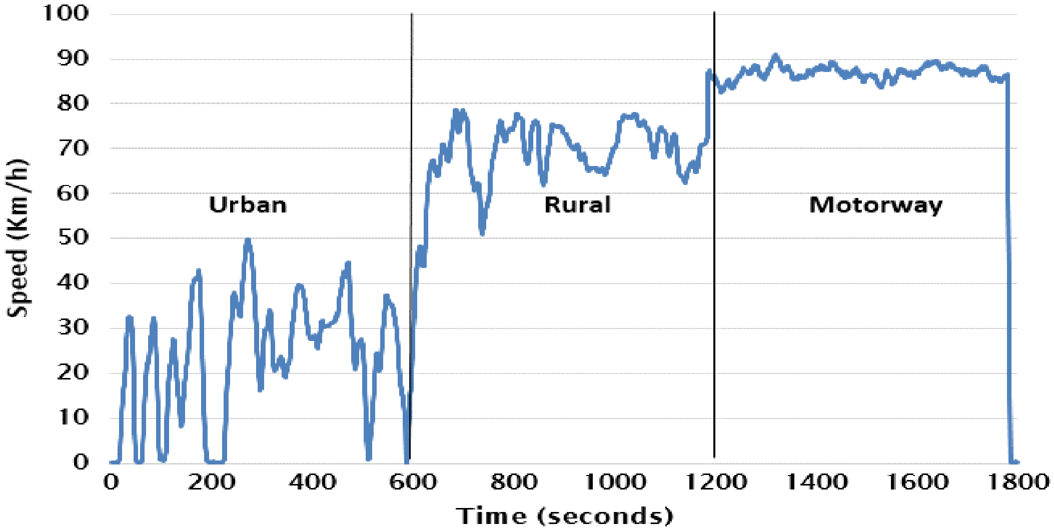


Figure 11. The European Transient Cycle (left) illustrates differences in average and maximum speeds for different duty cycles.

3. LITERATURE REVIEW

Chapter Aims:

To define the concept of sustainable transport and the relationship between freight and climate change

To explain how the principles of kinematic physics equations are related to the energy consumption savings produced by low carbon technologies

To present previous models addressing the technology selection problem

To introduce previous low carbon technologies studies

To review the literature exploring waste-to-fuel pathways

To introduce decision making approaches and a review of evidence of vehicle simulation software

This Chapter introduces the concept of sustainable freight, the science behind global warming and the links between road freight and GHG emissions. This section reviews the evidence found in the literature regarding low carbon technologies for HGVs, relevant trials undertaken and tools developed by third parties that can help to specify HGVs. A special attention has been paid to fuel technologies and waste-to-fuel pathways in the food supply chain due to the possibilities that this presents to the industrial sponsor. At the end of this section, operational research techniques and approaches that can support the decision process of the technology and vehicle specification procurement problem are presented. A diagram that represents the different sections covered in this chapter is illustrated in Figure 12.

3.1 DEFINING SUSTAINABLE FREIGHT

Sustainable development is about providing the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland et al., 1987) and it is strongly linked to the concept of equity (fairness, social justice and quality of life). The United Nations already identified the role of technology as a driver for a new era of economic growth and the need for adopting consumption patterns within the limits of the planet's ecological means (Brundtland et al., 1987). This emphasised almost 30 years ago, the need for recycling and reducing the depletion of non-renewable resources such as fossil fuels. This thesis contributes to both of these objectives by reducing vehicles' energy consumption while assessing the opportunity to use waste to produce renewable fuels.

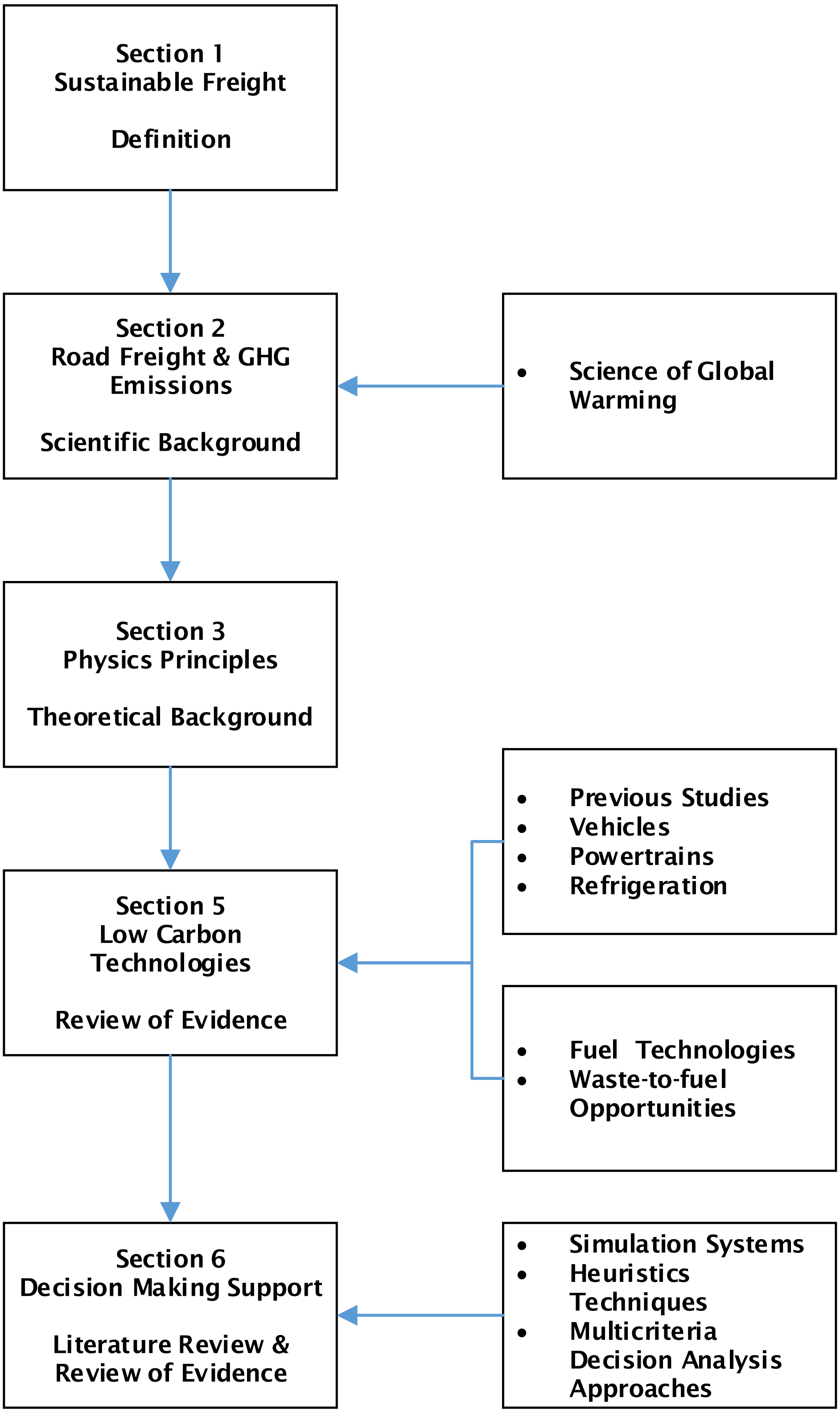


Figure 12. Sections of the literature review.

Sustainability is the equilibrium sought when balancing economic, social and environmental systems and it is typically illustrated in the literature as the intersection among three circles (Figure 13), in a similar fashion as first introduced by The World Bank (1996) and a year later by International Council for Local Environmental Initiatives (2005).

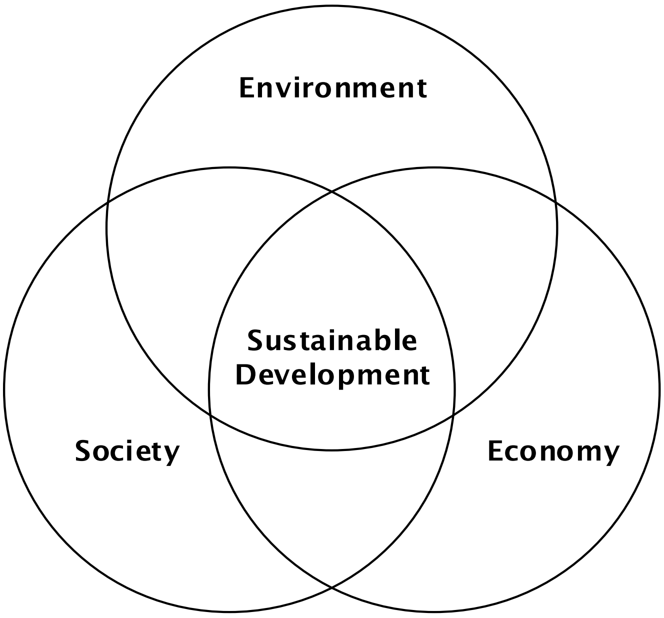


Figure 13. Common three ring illustration of sustainability.

Early work from The World Bank (1996) discussed the synergies and trade-offs of sustainable transport (Figure 14) and identified some of the negative impacts on the environment and ecology from improperly designed and executed transport development strategies. In this area, the report focused on the impacts on human health and safety and the global warming issue was not at the time a concern. Based on Brundtland et al. (1987); DETR (1999); ICLEI (2005); The World Bank (1996); Zhang et al. (2012) it can be concluded that sustainable transport is about reconciling economy and society needs in an environmentally responsible way, considering equity and fairness across generations, social stratification and geographic boundaries. Narrowing down the concept of sustainability to the freight distribution arena, DETR (1999) identified climate change as one of the key areas to focus on to minimise the impacts of logistics operations on the environment (Figure 15). TfL (2007) defined sustainable freight distribution as 'the balanced management and control of the economic, social and environmental issues affecting freight transport that complies with or exceeds environmental standards, regulations or targets aimed at reducing emissions of climate change gases, improving air quality and minimising impacts from accidents, spillages or wastes. Ensures freight is run efficiently, reduces unnecessary journeys, minimises journey distances and maximises loads with effective planning. Complies with labour, transport and human rights standards and regulations ensuring that employees and communities affected by freight can function in a healthy and safe environment. Minimises the negative impacts of freight activities on local communities'. This definition highlighted the relevance that GHG emissions have acquired in recent years to promote greater environmental sustainability in freight transport.

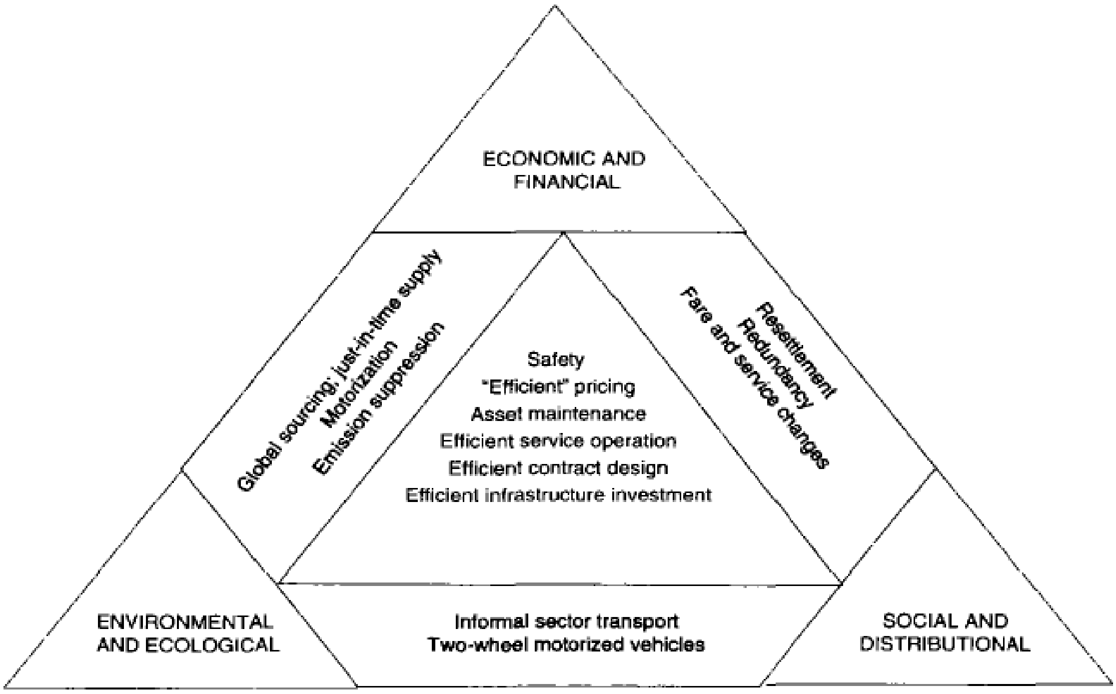


Figure 14. Three dimensions of sustainable transport. Source: The World Bank (1996).

The framework developed in this research influences several sustainability dimensions. Typically, by reducing fuel consumption, air quality emissions are also reduced (at least for vehicles within the same level of EU Emission Standard); as there is a focus on cost savings, this affects the economic dimension of distribution by improving competitiveness and therefore promoting business growth and prosperity. The framework also allows the evaluation of carbon price mechanisms and the weighting of GHG emissions criteria against economic impact and technological maturity, safety and limitations' risks.

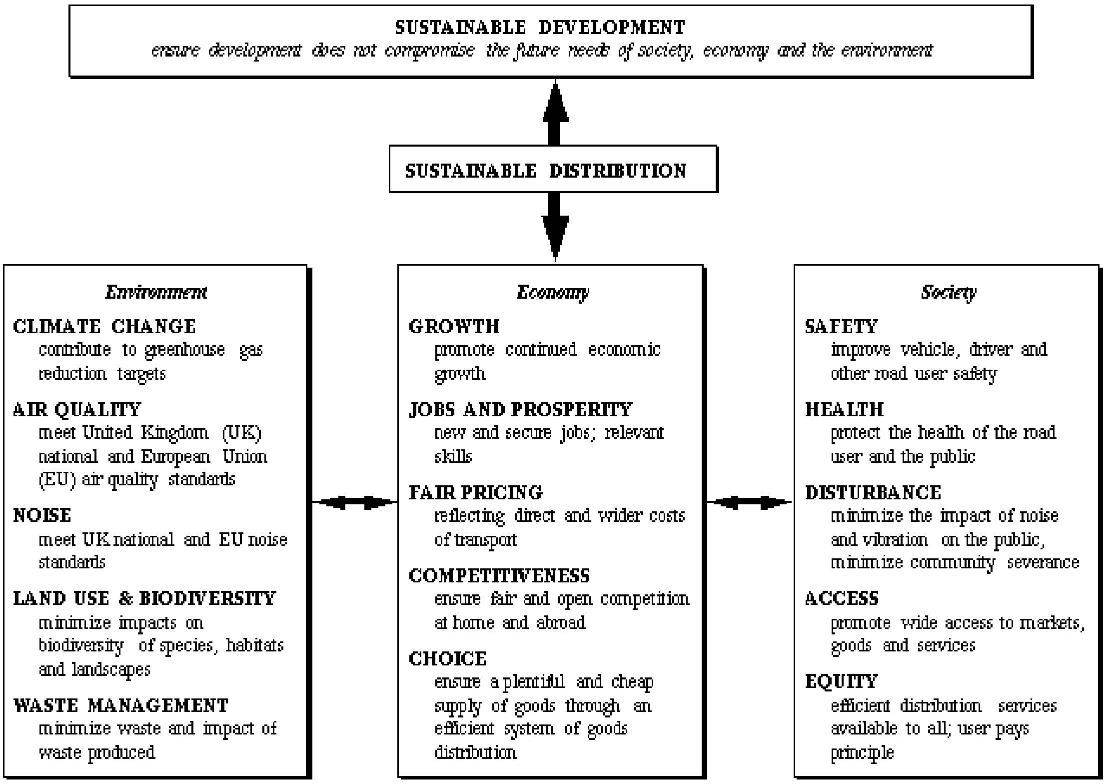


Figure 15. Sustainable distribution. Source: DETR (1999).

3.2 ROAD FREIGHT AND GHG EMISSIONS

Around 85% of the world's energy is provided by fossil fuels, a dependency that increases up to 98% in the case of transport (Barnier, 2007). The transport sector consumes 55.1% of the total oil demand worldwide, with road transport accounting for 43.2% of the total in 2013 (OECD/IEA, 2014). From this percentage, gasoline represents 59% and diesel 39%. In 2010, transport contributed 14% of global GHG emissions (IPCC, 2014) and in the UK, it represents over a fifth of all GHG emissions (Figure 16), with road haulage by HGVs representing almost a similar percentage (Figure 17) which means that HGVs are responsible for 4.4% of all UK GHG emissions. Diesel is the main fuel choice for commercial vehicles in the UK (Freight Transport Association, 2011, Hill et al., 2011), and the USA (National Research Council, 2014). The reason for this is that diesel engines are more efficient than gasoline and this leads to a higher fuel economy. According to Ntziachristos and Dilara (2012), diesel engine HDV offer better thermal efficiency, cost, power density and range than other engine/motor based technologies.

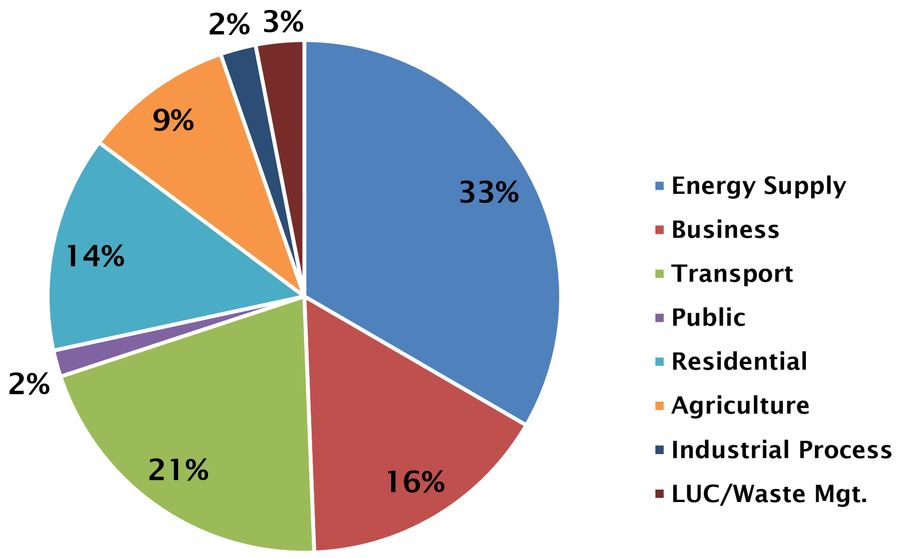


Figure 16. UK estimated GHG emissions by source category in 2013. Adapted from DECC (2015a).

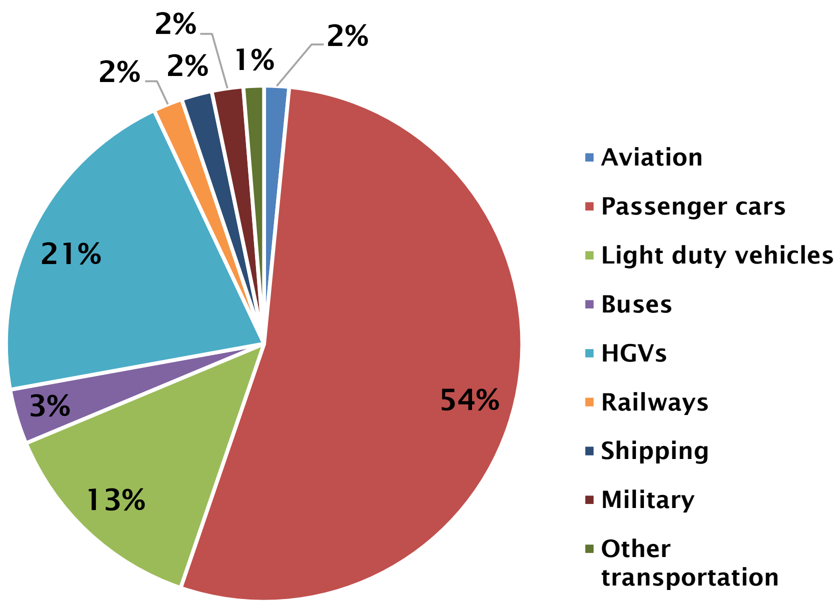


Figure 17. UK transportation GHG emissions from different modes in 2013. Adapted from DECC (2015a).

Diesel is a mixture of hydrocarbons obtained from petroleum with a number of atoms of carbon and hydrogen (C_xH_y). The combustion of hydrocarbons produces air quality (AQ) pollutants and GHG gases (Equation 1); the latter being considered the main contributors to global warming (Barreto et al., 2003, Lee et al., 2011, IPCC, 2014). The link between GHG emissions and global warming is well established

(Lashof and Ahuja, 1990, Stern, 2007, Forster et al., 2007, IPCC, 2013) and can be traced down to the mid-1980's (Hughes, 1992). GHG gases contribute to climate change due to their positive radiative forcing and include mainly carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_20) and fluorinated gases such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6) (NAEI, 2013, IPCC, 2013). Carbon dioxide is used as a baseline gas for measuring the global warming potential (GWP) of all other GHGs which are converted to their CO_2 equivalent (CO_2 eq.). Observations show that global temperatures have been rising since the industrial revolution (Figure 18 and 19) with some predictions forecasting temperature increases of around 4°C by the end of the century and sea level rise of up to 1 metre (IPCC, 2013). Atmospheric concentrations of CO_2 emissions were 391 ppm in 2011 (Figure 19), exceeding pre-industrial levels by 40% (IPCC, 2013) and it has been suggested that the worst impacts of climate change may be averted if CO_2 levels do not exceed 550 ppm CO_2 eq. (Stern, 2007).

$$C_xH_y + Air = H_2O + CO_2 + CO + PaHs + NO_x + PM_x + SO_2 + VOC\ (+Pb)$$

Equation 1. Reactions result of the combustion of hydrocarbons.

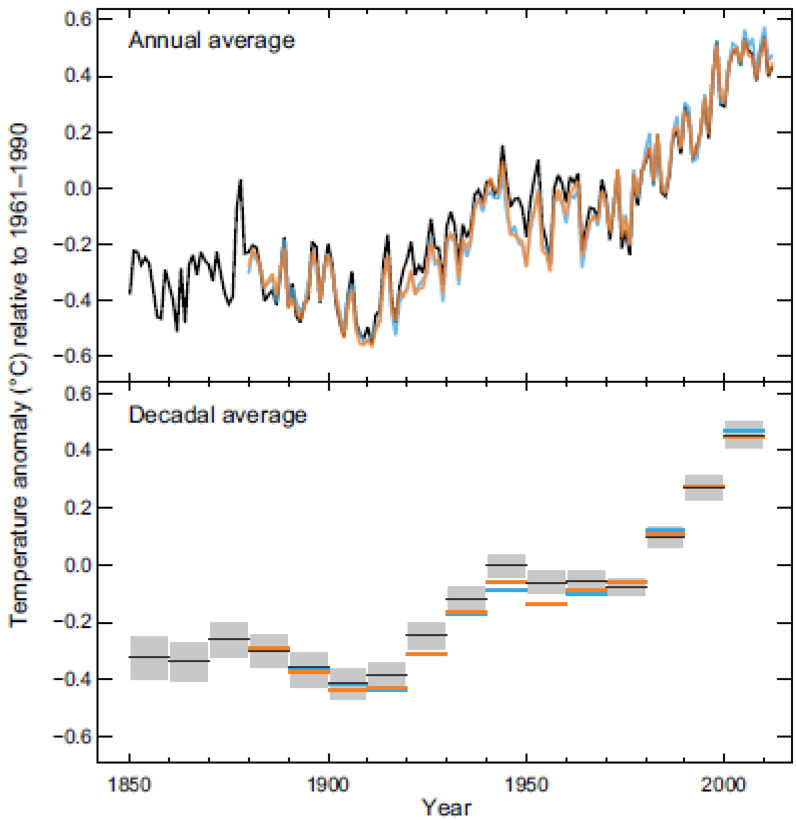


Figure 18. Observed globally averaged combined land and ocean surface temperature anomaly 1850-2012. Source: IPCC (2013).

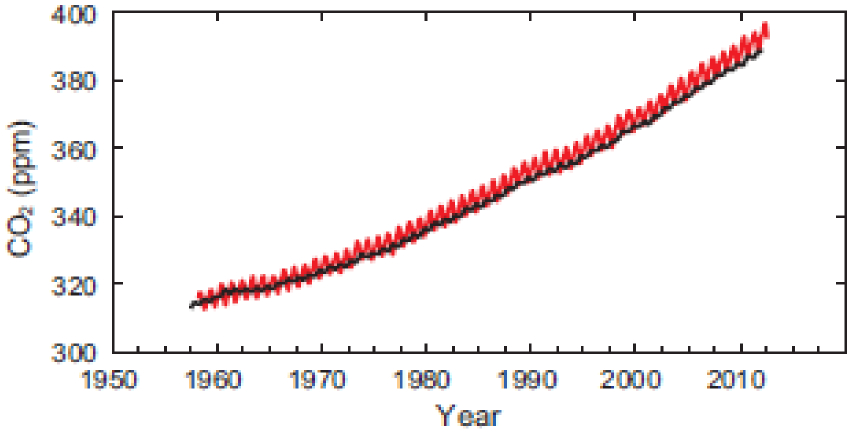


Figure 19. Atmospheric CO_2. Source:IPCC (2013).

Research suggests that demand for oil will continue to rise despite developing more fuel efficient vehicles due to population increases and vehicle ownership levels. Governments around the world are now defining policies and legislation that seek to mitigate the negative impacts of global warming and the European Commission (2010a) has set about reducing GHG emissions by 80-95% below 1990 levels by 2050 (European Commission, 2010a). With this in mind, the EU is committed to achieving a series of climate and energy targets by 2020, which include a reduction in EU GHGs of at least 20% below 1990 levels, an objective reduced to 10% for the transportation sector (European Commission, 2010b) due to the difficulty to replace fossil fuels. Intermediate objectives have been set-up for 2030 with a 40% target reduction of GHG emissions compared to 1990 along with a 27% improvement in energy savings and renewable energy use (European Commission, 2014). In the UK, mandatory targets up to 2027 have been set with a target reduction of GHG emissions of 50% (Committee on Climate Change, 2012). The extent to which these objectives are achievable is arguable. Despite an apparent political goodwill, it seems that these objectives may not be realistic, with some forecasts predicting an increase on energy demand worldwide of 37% between 2013 and 2035, an increase mainly generated by non-OECD countries (BP, 2015). This translates to an increase of carbon emissions of 25% over this period (at 1% per annum). Appendix 3 includes a list of relevant EU directives, regulations and policies focused on reducing GHG emissions from HGVs. By 2035 the global fleet of commercial vehicles and passenger cars is expected to double from 1.2 billion today to 2.4 billion, mostly occurring in the developing world. Despite vehicle efficiency improvements, transport fuel demand may grow by 30% (BP, 2015). This could mean that when the number of vehicles double, 89% of energy in transport will still come from oil and just 3% from natural gas; and therefore 92% of the energy will come from fossil fuels. The projected increase in vehicle ownership levels worldwide justifies the creation of public entities that work to reduce carbon emissions from transport. Appendix 4 include a list of UK bodies, research centres and programs whose main aim is contributing to the R+D of low carbon technologies in transport.

The whole UK food chain emitted around 115 million tonnes of CO_2 eq. in 2009[3] (Defra, 2011a), representing 20% of all UK GHG emissions associated with economic activity (Audsley et al., 2009). Commercial Transportation of food for UK consumption represents around 9% of the GHGs emissions associated with the food supply chain (Defra, 2011a) and between 1.8% (Smith et al., 2005, FRPERC et al., 2010) and 2.5% (Garnett, 2003) of total UK carbon emissions. Food transportation activity has grown since 1992, with small decreases due to the recession of 2007; partially recovering by 2010 (Figure 20). Urban food kms represent deliveries of food in UK urban areas by cars, HGVs and vans; HGV transport of food kms represent just HGVs. The drops in 2002 and 2007 were due to changes in the methodology. The increase of 6.4% from 2009 to 2010 is explained by an increase in car travel. HGV food kms represent the deliveries of food by HGVs in all areas and HGV transport of food for UK consumption represent the same but measured in tonnes kilometres instead of vehicle kilometres. A down trend is evident since 2004, despite a recovery in 2010. The HGV tkm have the same level as in 2007, despite an increase in 2010. All these trends from 2005 to 2010 have some similarities to GPD and they have been in line with UK economic outputs such as manufacturing and construction. Total CO_2 emissions from food transport estimate emissions from transport fuel used by road hauliers and there is a downtrend since 2006 (4% lower).

Road is the main mode of freight in the EU representing over 45% of all tonne-kilometres transported in 2011, while sea represented almost 37%, rail 11%, inland waterway 3.7%, oil pipelines 3.1% and air transport a mere 0.07% (European Commission, 2013d). As other modes are less carbon intensive in tkm, modal shift from road to rail or water is environmentally always a good approach for reducing freight GHG emissions. The EU set a goal of a 50% shift of medium distance freight journeys to rail by 2050 (European Commission, 2011). In contrast, DECC (2013a) foresees an increase in the number of HGVs globally from 52 million in 2011 to 130 million by 2050. As a result, reducing GHG emission from HGVS is not only desirable and necessary but will become mandatory. In the EU, there are mandatory maximum average CO_2 emissions for new cars and vans; however, this is not the case for HDVs, where the strategy focuses on measurement and

[3] Excluding overseas production, food packaging, food waste and land use change.

reporting (European Commission, 2015). In the US in 2011, the fuel economy standard for diesel engines was adopted, setting voluntary CO_2 emissions limits on diesel tractor unit of 354 g/kWh and 343 g/kWh from 2014 and 2017, respectively; an improvement of 23% with respect to HGVs from 2010 (ICCT, 2011). Recently, the “Phase 2 GHG Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles” has just been proposed with the aim of improving energy security and reducing carbon emissions from new vehicles (starting in 2018) and their transport refrigeration units (TRUs) by up to 24% by 2027, relative to the baseline of the vehicles of the Phase 1 (US EPA et al., 2015). The US Government expects that this will save 284 billion litres of fuel and 1 billion metric tons of carbon pollution while delivering $230 bn. in benefits to society and $170 bn. in transportation cost reductions (US EPA et al., 2015).

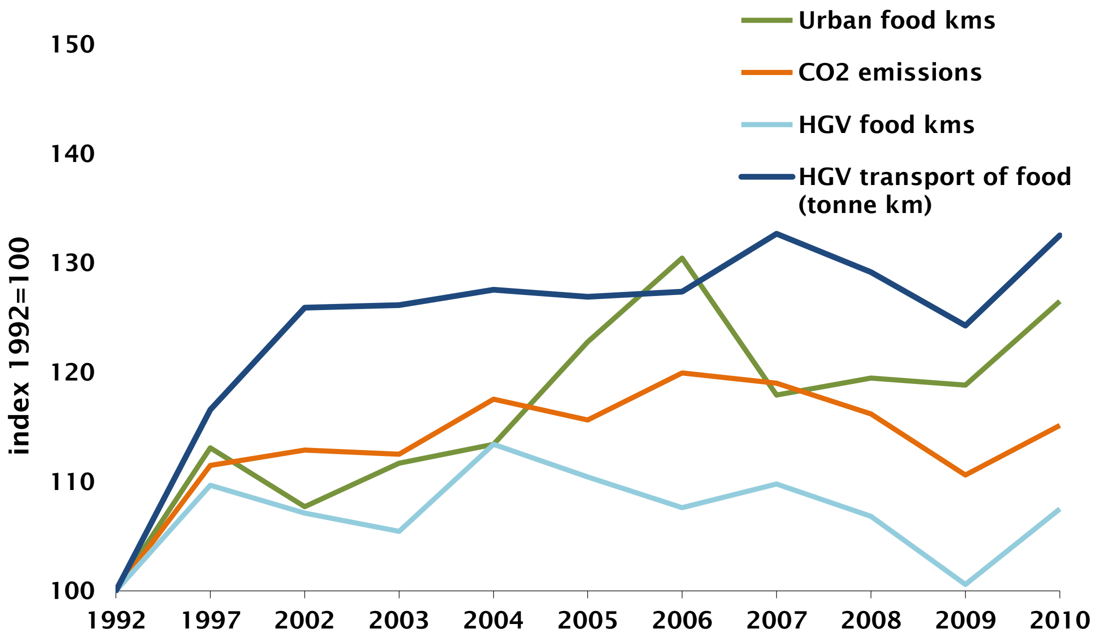


Figure 20. Indicators of the external impact of food transport. Adapted from Defra (2014).

3.3 ENERGY CONSUMPTION IN TRUCKS

The tractive forces required by a vehicle to overcome the rolling, drag, acceleration and gradient forces is shown in Equation 2. Relevant factors that affect rolling forces include mass, gravity and speed. Factors that affect drag forces include density of air, drag coefficient, the frontal area of the truck and speed while acceleration forces depend on acceleration, mass and speed. Gradient forces depend on mass, gravity, the gradient of the road and speed. In this context, power is the product of a force on a vehicle and the vehicle’s velocity (movement). The mechanical power required to move a vehicle is work divided by time and it can be obtained by multiplying these forces by the distance. If the time increments are in periods of 1 second, then power is equal to work (Equation 3). As a result, the power or energy required by a vehicle to overcome all driving forces and efficiency losses is related to its driving cycle. This is developed further in Equation 4. The power needed to overcome all forces and efficiency losses appears in Equation 5.

$F_{res} = F_{roll}+F_{air}+F_{acc}+F_{grd}$

Equation 2: Driving resistances forces. (Source: National Research Council (2010).

Where:

F_{res}= Resulting forces needed to propel a vehicle (Newtons).

F_{roll}=Rolling force

F_{air}=Aerodynamic drag force

F_{acc}=Acceleration force

F_{grd}=Gradient force

$P = \frac{dW}{dt} = \int_{t1}^{t2} F \times v \, dt$

Equation 3: Mechanical power.

Where:

P = Mechanical power to overcome tractive forces to propel a vehicle (watt)

W = Work (Joules)

*d*t = Time increment (s)

t_1= Starting time (s)

t_2= Finishing time (s)

F=Forces

v = Speed (m/s)

$P_{res}= mgC_{rr}v + \frac{1}{2}\varrho_a C_D A_F v^3 + mav + mg \sin \theta \, v$

Equation 4: Adapted from National Research Council (2010) and Hausberger et al. (2012).

Where:

P_{res} = Power demand to overcome tractive forces to propel a vehicle (Watt)

m = Vehicle mass (kg)

g = Gravitational constant (9.81 m/s^2)

C_{rr} = Tyre rolling resistance coefficient

v = Speed (m/s)

ϱ_a = Density of air (kg/m^3)

C_D = Aerodynamic drag coefficient

A_F = Frontal area (m^2)

a = Acceleration (m/s^2). This is (dv/dt)

θ = Road gradient (degrees from horizontal)

Equation 5: Total mechanical power necessary to overcome tractive forces and efficiency losses of the powertrain.

$$P_{Tot} = \frac{1}{\eta_{eng}\eta_{trans}} P_{res}$$

Where:

P_{res}=Resulting power needed for the trip (Equation 4).

η_{eng}=efficiency engine.

η_{trans}=transmission.

Rolling resistance forces are independent of speed, while aerodynamic forces are a function of the speed to the power of two (Figure 21). However, looking at power (excluding efficiency losses), rolling resistance has a linear relationship with speed and the aerodynamic power has a cubic relationship with it (Figure 22). This means that at high speeds, aerodynamic drag becomes more relevant in power consumption than rolling resistance and therefore, vehicles running at high speeds tend to focus on improving aerodynamics to reduce fuel consumption. At lower speeds, reducing rolling resistance and mass present better opportunities to reduce energy consumption. Figures 21 and 22 illustrate that for a given type of HGV and speed, there is a crossover point where the aerodynamic drag is equal to rolling forces. Over that speed-point, aerodynamic drag is stronger than rolling resistance.

When losses in the transmission system (e.g. gearbox transmission ratio, rotational speeds, engine maps) and auxiliary losses are taken in consideration, the fuel consumption is more similar to the one that appears in Figure 23. At very low speeds, the characteristics of the engine map leads to a higher energy consumption. This curve is the result of Equation 5 once the additional electricity power demand from the engine (oil, coolant and fuel pumps) and the alternator plus other auxiliary equipment such cooling fan, air compressors, steering pumps and other hotel loads such as air conditioner, radios, telematics devices are taken in consideration. On top of that, an additional power demand exist for those vehicles using auxiliary alternator transport refrigeration units in their trailers (Equation 6).

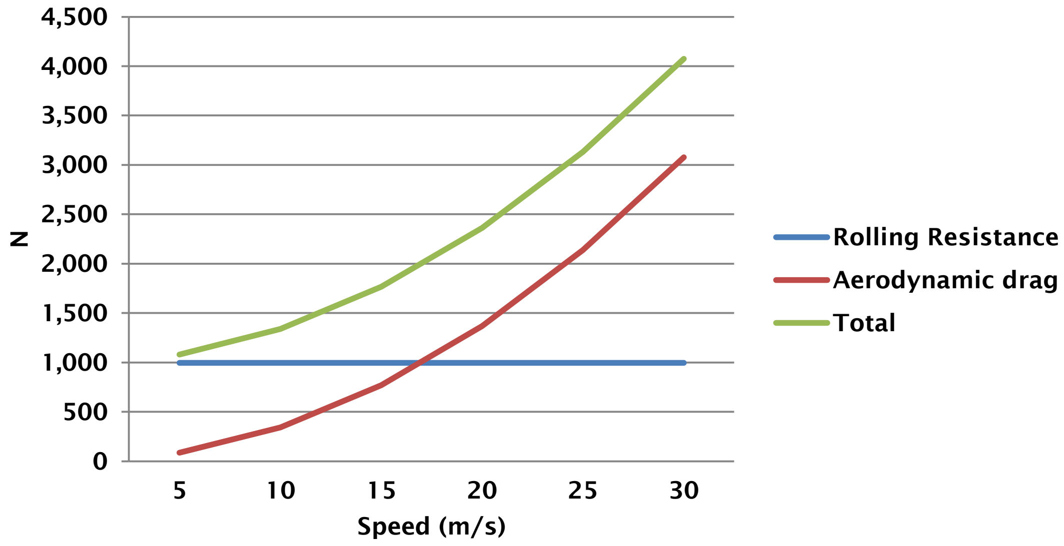


Figure 21. Representation of the impact of speed on the rolling and aerodynamics forces that appear in Equation 1.

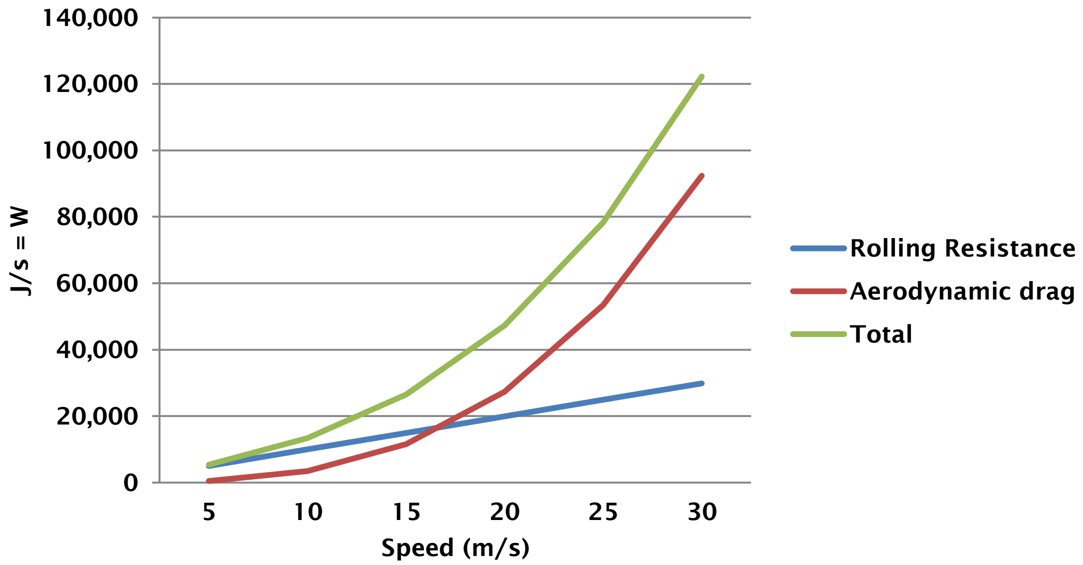


Figure 22. Representation of the impact of speed on rolling and aerodynamic power needed to overcome forces that appear in Equation 1.

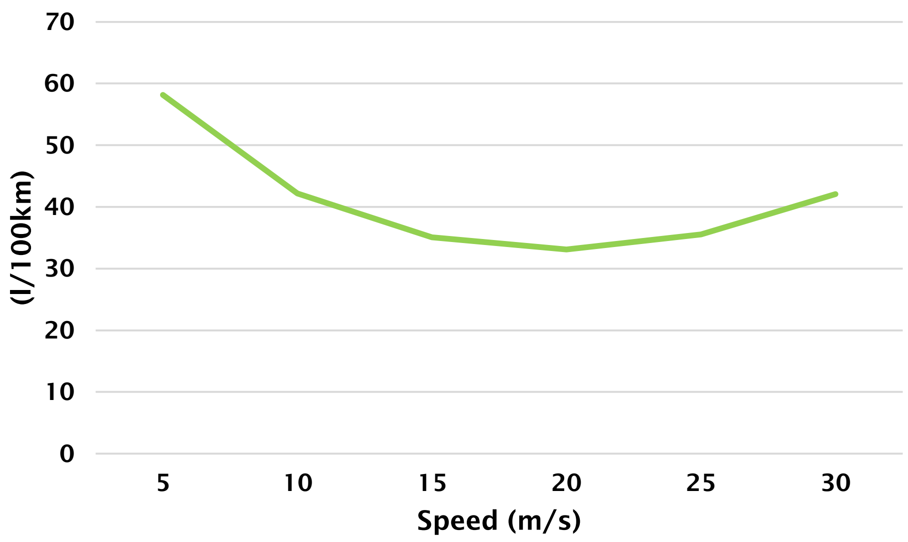


Figure 23. Typical fuel consumption of a 4 axle HGV (diesel) in 2015 according to vehicle speed. Adapted from DfT (2014b).

Equation 6: Total mechanical power necessary to overcome tractive forces and efficiency losses of the powertrain.

$$P_{Final} = P_{Tot} + P_{aux}$$

Where:

P_{Final}= Final Power required.

P_{Tot}= Total mechanical power required to overcome driving forces and efficiency losses of engine and powertrain (Equation 5).

P_{Aux}= Auxiliary power demand from the engine map, ancillary equipment, hotel loads and transport refrigeration units.

It is estimated that a HGV powertrain consumes half the energy available (Figure 24). The efficiency of the powertrain (brake power) represents 42% of the total energy required (National Research Council, 2010, National Research Council, 2012, Baker et al., 2009a). This efficiency is expected to reach around 52% by 2019 (Eckerle, 2007); however, there is a theoretical limit that can be achieved on internal combustion engines after which solutions must focus on other areas (e.g. decarbonising energy sources). The percentages in blue in Figure 24 represent the current values as reported by Cooper et al. (2009) and the ones in grey (between brackets) represent the potential values achievable by 2019 as reported by Eckerle (2007).

The share of driving resistances in the total cycle work changes considerably with the duty cycle, as it was deducted from previous equations; this is illustrated in Figure 25. While air resistance represents the largest share of resistance in motorway driving for all vehicles, this percentage is very low in urban cycles as average speeds are much lower. For delivery vehicles, rolling resistance is the dominant force in urban driving, while for city buses, auxiliaries represent the highest share. This is likely to be due to the use of air conditioning, heating, alternators, etc. As it can be seen, vehicle category and driving cycle have a considerably impact on the energy requirements of HGVs.

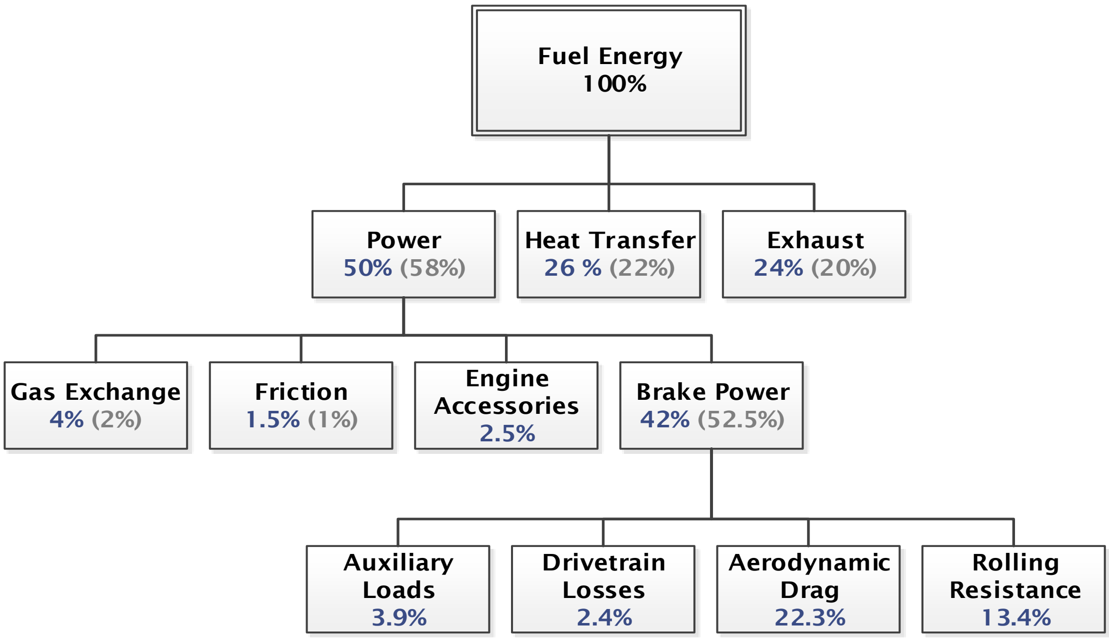


Figure 24. Energy balance of fully loaded Class 8 tractor-trailer on a level road at 65 mph. Adapted from Eckerle (2007) and by Cooper et al. (2009).

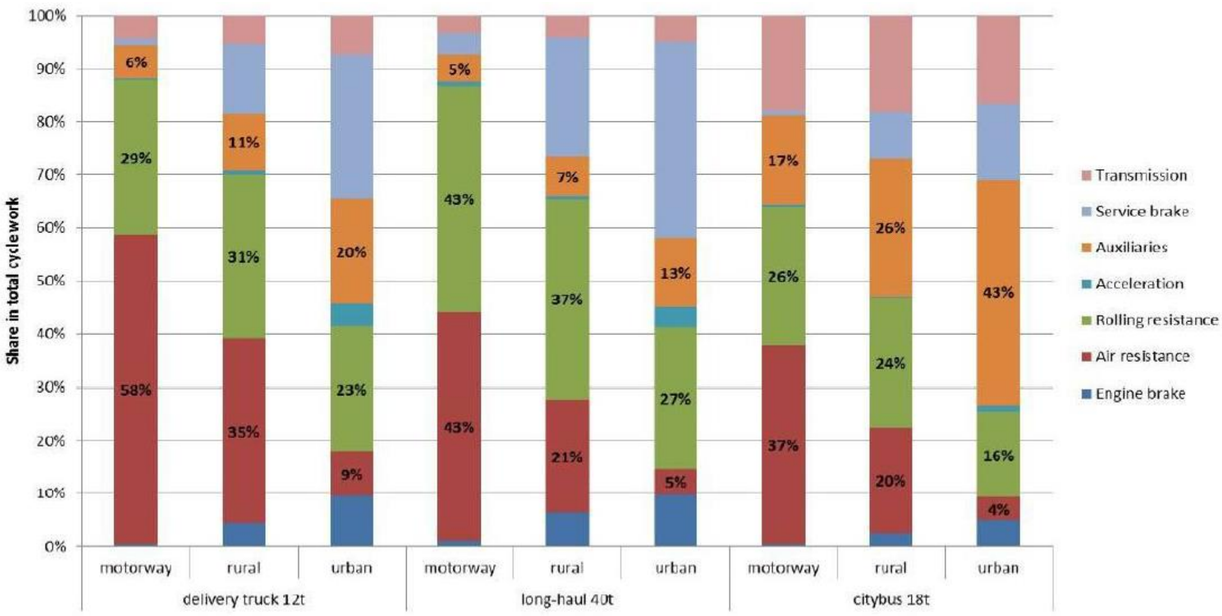


Figure 25. Share of the driving resistances in total cycle work. Source: European Commission et al. (2014).

After calculating the power required to overcome all forces and losses for a trip, it is possible to work out how much fuel is required by converting the total Joules needed into litres of fuel (Equation 7). By multiplying the litres of fuel by their carbon emission factor, it is possible to calculate the GHG emissions per tonne-kilometre (Equation 8). Calculating the GHG emissions per vkm does not give a clear picture of the energy efficiency of a vehicle, as the energy consumption and GHG emissions can vary significantly depending on the type of load carried (mainly due to the mass or volume loaded) and as a result, typically, this is normalised with a unit of payload (e.g. tonne-km or m^3-km). Tonne-kilometre (tkm) is the standard measure for freight movements (McKinnon, 2010, Hausberger et al., 2012), representing the movement of one tonne of load over one kilometre distance. It is typically used in performance ratios such as freight intensity (tkm/GDP), productivity (tkm/vehicle), payload (tkm/vkm), fuel consumption (fuel consumed/tkm) and carbon efficiency (g CO_2eq./tkm)(McKinnon, 2010). In Europe, carbon emissions per tkm is the standard indicator in carbon accounting of road haulage (Defra, 2011b). In the US, load specific fuel consumption (LSFC) is considered as a precise metric for measuring fuel consumption; it is measured as gallons of fuel per payload per 100 miles (National Research Council, 2014) and carbon emissions per tonne per 100 miles is a similar indicator. These sorts of metrics allow the integration of technologies such as double decker trailers (DDT) or draw-bar combination vehicles that, despite increasing vehicle mass and therefore fuel consumption and GHG emissions per vkm, reduce fuel consumption and GHG emissions per tkm or m^3km as the increase in fuel consumption can be more than offset by a higher payload transported.

Equation 7: Fuel Consumption of a vehicle to overcome tractive forces and efficiency losses of the powertrain.

$$\text{Fuel Consumption (L)}=\frac{1}{LHV_{fuel}}\,P_{Tot}$$

Where:

P_{Tot}=Total mechanical power needed (Equation 5)

LHV_{fuel}= Energy density of fuel (Lower heating value of diesel) in J/L.

Equation 8: Carbon footprint of a trip.

$$\text{Carbon Footprint (kg } CO_2 \text{ eq.)} = \frac{\text{FC (L) x EF}}{tkm}$$

Where:

FC (L) = Fuel Consumption in litres. This is the outcome of Equation 7.

EF= Emission factor for the fuel used in kg of CO_2 equivalent GHG gases.

tkm= tonnes carried multiplied by the km run during the trip.

3.4 FUEL CONSUMPTION REDUCTION STUDIES

The EU White Paper 'Roadmap to a Single European Transport Area' (2011), suggests that it is possible to achieve a 60% reduction in GHGs emissions by 2030, in respect to 1990 levels, by improving 'vehicle's efficiency through new engines; materials and designs; cleaner energy use through new fuels and propulsion systems'. Similarly, the European Commission (2015) suggests that state-of-the-art technologies can achieve cost-effective CO_2 reductions of 30% in new HDVs. The literature seems to support such targets with fuel consumption reductions of 50% being considered as possible in the period to 2020 (Cooper et al., 2009, National Research Council, 2010, National Research Council, 2012).

The results of fuel consumption reduction (FCR) studies from different geographical areas can differ considerably due to different vehicle standards, regulations and legislation. Speed limits influence driving cycles while regulatory gross vehicle weight (GVW) and vehicle size limits, have an impact on the vehicle characteristics (e.g. mass, aerodynamic drag) which influences energy requirements. For this reason, the findings of the literature based on trials and simulations conducted on different geographic areas are not always comparable. Based on data from US EPA (2008), Law et al. (2012), Ecopoint Inc. (2013) and Gov.UK (2013), Table 4 has been created summarising some of the key differences that need to be taken in consideration when comparing different studies from the literature.

There is no homogeneous classification specifying the characteristics of an urban, regional and long-haul duty cycle. For Hausberger et al. (2012), urban freight relates to deliveries from a central store to some selling points (inner-city with some suburban roads). In regional deliveries, consumer goods are supplied from a central warehouse to local stores (inner-city, suburban, regional and also mountain roads). Long haul are deliveries to national and international sites (mainly run over highways and a small share of regional roads). There is no agreement either regarding the theoretical average annual driving distance; however, in all studies and surveys this distance increases from urban deliveries to long-haul.

In the EU, the typical medium duty truck undertaking urban deliveries is a 7.5t 2-axle rigid, whereas heavy duty (motorway work) is carried out by articulated vehicles with GVW over 32.5t and 3-axles (Baker et al., 2009a). The US legal GVW tends to be lower and maximum speeds higher than in the EU. There are also considerable differences in vehicle length. In the UK, the maximum legal length for rigid vehicles is 12 m and 16.5 m for articulated vehicles (or 18.75 for a lorry with a trailer) while in the US, the total length of articulated vehicles can be as much as 21.3-22.9 m (Law et al., 2012).

Table 4. Typical baseline parameters for HGVs trials and simulations in EU and US low carbon technologies studies.

Baseline	Urban Delivery		Regional Delivery		Long-Haul	
	EU	US	EU	US	EU	US
Engine Displacement (L)	6.7	6.7	7.2	6.7	12.4	12.9
GVW (kg)	7,500-14,000	7,257-11,793	7,500-16,000	11,794-14,969	16,000 ->40,000	14,969-36,364
Annual Activity (km)	40,000	32,187-120,701	60,000	40,234-120,701	80,778	75,000-200,000
Fuel Consumption (L/100km)	21	20-47	25.3	29-59	30.6	31-59
Vehicle Class	N2 / O3	Class 5/6	N2-N3 / O3-O4	Class 7	N3 / O4	Class 8
Type Roads	Built-up areas	Residential	Dual Carriageways	Other limited access roads	Motorways	Freeway (rural)
Legal Speed limit (kph)	48	Up to 56	Up to 96	Up to 121	96	Up to 121[4]
Examples of Driving Cycles	WHVC (Urban)	EPA HD-UDDS	WHVC (Rural)	CARB HHDDT	WHVC (Motorway)	NESCAUM /SwRI

Based on Class-8 heavy-duty long-haul semi-trailers and following a California Heavy Duty Diesel Truck Drive Cycle, Cooper et al. (2009) simulated 32 low carbon technologies combined within 14 technology packages and found that fuel consumption could be reduced by 20% in 2012 and by 50% in 2017 while providing net savings for the operator. This was possible by combining aerodynamic and lower rolling resistance improvements in hybrid powertrains with heat recovery and limiting speed to 60 kph. The extent to which slowing down a fleet to such a low speed is realistic is debateable as the impact of this strategy in breaching time windows may have an opposite effect as more vehicles may be required to provide the same level of service quality to customers. Similarly, the National Research Council (2010) suggested that Class 8 vehicles could achieve 51% FCR between 2015-2020 with a FCR of 20% coming from advanced engines, 11.5% from aerodynamic improvements, 11% from lower rolling

[4] Texas up to 137.

resistance, 7% from transmissions and drivelines, 10% from hybrids and 1.25% from weight reductions. A medium duty class 6 box truck operating in regional haul (assuming 241 km/day at an average speed of 48 km/h) could achieve almost 50% FCR with the greatest potential coming from the use of hybrid powertrains (30% FCR) and waste heat recovery (14% FCR). There was less potential for lightweight materials and transmissions (4% FCR each), rolling resistance tyres (3%) and aerodynamic fairings (less than 1% FCR).

The review of the SuperTruck program conducted by the National Research Council (2012) investigated advances in low carbon technologies (LCT) for long-haul Class-8 HGVs and aimed at fuel savings of 33%, identifying fuel saving opportunities from predictive cruise control (up to 5%), speed limiters (up to 3%), aerodynamic improvements (up to 12%) and drivers training (over 1.9%). In highway driving, the National Research Council (2012) also identified considerable fuel savings waste heat recovery (almost 17% FCR) and single wide base tyres (15% FCR). In urban duty cycles, the main potential savings came from hybridisation (38%), intelligent transport systems (up to 15%) and driver training (up to 17%). In contrast, several other studies suggest fuel savings from optimal driving of around 10% can be achieved but these benefits are likely to diminish over time if training regimes are not maintained (Connelly et al., 2011, Hill et al., 2011). Kompfner and Reinhardt (2008) quantified the long term fuel saving effect of improved driving as being 7%. This highlights how important driving behaviour is on fuel consumption. The Supertruck program also identified that increasing size and weight also presented an opportunity to save up to 28% fuel on a unit payload basis for any cycle. However, this is arguable because the turning circle of longer vehicles may be too narrow for urban roads. This is also arguable because this is not always feasible as operators transporting certain appearances of loads (e.g. refrigerated cages) may not be able to take advantage of double decker trailers (DDTs).

According to Baker et al. (2009a) European articulated HGVs under long-haul duty cycles benefit the most from vehicle technologies such as aerodynamic trailers (10%), electric bodies (e.g. cryogenic refrigeration) and vehicle platooning (10%). Medium duty HGVs in urban deliveries benefit the most from powertrain technology improvements such as hybridisation (20%) or plug-in electric trucks (100% FCR at point of use) (Baker et al., 2009a). The study also covered the potential for reducing carbon emissions by using second generation biofuels (e.g. biomethane) and alternative fuels (e.g. natural gas).

Hill et al. (2011) reviewed different low carbon technologies for informing potential policy actions. This study suggested that urban operations can achieve 20-30% FCR by mainly improving powertrain efficiency on long haul operations and targeting vehicle drag losses. The savings reported were lower than other sources because neither fuel technologies nor operational measures were taken into consideration.

The University of Surrey designed a 40t 2-axle HGV concept capable of 12% FCR in medium duty and 8% in heavy duty motorway driving with a 10t load and whole life costs, £1,500 cheaper than the baseline vehicle (Connelly et al., 2011). This was possible by integrating a parallel mild-hybrid powertrain with regenerative braking as well as downsizing the engine to reduce weight, incorporating reduced rolling resistance, thermoelectric recovery of wasted heat and an aerodynamic shaped 'teardrop' trailer with aerodynamic fairings. With a payback of almost 5 years, the solution would most likely not be acceptable to businesses, as rigid vehicles for the industrial sponsor have a life expectancy of 5 years. However, the payback could improve if the mileage would be more closely matched to reality. Consistent with all the literature, at high speeds (90% motorway driving) aerodynamic improvements represented the major contributor to fuel reduction while at low speeds alternative powertrain (hybridisation) offered the greatest savings. In a rural cycle (a mix of high and low speeds), the contribution of both factors was similar. An additional 9% of fuel could be saved through a better management of auxiliary power.

According to Law et al. (2012), the combination of low carbon technologies for heavy goods vehicles could reduce fuel consumption by 46%, 41% and 47% for urban, regional and long haul deliveries respectively. The same study also estimates that by 2030 the GHG emissions savings for each duty cycle can reach 19%, 26% and 30%, assuming all applicable technologies and 13%, 20% and 17% for technologies with a payback of less than 3 years. Similarly, Hill et al. (2011) estimate fuel consumption reductions (FCRs) of 32%, 40% and 50% for urban, regional and long-haul duty cycles.

Kay and Hill (2012) focused on carbon savings rather than FCR and highlighted the importance of alternative powertrains and fuels. Their study suggested 50% WTW carbon savings by using pure electric vehicles in urban deliveries and up to 65% GHG savings switching from diesel to biomethane in long haul operations.

The analysis of the literature review shows that the carbon savings delivered by LCTs vary geographically and chronologically. The reasons involved, as previously explained, include the differences on vehicle designs and driving cycles but also the fact that the more modern vehicles improve year on year and there is less potential for improvement over time.

3.5 REVIEW OF LOW CARBON TECHNOLOGIES

While there are a number of technologies that can reduce fuel consumption, it is often difficult for logistics companies to identify which are the ones that are most beneficial. The literature on low carbon technologies for HGVs is extensive and global; with the main contributions focusing on US and European fleets. Most of the literature classifies low carbon technologies in three main groups: vehicle, powertrain and fuel technologies and it quantifies the fuel consumption reduction (FCR) that can be achieved by each individual technology or by packages of them. The studies are based on simulation results, dynamometer tests, engine bench tests or real world trials for urban, regional and/or long-haul duty cycles. Live trials typically follow the SAE J1321 Type II standard; to determine changes in fuel consumption for trucks and buses over 4,536 kg GVWR on a test track (SAE, 2012).

The literature review and review of evidence has been used to build a mindmap, where each LCT has been classified according to the main physics principles that they are influenced by. Due to the particularity of the type of operations of the industrial sponsor, the mindmap (Figure 26) consists of a catalogue of low carbon vehicle, powertrain, fuels but also transport refrigeration technologies. The technical characteristics of each technology, their advantages and disadvantages as well as supply chain information has been included (e.g. manufacturers, suppliers and industrial consumers). A copy of this Mindmap is accessible in the CD accompanying this thesis.

3.5.1 VEHICLE TECHNOLOGIES

After reviewing the literature, vehicle technologies have been defined as the technologies that have an influence on rolling resistance, aerodynamic drag, acceleration, gradient forces and ancillary losses that are not directly related to the powertrain, fuel or trailer refrigeration technologies. Figure 27 illustrates this classification.

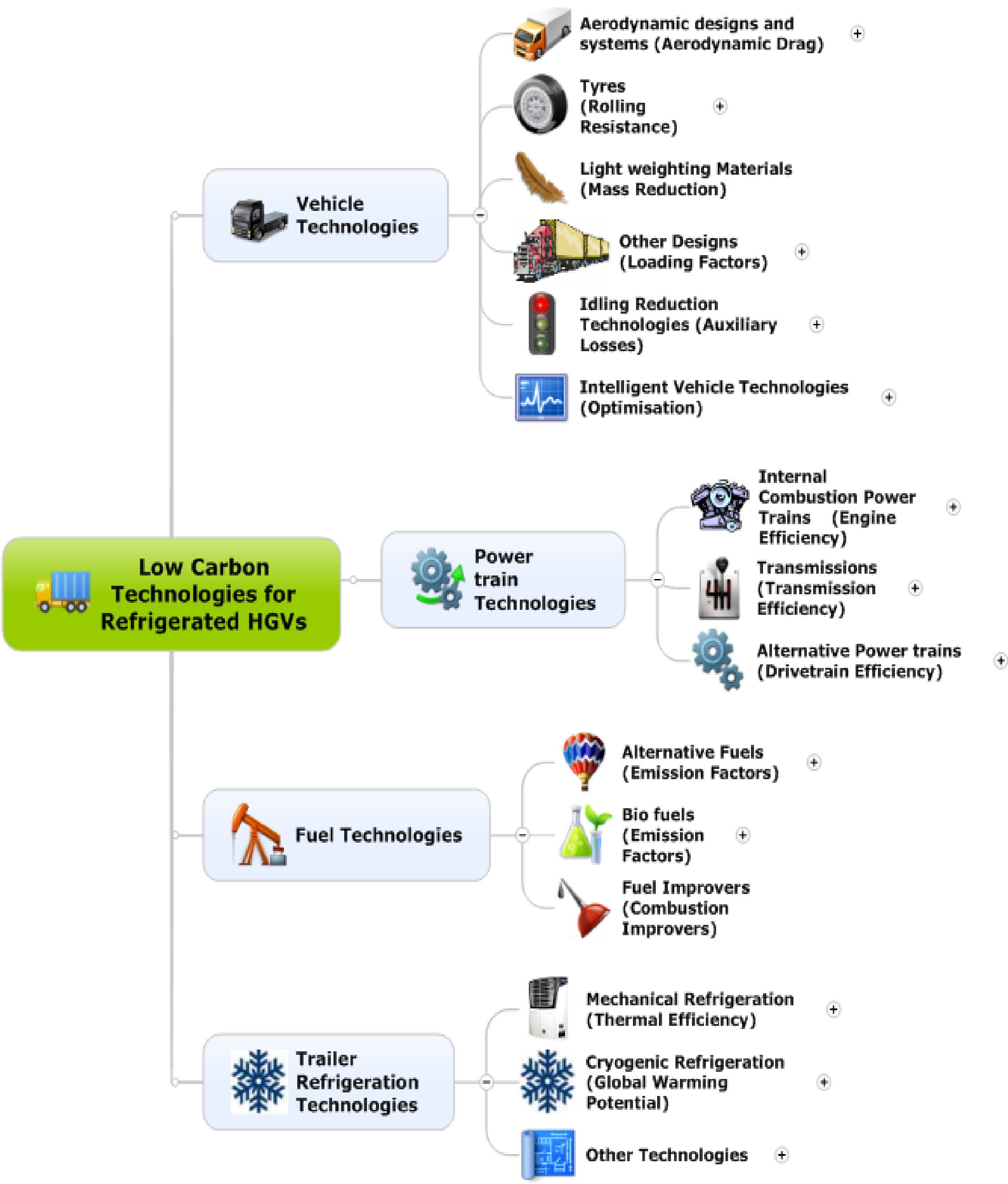


Figure 26. Low carbon technologies for refrigerated heavy goods vehicles.

3.5.1.1 ROLLING RESISTANCE

The force required to overcome rolling resistance depends on the vehicle mass, gravity and the rolling resistance coefficient of the tyre-road interaction (Equation 9), and as a result, vehicle Lightweighting and the reduction of tyre's rolling resistance are the areas where manufacturers focus on. As it can be observed in Figure 27, examples of such technologies include low rolling resistance tyres, new generation wide-base single tyres (also known as super singles), tyre pressure management systems, new tyre designs capable of recovering energy (not in commercial stage yet).

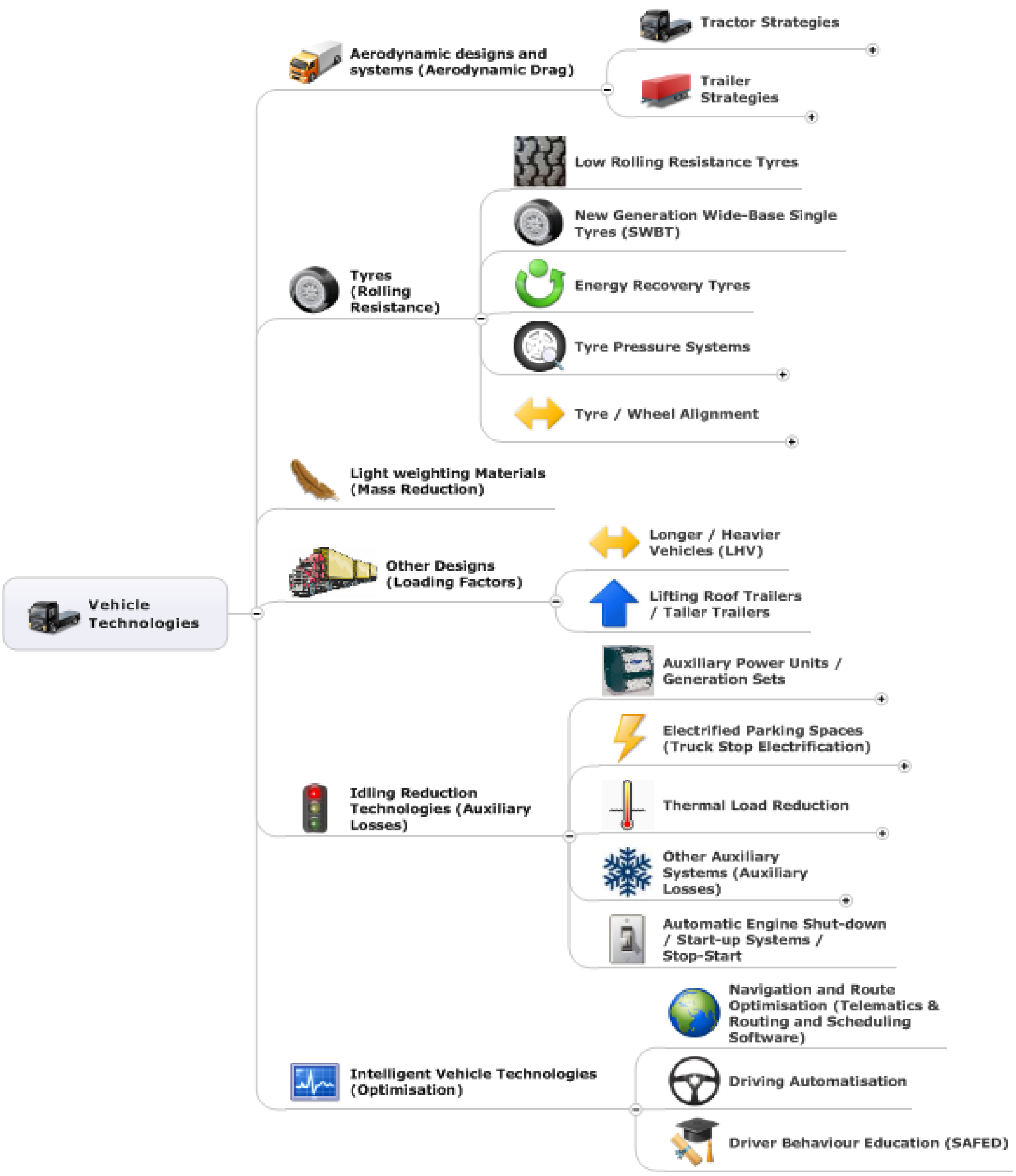


Figure 27. Classification of low carbon vehicle technologies for HGVs

Equation 9: Rolling Resistance forces.

$$F_{roll} = mgC_{rr}$$

Where:

F_{roll}= Rolling resistance force (N)

m= vehicle mass (kg)

g= Gravitational constant (9.81 m/s^2)

C_{rr}= Rolling resistance coefficient

The findings of the literature, relative to fuel savings from reduced rolling resistance are summarised in Tables 5 and 6. The power required to overcome rolling resistance depends on the speed of the vehicle and therefore, this means that FCR from lower rolling resistance technologies varies according to the duty cycle. According to the National Research Council (2014), rolling resistance represents around 30% of the work needed to move a US 'line-haul truck' on a level motorway at its typical speed. This percentage could be up to 43% in Europe (Figure 25, page 37). This suggests that improvements in rolling resistance can have a considerable impact on the total vehicle fuel consumption.

Technologically, tyre rolling resistance is influenced by the tyre compound and thread wear (National Research Council, 2014), the irregularities of the pavement and the tyre inflation pressure. The use of compounds that reduce rolling resistance decrease tyres' life expectancy which means that they need to be replaced more often. There is a trade-off between GHG emissions savings and total costs that needs to be considered by decision makers. There are also other non-technological strategies that can help to reduce the deterioration of the rolling resistance coefficient. For example, keeping a correct wheel alignment maintains the same air pressure in both sides of the vehicle's tyres and preserves the thread depth which can save up to 4.5% of fuel consumption (Vonk et al., 2013). Transport Canada (2006) reported that inflating tyres with nitrogen can yield a 4% FCR. This has not been validated by any other study and bearing in mind that 76% of the normal air used to inflate tyres is already nitrogen anyway, the potential for fuel savings seems exaggerated.

The FCR that can be achieved by using new generation single-wide based tyres (SWBT) varies between 2.1% in urban and up to 12% in long-haul duty cycles (depending on the source), leading in some cases to a 10% improvement in fuel economy while reducing NO_x emissions (National Research Council, 2014). As two conventioABBREnal tyres are replaced by a wider one, not only does the C_{rr} decrease but also around 340kg of vehicle mass can be reduced in a 5 axle tractor-trailer combination (National Research Council, 2014). In the UK, Bridgestone commercialises the Greatec M709 Ecopia, a drive tyre (495/45 R 22.5) and the R166II, a trailer tyre (435/50 R19.5), with a maximum carrying capacity of 5.8 and 4.5 tonnes per tyre respectively (Bridgestone, 2014).

Table 5. Reported FCR from rolling resistance improvements.

Technology	Fuel Consumption Reduction (FCR)	Source	Comments
Low Rolling Resistance Tyres 	Up to 5%	Baker et al. (2009a)	Quotes several third party studies with FCR from 4% to 13%.
	Up to 5%.	The Volvo Group (2012)	
	1% 3% 5%	Hill et al. (2011)	Urban Regional Long haul
Figure 28. LRR tyres.	2%-4%	Vonk et al. (2013)	Long haul
New Generation Wide-Base Single Tyres (WBST)	Around 10%	National Research Council (2010)	Quotes studies from Laclair, 2005 and Capps et al. 2008
	2% single tractor axle 6%-10% whole vehicle	Baker et al. (2009a)	Potential for increased payload
	4% 6% 5%	Hill et al. (2011)	Urban Regional Long haul (with Aluminium wheels)
Figure 29. New generation WBST. Source: Bridgestone (2014).	2.1%-4.2% 9%-12%	Law et al. (2012)	Urban Regional / Long haul

The benefits of installing automated tyre pressure adjustment systems (Figure 30) vary between duty cycles and from study to study. While Hill et al. (2011) and Platform for Aerodynamic Road Transport (2013) did not appreciate any significant improvements; Baker et al. (2009a) quantified these at around 7-8%. The FCR of these systems is difficult to measure because this depends on the baseline vehicle and previous tyre maintenance schedule. The installation of such systems in HGVs whose drivers keep tyre pressure regularly at an optimal level have a much lower leeway to reduce fuel consumption. According to Onoda and Gueret (2007) in average EU trucks are under-inflated by 0.5 bar. In the US around 7% of all tyres are under-inflated by 3 bars , and only 44% are within ±0.34 bars (Brady et al., 2007). More recent studies suggest that in the US, around 20% of trucks, trailers and lorries operate with tyres under-inflated by 1.37 bar and only 46% are within 0.34 bar of the optimal level (NACFE, 2013). Therefore comparing the latter two studies there has been little progress from the 44% reported in 2007 to the 46% reported 2013. This means that for almost half of the fleets, automatic tyre pressure systems will have no effect. For the rest, under-inflation will affect the rolling resistance coefficient of the tyres and therefore it will increase fuel consumption. National Research Council (2014) also mentions the advantage of such systems when working in combination with SWBT to avoid these running flat, also increasing tyre life, safety and improving fuel efficiency.

Table 6. Reported FCR from tyre inflation systems.

Technology	FCR	Source	Comments
Automatic Tyre Pressure Adjustment  Figure 30. Automatic tyre pressure system fitted on a wheel.	1%	Onoda and Gueret (2007)	Truck tyres are underinflated by 0.5 bar
	7%-8%	Baker et al. (2009a)	
	0.5%-2.5%	Platform for Aerodynamic Road Transport (2013)	
	1% 2% 3%	Hill et al. (2011)	Urban Regional Long haul
	0.6% Tractor 0.6% Trailer	Law et al. (2012)	Regional / Long haul
	0.5%-2.5%	Vonk et al. (2013)	Long haul

In discussions with Continental (2015), the manufacturer said that the C_{rr} of their EcoPlus tyres in 2015 was considerably lower than a similar low rolling resistance tyre from 2010; however, this is difficult to verify as all the major tyre manufacturers interviewed during this research (Michelin, Goodyear and Continental) declined to provide the specific C_{rr} of any of their tyres, as they consider this parameter to be confidential. On the other hand, they need to report this to EU authorities as requested by the EU tyre labelling regulation 1222/2009 (European Commission, 2009b). In the regulation, tyres are ranked from an ‘A’ to ‘G’ scale according to their energy efficiency class. For any type of tyre (HGVs use type C2) within the same energy band, the differences in rolling resistance can be around 1.1-1.2 kg/t. Manufacturers must follow the ISO 28580 standard when testing each of their tyre models to advertise their fuel efficiency band. The National Research Council (2014) criticises the robustness of the commercial vehicle tyre test procedure and suggests that the analysis of C_{rr} should be carried out by a single laboratory instead of each manufacturer providing their own results. As a result, the lack of transparency and testing consistency makes it difficult to compare the real impact of tyres within the same band from different manufacturers and therefore, the results reported in the literature must be treated with caution.

3.5.1.2 LIGHTWEIGHTING MATERIALS

Mass affects rolling resistance, acceleration and gradient forces (Equation 4). Substituting steel with Aluminium and plastic composites and other light weight material alloys can reduce engine, drive-train, wheel rim, fuel tank and trailer weight (e.g. with aluminium composite panels). The literature suggests that savings of up to 5% are achievable (Table 7). Furthermore, lower trailer mass may allow in some cases, an increase in vehicle payload, reducing carbon emissions per tkm even further. Due to the high costs of lighter materials, their use is limited. Smaller weight reductions also lead to noticeable fuel savings (2.2-5%), depending on the duty cycle.

Table 7. Literature review of the FCR from reducing vehicle mass.

Technology	FCR	Source	Comments
Light Weight Materials	5%	Baker et al. (2009a)	
	3%-5% 2.2%	Hill et al. (2011)	Urban (454kg) Regional / Long Haul (450kg)
	5%	National Research Council (2010)	Weight reduction 2,268 kg

The installation of other LCTs needs to be considered as they can have a negative impact on the kerb weight of the vehicles. Detailed examples of these are reported by ACEA (2015) and Meszler et al. (2015). For example, the implementation of air quality emission standards legislation led to vehicles 80-150 kg heavier (ACEA, 2015). This could potentially have increased vehicles' fuel consumption and therefore, carbon emissions; however, this was not the case with Euro 6 vehicles as revealed from personal communications with vehicle manufacturers. The reason is that they redesigned their Euro VI powertrains completely improving engine's efficiency.

3.5.1.3 AERODYNAMIC DRAG

Aerodynamic drag is improved by reducing drag coefficient, frontal area and vehicle speed (Equation 10). Technologies that reduce drag resistance include speed limitation devices and more aerodynamic designs for trucks and trailers. Aerodynamic enhancements can be divided into tractor and trailer improvements

(Figure 31) and benefits from vehicle platooning. The outcome of the literature review and review of evidence of aerodynamic improvements for tractor units appear in Table 8, trailers and boxes in Table 9 and for tractor and trailers in Table 10.

Figure 31. Technologies that can save fuel by reducing aerodynamic drag.

The FCR of tractor aerodynamic improvements varies between 2% and 7% by using cab deflectors and fairings (Platform for Aerodynamic Road Transport, 2013, Baker et al., 2009a, Law et al., 2012). Replacing mirrors with cameras can generate between 1.5% to 3% FCR (National Research Council, 2012). Long-haul aerodynamic trailers can achieve FCR of up to 11% (Hill et al., 2011), with teardrop shape semi-trailers obtaining slightly over 11% (Baker et al., 2009a). Results from simulations from the University of Gratz show that a lowered trailer rear end (bent roof) results in lower air resistance force in the driving direction leading to fuel savings of 6.5% with a reduction in payload space of 5% (Hirz and Stadler, 2013).

Equation 10: Drag force equation

$$F_{air} = \frac{1}{2} \rho_a C_D A_F v^2$$

Where:

F_{air} = Aerodynamic drag resistance (N)

ρ_a = Density of air (kg/m^3)

C_D = Aerodynamic drag coefficient

A_F = Frontal area (m^2)

v = Speed (m/s)

A technology of particular interest is the innovative spray suppression mudflaps (Table 10). These mudflaps present an excellent return on investment as studies suggest that FCR between 0.5% and 3.5% is achievable at a very low cost (Baker et al., 2009a, Hill et al., 2011, Platform for Aerodynamic Road Transport, 2013, Vonk et al., 2013). A real world trial has been conducted during this research to ascertain the veracity of such claims and the results are presented in Chapter 5.

More innovative aerodynamic improvements include pneumatic blowing devices that control actively the aerodynamic flow of air at the rear of the trailer reducing fuel consumption by 8%. This has a similar function as boat-tail extenders by improving aerodynamic drag. However, the latter extend the length of the vehicle, reducing vehicle payload if dimensions' regulations are not upgraded to accommodate for the extra length. This is an area that should be considered by policy makers as these extenders can achieve a FCR of up to 5% (National Research Council, 2014).

Another approach to reduce drag is vehicle platooning. Baker et al. (2009a) reported a FCR of 20% by combining vehicle convoys with ITS technologies. By creating an electronic tow bar that keeps vehicles at an optimal distance, a head semi-trailer can produce fuel savings in other HGVs behind it by reducing air drag and also by delegating driving to a more experienced driver. These results were similar to the predictions of Bonnet and Fritz (2000) who found that at 80 km/h simulated electronic tow-bar systems reduced the FC of a rear 28t vehicle by 21%, and 17% for a 40 tonne, and 6% for the front vehicle. This is consistent with the European SARTRE project, which expected to demonstrate fuel savings of around 20% (SARTRE, 2012).

Table 8. Reported FCR that can be achieved by using vehicle technologies that reduce the power needed to overcome aerodynamic drag

Technology *Tractor Unit*	FCR	Source	Comments
Cab Roof Deflector / Fairing  Figure 32. Lorry with a cab deflector fairing.	2.3%-4.8%	Baker et al. (2009a)	Lower bound 40t drawbar. Higher bound 17t rigid.
	7%	Platform for Aerodynamic Road Transport (2013)	
	2%-3%	Law et al. (2012)	Urban
Replacing Mirrors with Cameras	1.5%-3%	(National Research Council, 2012)	
Aerodynamic Mirrors  Figure 33. Aerodynamic Mirrors.	0.2%	Platform for Aerodynamic Road Transport (2013)	

Table 9. Reported FCR that can be achieved by using trailer technologies that reduce the power needed to overcome aerodynamic drag

Technology *Trailer Unit*	FCR	Source	Comments
Under tray System  Figure 34. Aerodynamic Trailer with under tray.	Over 10%	US DoE (2013a)	
	5%	National Research Council (2014)	$1000 and up depending on design and mounting
Aerodynamic Trailers  Figure 35 Aerodynamic lorry.	1% 11%	Hill et al. (2011)	Urban Regional / Long Haul
Side Skirts/Panels  Figure 36. Trailer side skirt and panels.	0.4%-1%	Baker et al. (2009a)	Also quotes Canadian live trial 6.4%.
	5%	Platform for Aerodynamic Road Transport (2013)	Lower bound 40t drawbar. Higher bound 17t rigid.
	5.2%	Cooper et al. (2009)	
	2.7%-6%	Vonk et al. (2013)	
	2%-3%	Law et al. (2012)	Long Haul
	4-5%	National Research Council (2014)	Urban / Regional / Long Haul Depending on design and mounting

Technology *Trailer Unit*	**FCR**	**Source**	**Comments**
Tapered Roof	**01%- 0.5%**	**Baker et al. (2009a)**	**Lower bound 40t drawbar. Higher bound 17t rigid.**
Front Fairing  **Figure 37. Front fairing.**	**0.7%- 3.6%**	**Baker et al. (2009a)**	**Lower bound 40t drawbar. Higher bound 17t rigid.**
Boat-Tail Extenders  	**4.5%**	**Platform for Aerodynamic Road Transport (2013)**	
	2%-4%	**Law et al. (2012)**	**Regional / Long Haul $800 and up depending on design and mounting**
Figure 38. Boat tail extenders. **Source: Platform for Aerodynamic Road Transport (2013).**	**≥1% and 5%**	**National Research Council (2014)**	
Pneumatic Blowing / Active flow control  **Figure 39. Active flow control.** **Source: Georgia Institute of Technology (2005).**	**8%**	**National Research Council (2010)**	**Quotes Englar (2005)**

Technology *Trailer Unit*	FCR	Source	Comments
Teardrop Shape with side skirts (Box Van)  Figure 40. Teardrop shaped trailer.	11.2%	Baker et al. (2009a)	Quotes trials from Don-Bur with FCR varying 4%-23.7% Urban Regional Long haul
	1% 6.5% 5%	Hill et al. (2011)	Urban Regional Long-Haul

Table 10. Reported FCR that can be achieved by using technologies that reduce the power needed to overcome aerodynamic drag in tractor and trailers.

Technology *Tractor & Trailer*	FCR	Source	Comments
Spray Reduction Mud flaps  Figure 41. Spray suppression mudflaps.	Around 3.5%	Baker et al. (2009a)	Quotes 2% from U.O. Strathclyde
	1.5%	Platform for Aerodynamic Road Transport (2013)	
	0.5%-1.5%	Vonk et al. (2013)	Long-haul
	1% 2% 3.5%	Hill et al. (2011)	Urban Regional Long haul
Gap Interface (Cab Collars)	0.6%-1%	National Research Council (2010)	
	0.5%-1% 1%-2%	Law et al. (2012)	Urban Regional / Long haul $650
	≥1%	National Research Council (2014)	Urban Regional / Long haul $650

3.2.1.1. GRADIENT & ACCELERATION

Climbing resistance is the factor that influences power requirements the most (Connelly et al., 2011). Understanding clearly if the vehicle is going to run in relatively flat areas is critical to specify the most appropriate powertrain size. It is possible to reduce the energy required to overcome gradient forces (Equation 11) by reducing vehicle mass and speed, by recovering energy when going downhill and also by accelerating before climbing a hill. Examples of such technologies include lightweighting technologies (Table 7) and predictive cruise control (Table 11). Cruise control uses topographic information of the road gradient to adjust the drivetrain operation and save fuel. The device can detect if a hill is approaching and increase the vehicle' speed before start climbing to save some energy due to accumulated inertia. Studies indicate no fuel savings in urban duty cycles and between 1% and 5% in regional and long-haul ones (Table 11).

Equation 11: Gradient forces.

$$F_{grd} = mg \sin \theta$$

Where:

F_{grd} = Gradient forces

m = Vehicle mass (kg)

g = Gravitational constant (9.81 m/s^2)

θ = Road gradient (degrees from horizontal)

Table 11. Fuel Savings from predictive cruise control technologies.

Technology Management	FCR	Source	Comments
Predictive Cruise Control	0% 1%-2%	Law et al. (2012)	Urban Regional / Long Haul
	0% 5%	Hill et al. (2011)	Urban Regional / Long Haul

Acceleration forces (Equation 12) can also be smoother with technologies such as adaptive cruise control delivering fuel savings around 1% (National Research Council, 2010) . Driving assistance technologies can also help to influence drivers' behaviour by emitting signals when harsh accelerations occur (e.g. over speeding engine's rpms); this type of information is also analysed by some telematics systems and can be related to driver's performance improvement targets.

Equation 12: Acceleration forces.

$$F_{acc} = ma$$

Where:

F_{acc} = Acceleration force
m = Vehicle mass (kg)
a = Acceleration (m/s^2). This is (dv/dt)

3.5.1.4 OTHER VEHICLE DESIGNS

Other designs refer to trailers that increase loading factors and include longer heavier vehicles also known as mega-trailers, giga-liners or long combination vehicles), taller trailers that use lifting roofs and double decker trailers (Figure 42). These trailers increase vehicle mass and aerodynamic drag; however, due to their higher capacity, carbon emissions per unit of payload decrease. As these vehicles must also meet the maximum legal standard GVW, they tend to be used on lighter commodities (e.g. paper products, empty plastic bottles, and empty shipping containers), despite having a higher volume capacity.

Figure 42. Double decker step-frame curtain trailer.

Ceuster et al. (2008) reported that longer heavier vehicles' payload could increase between 30%-50%, reduce fuel consumption and GHG by at least 10% and congestion levels between 7%-10% due to a decrease on trips of 33%; since 2 longer heavier vehicles could replace 3 conventional HGVs. Similarly, in Australia, VREF CoE-SUFS (2015) found that these vehicles could improve the productivity of rigid lorries by 20% and 33% for articulated trailers. In the US, the National Research Council (2010) reported fuel savings of 20% per unit of freight quantity. The regulations of different countries limits the dimensions of such vehicles due to safety concerns and the potential damage on roads. In the UK, the Government is allowing the trial of a potential quota of up to 1,800 longer heavier vehicles with a maximum length of 15.65 m instead of the typical legal maximum of 14.6 m (DfT, 2013a).

Refrigerated double decker trailers (DDT) are well suited for transporting up to 44 pallets (Gray & Adams, 2013). The height of two UK pallets is around 3.04 m while the typical internal height of a DDT is at least 3.1 m. DDT are not a good solution when dealing with the transportation of regrigerated food on rolling cages, as these are too high to be double stacked and fitting the evaporators inside the trailer box. As longer-heavier vehicles are not suitable for city logistics and DDT are not ideal for rolling cages, both types of designs were not included in quantitative evolutionary model developed in this research.

3.5.1.5 ANTI-IDLING

Truck idling happens when the engine is continuously running despite the fact that the vehicle does not use power for traction. In these cases, energy is needed to power auxiliary systems (e.g. wipers, telematics units, etc.) and on-board hotel loads such as cabin heating/refrigeration, lighting, electronic devices (e.g. GPS, phones) and electrical appliances (e.g. fridges, microwaves). Truck idling is also necessary to run 3 phase alternator refrigeration units. Some of the technologies that can reduce fuel consumption by avoiding vehicle idling are illustrated in Figure 43. Anti-idling technologies could be classified in three main groups: auxiliary power units powered by fuels, fuel cells or batteries; electrified parking spaces; and heating and cooling devices and strategies. Stop-start devices also avoid engine idling by switching it off each time a vehicle stops; however, it may be accurate to classify this technology as a mild form of powertrain hybridisation. It is also possible to install timers that swtich the engine after the vehicle has stopped for a few minutes.

In the US, there are many states that have legislated excessive idling to avoid air quality pollution and also GHG emissions. Studies from the American Transportation Research Institute found that Class 7 trucks spend 200 hr./year idling, Class 8 Non Sleeper trucks (day cabs) 312 hr./year and Class 8 Sleeper trucks up to 1,456hr/year (Hennessy, 2010) at an average cost of $3.00/hr. (National Research Council, 2010). Class 8 trucks were estimated to generate more than 11 tonnes of CO_2/year per truck. According to the literature review, the FCR that can be obtained with anti-idling technologies vary from 1.3% to 40% depending on how much idling time the vehicle typically does and the type of energy used (Table 12).

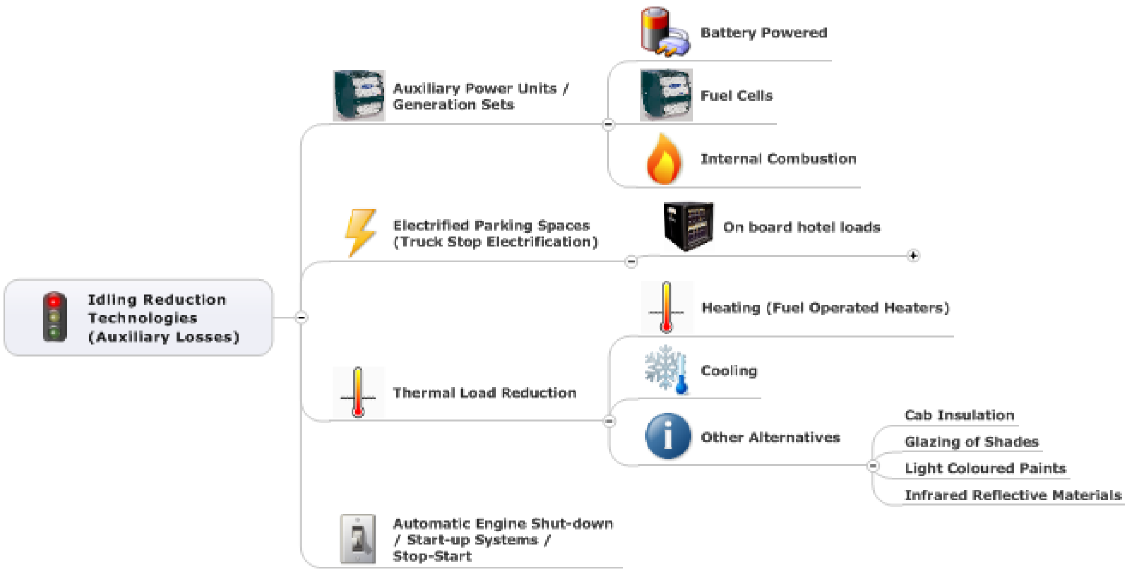


Figure 43. Anti-idling technologies.

Truck electrification is an external technology that eliminates the need for consuming fuel while stationary by plugging in the vehicle to the grid to power on-board hotel loads and also connecting heating and cooling adapted hoses through the vehicle window. It is estimated that this idling reduction system can yield fuel savings between 5-9% (Cooper et al., 2009).

Auxiliary power units (APUs) using alternative fuels (e.g. gas) or biofuels can also reduce GHG emissions. APUs based on proton exchange fuel cells (PEMFCs) can produce heat and electricity with zero tailpipe emissions; however, as hydrogen is an energy carrier its WTW GHG emissions will depend on the process and energy grid mix to produce it. When hydrogen contacts air, the fuel cells produce electricity, heat and water. Nonetheless, they require a battery to store energy and generate a stable flow. Solid Oxide Fuel Cells (SOFC) reform hydrocarbon fuels such as liquid or gas fossil fuels and biofuels into a hydrogen rich syngas that is converted into direct-current electricity without combustion, producing water vapour and a small amount of CO_2 as by-products. Other of their advantages include quieter operations (around 55 dB (A)) and low vibrations. In Europe, the METSOFC project developed a next generation SOFC stack technology (TOPSOE, 2010) which preceded the METSAPP project whose main goals were to deliver a robust 1-3kW fuel cell stack solution (METSAPP, 2015). Very recently, the DESTA (2015) project has achieved this objective by producing a mobile SOFC with a net power of 3kW generating very low NOx, no diesel particles and reducing CO_2 emissions by 71%.

Table 12. Anti-idling technologies.

Technology Anti-Idling Technologies	FCR	Source	Comments
Automatic Engine Shut-down	3%	Cooper et al. (2009)	
Auxiliary Power Units  Figure 44. A 3 kW SOFC for HGVs. Source: AVL (2015).	4%-7%	Cooper et al. (2009)	Internal Combustion SOFC
	40%	Baker et al. (2009a)	
	71%	DESTA (2015)	
Batteries  Figure 45. Hybrid truck battery.	5%-9%	Cooper et al. (2009)	
Fuel Operated Heaters  Figure 46. Fuel tank cab heater.	1.3%-2.3% 2.91%	Vyas et al. (2003)	
Truck Electrification	5%-9%	Vyas et al. (2003)	

Thermal management technologies that assist in the reduction of energy consumption for heating tractor cabs include fuel operated coolant heaters. These are useful to heat the engine and avoid cold starts and also to heat the fuel tank to avoid the waxing effect of biodiesel in winter. Fuel operated air heaters (bunk heaters) supply warm air into the cabin or bunk. These technologies avoid idling and vehicle vibrations which improves driver's comfort, they deliver 1.3%-2.3% fuel savings, and reduce engine wear.

3.5.2 POWERTRAIN TECHNOLOGIES

Lower carbon powertrain technologies are technologies that generate tractive power more efficiently, leading to fuel savings and carbon emissions reductions. The review of the literature and commercial evidence has led to the classification of energy efficient powertrain technologies in three main groups; technologies that can improve the internal combustion efficiency of conventional engines, technologies that focus on improving drivelines and alternative powertrains (Figure 47).

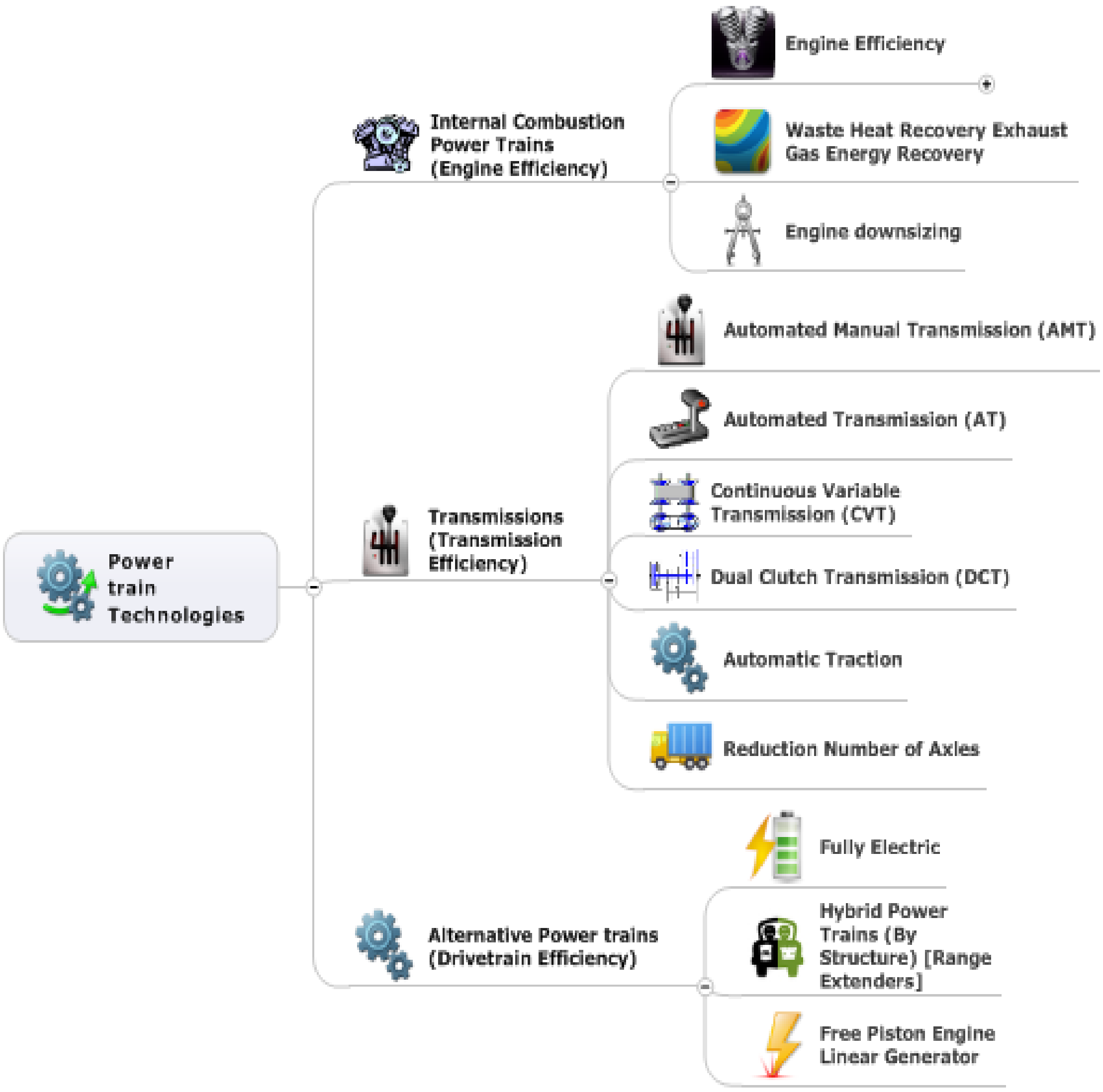


Figure 47. Classification of powertrain technologies.

3.5.2.1 CONVENTIONAL POWERTRAINS

Conventional powertrains refer to improvements of internal combustion engines running on liquid or gas fossil or bio fuels. This can be done by using low carbon technologies (Figure 48) but also by understanding the operational characteristics of the fleet and downsizing engines whenever possible. Despite the fact that most HGVs run on diesel and therefore, they work through compression ignition, some of the technologies included in the mindmap refer to spark ignition engines as gas vehicles are becoming more popular. The US DoE (2013b) considers that depending on the casting materials and the engine design used, the approximate diesel and gas engine maximum theoretical efficiencies are under 55% and 43% respectively which limits how much these can improve in the long run.

Waste heat technologies recover heat from the exhaust to improve the thermal efficiency of the vehicle. This can be done through the turbo compound drive, heat exchangers (bottoming cycles) and thermo-electrical processes (Baker et al., 2009a). Depending on the duty cycle, HGV fuel savings have been reported in the range of 1% to 6% (Table 13).

Up to a maximum theoretical limit, engines' efficiency can be improved mainly through better gas exchange (Table 14), reduction of friction (Table 15), and reduction of parasitic losses (Table 16) as well as modifying the internal combustion process with technologies such as the ones illustrated in Figure 48. Parasitic losses refer to ancillary equipment that support engine operations such as air compressors, pumps, fans and power steering (National Research Council, 2010) and represent 2.5% of the energy required by a vehicle (Figure 25, page 37). As can be seen in Tables 13-16, the FCR improvements in conventional diesel engines are rather limited and do not exceed 6% in any case. This is because diesel technology is reaching a high level of optimisation. Considering carbon emissions, this does not mean that conventional powertrains are likely to become obsolete as the decarbonisation of fuels can still guarantee a promising future for these technologies.

There are also new approaches to reduce conventional engines FCR such as the use of a pneumatic booster (Figure 49). This is a technology that injects compressed air from an auxiliary tank into a turbocharged internal combustion engine's manifold which increases torque and fuel efficiency (Knorr-Bremse AG, 2012).

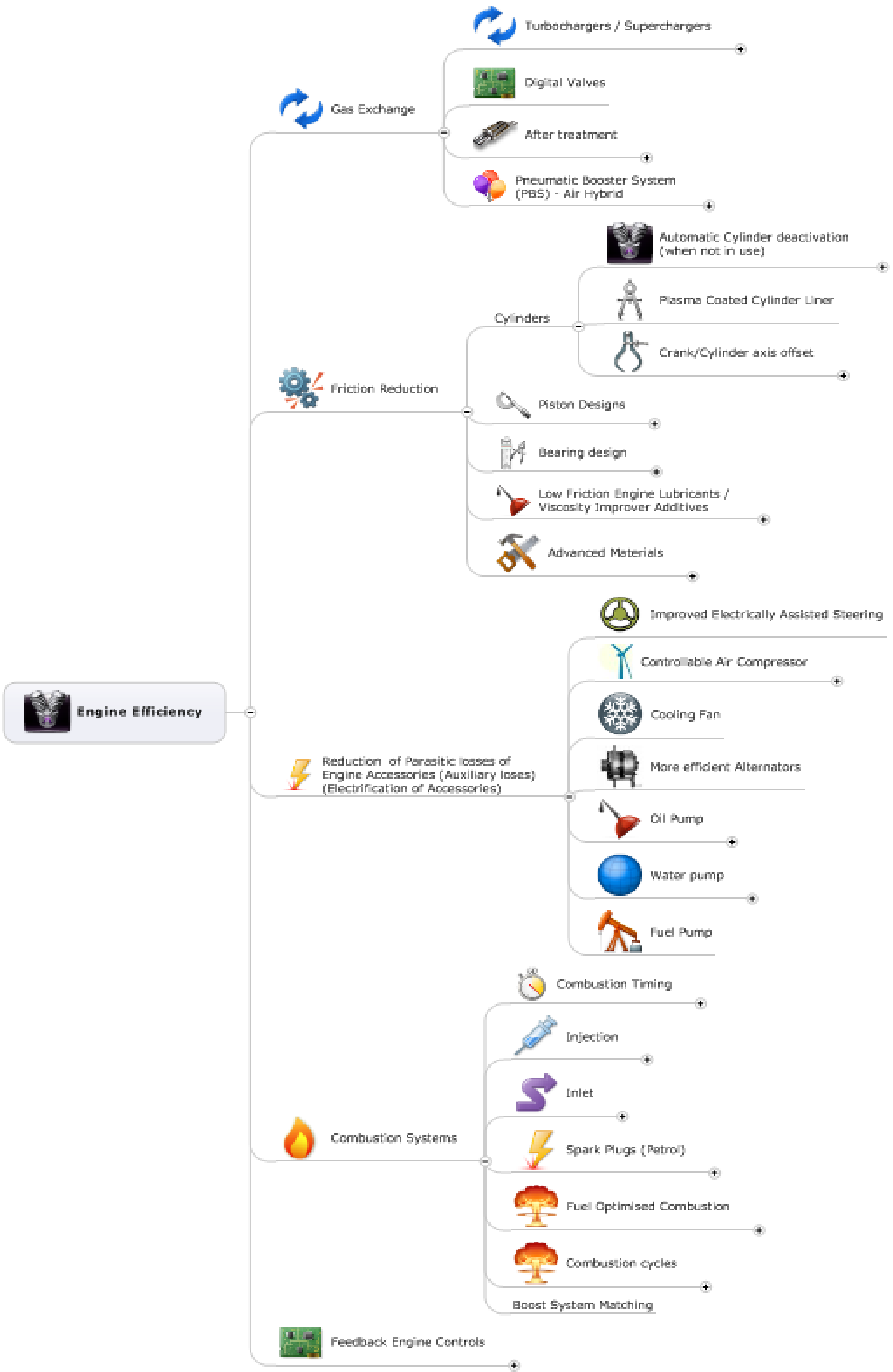


Figure 48. Technologies that can improve engine efficiency.

Table 13. Wasted heat recovery technologies through thermal efficiency improvement.

Technology *Waste Heat Recovery Thermal Efficiency*	FCR	Source	Comments
Bottoming Cycles	3%-6%	Baker et al. (2009a)	
	1.5% 2.5% 5%	Hill et al. (2011)	Urban Regional Long haul
Thermoelectric Generators (Electric Turbo compound)	2%	Baker et al. (2009a)	
	1% 2.5% 3%	Hill et al. (2011)	Urban Regional Long haul

Table 14. Engine efficiency technologies through gas exchange improvement.

Technology *Engine Efficiency (Gas Exchange)*	FCR	Source	Comments
Turbo/Super Chargers	2.5%-3%	Cooper et al. (2009)	
	3% 3%-5%	Hill et al. (2011)	Electrical Drive Mechanical Drive
Gas Exchange	Up to 2%	Baker et al. (2009a)	Including electric assisted 2 stage turbocharger, EGR & VVT
Pneumatic Booster System	1.5%-2%	Baker et al. (2009a)	
 Figure 49. PBS. Source: Knorr-Bremse AG (2012)	1.5% 3.5%	Hill et al. (2011)	Urban / Regional Long Haul

Table 15. Engine efficiency technologies through friction reduction improvements.

Technology *Friction Reduction*	FCR	Source	Comments
Piston design and cylinder surface improvement	0.5%	Baker et al. (2009a)	
Crankshaft bearing materials	0.5%	Baker et al. (2009a)	
Oil Specification Change	1.5%	Baker et al. (2009a)	
	1%	National Research Council (2010)	

Table 16. Engine efficiency technologies through auxiliary Loads improvements.

Technology *Auxiliary Loads*	FCR	Source	Comments
Controllable Air Compressor With Electric/Air actuated clutch	0%	Hill et al. (2011)	
	1% 1.5% 1.5%	Baker et al. (2009a)	Urban Regional Long haul
Oil Pump	1%-3%	Baker et al. (2009a)	Variable or Electric
Water Pump	0.7% 1%-4%	Baker et al. (2009a)	Mechanical Electrical

3.5.2.2 TRANSMISSIONS

The outcome of the literature review reveals that in addition to reducing the number of axles and using low friction lubricants, there are five main low carbon transmission technologies (Figure 50). Reducing energy consumption from transmissions can also benefit from reducing the number of axles of the vehicle and using better transmission lubricants. Transmissions are used to couple the engine to the driveline. HGVs can be manufactured with automated manual (AMT), automated (AT), continuous variable (CVT) and dual clutch transmissions (DCT). According to Cooper et al. (2009), transmissions and drivelines can reduce fuel consumption by 7% by 2020 compared to HGVs without well specified ones. Some of the findings in the literature are summarised in Table 17.

AMT for HGVs can produce a 7% of FCR in heavy and 10% in medium duty cycles at an additional cost of £ 1,000-1,500 (Baker et al., 2009a). AMT use an electronic controller to clutch a manual transmission avoiding driver variability and improve efficiency (Cooper et al., 2009). The energy savings are obtained at a lower engine speed, which reduces friction and ‘pumping losses’, keeping the engine near optimal conditions (Meszler et al., 2015). DCT are similar to AMT but they include two clutches which allow uninterrupted shifting improving engine' efficiency by down speeding[5] (Meszler et al., 2015); however, due to the need to increase torque, they are not suitable for medium and long haul duty HGVs as they would have a penalty on GHG emissions (Baker et al., 2009a). AT are more suitable for urban and suburban operations as they can improve productivity by reducing shift time and reducing driver variability; however, it requires shift strategies to be defined. In long haul duty cycles, there are no benefits due in part to higher parasitic losses (National Research Council, 2010). CVT use belt-connected pulleys to provide continuous speed ratios to optimise transmission speed-load conditions. According to Frey and Kuo (2007), CVTs can reduce FC by 1% as the engine can work at its peak efficiency. All these advanced transmissions tend to be more complex and expensive to buy than conventional manual transmissions but for certain operations, they can give a favourable return.

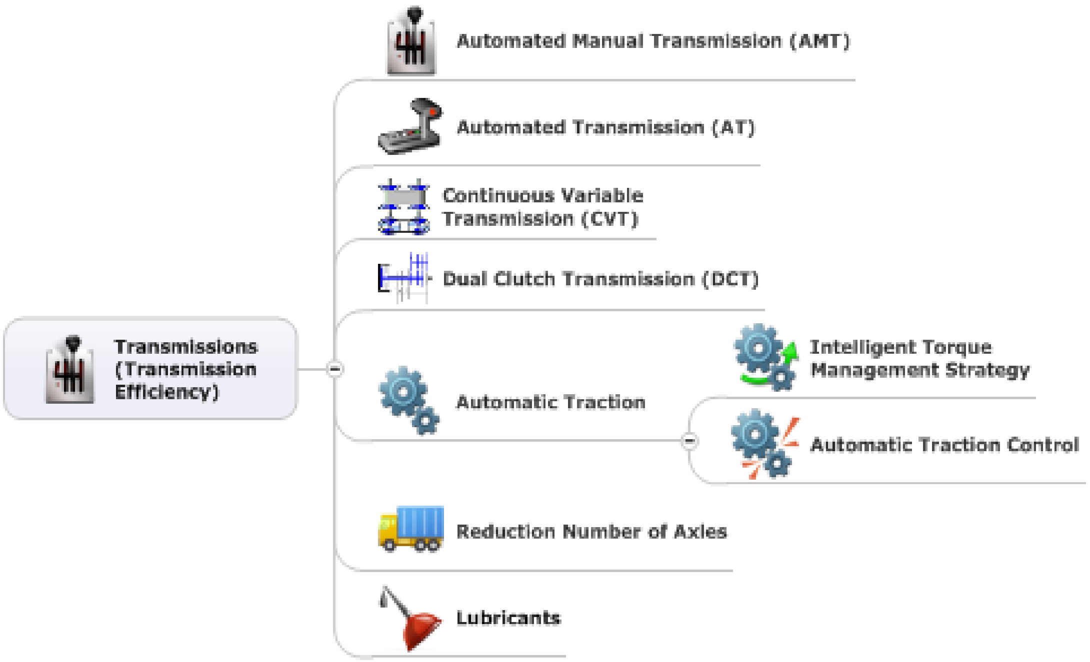


Figure 50. Classification of low carbon transmission technologies.

Automatic traction refers to controllers that can reduce fuel consumption by de-activating axle traction depending on the torque required. The Volvo Group (2015) indicates a maximum of 6% savings by proper engagement and disengagement of 6x6 axle for an off-road HDV. Intelligent torque control has a fuel saving potential of 4% (The Volvo Group, 2012) when used in combination with DCT.

[5] Down speeding consists on operating the engine at lower speeds (rpm) with high torque. This reduces friction, heat transfer and improves thermodynamic efficiency.

Table 17. Fuel savings from more efficient transmissions.

Technology *Transmissions*	FCR	Study (or DC)	Comments
Automated Manual	7%-10%	Baker et al. (2009a)	Compared to manual transmission
	4-8%	National Research Council (2010)	
Automated	0-5%	Cooper et al. (2009)	
	5% 1.5%	Hill et al. (2011)	Urban Regional / Long haul
	1%-1.5%	Law et al. (2012)	Regional / Lon Haul
Continuous Variable	1%	Frey and Kuo (2007)	For all duty cycles
Dual Clutch	0%	Meszler et al. (2015)	Regiona/Long-Haul
Lubricants	1%	Frey and Kuo (2007)	For all duty cycles

3.5.2.3 ALTERNATIVE POWERTRAINS

Alternative powertrains refer to the use of electric motors and hybrid powertrains instead of ICE. A list of technologies that can reduce GHG emissions in each of those areas are illustrated in Figure 51.

3.5.2.3.1 FULLY ELECTRIC POWERTRAINS

Electric trucks (e-trucks) use electricity accumulated in batteries in combination sometimes with fuel cells or electric generators to deliver the power required by the vehicle. Electric motors are less complex and much more efficient than ICEs. In combination with recharging technologies such as capacitors, catenaries or induction systems, batteries can also be downsized which presents the additional advantage of a lower vehicle mass and therefore, further energy savings.

Kay and Hill (2012) highlighted the importance of alternative powertrains. Their study suggested 50% WTW carbon savings by using pure electric vehicles in urban deliveries. Other advantages applicable to the UK include lower taxation and the exemption of some vehicle requirements such as vehicle excise duty (VED), yearly MOT or operator's license (DfT, 2012). Electric trucks can save 100% GHG emissions at their point of use (Baker et al., 2009a, Hausberger et al., 2012), they are quiet, have lower energy costs and for some vehicle types, lower whole life costs than conventional powertrains (Baker et al., 2009a). Unless the electricity is auto generated, WTW GHG emissions of EVs depend on the carbon intensity of the national grid mix. In countries such as Poland, where most of the electricity generated comes from coal, or in the UK, where around 50% of the electricity is produced from fossil fuels, WTW GHG emissions of electric vehicles (EV) are much higher than in countries like France where most of the electricity is produced from nuclear power stations.

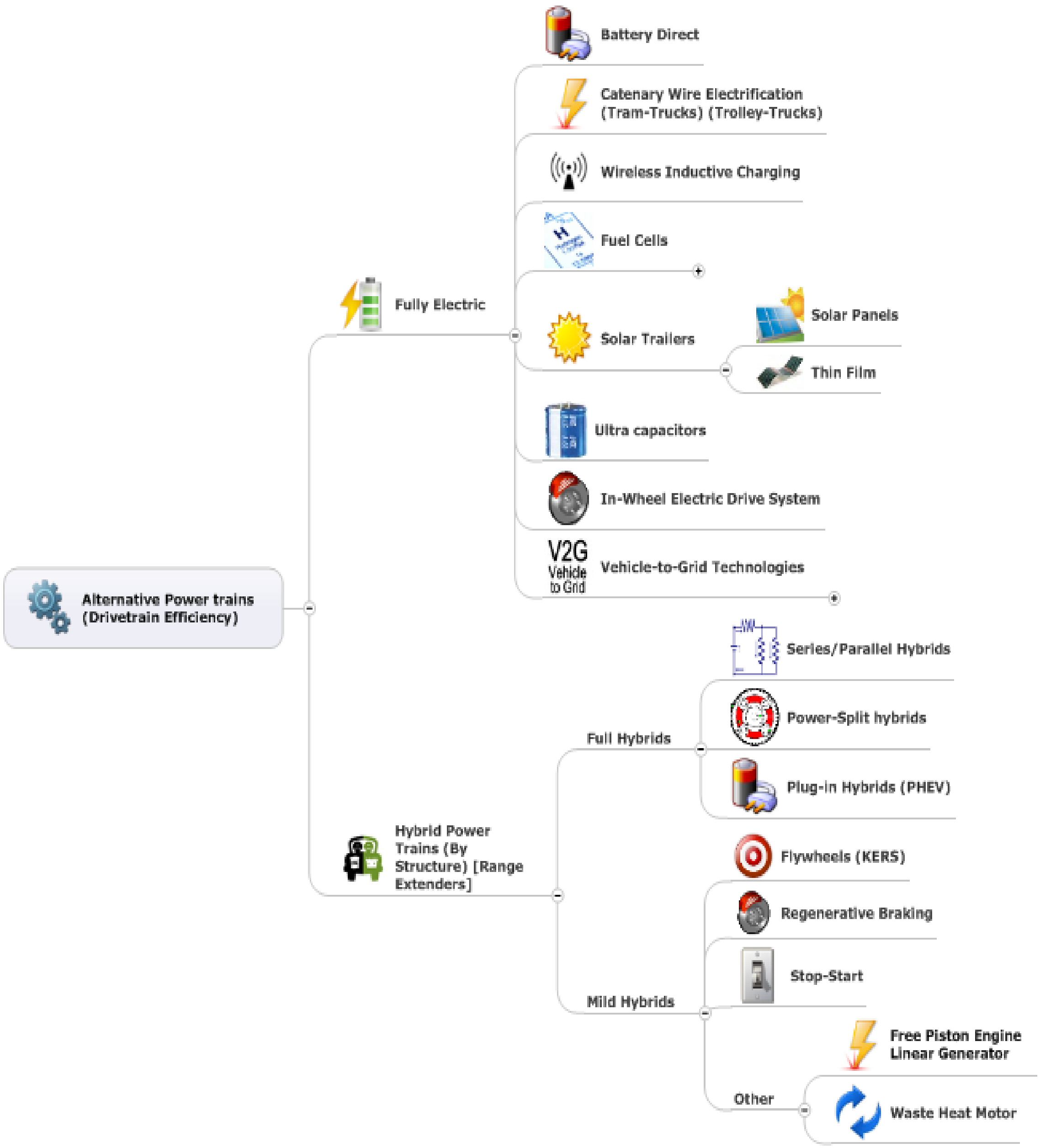


Figure 51. Classification of alternative low carbon powertrains.

Currently, there are no plug-in electric articulated semi-trailers anywhere in the world except for port drayage or trunking operations in distribution centres. E-Trucks are typically constrained to no more than 12 tonnes, have a short range (typically under 100km), lower residual value than diesel vehicles, present performance issues under cold weather (Baker et al., 2009a) and require long recharging times. The lack of range limits their operations to city logistics. However, for drayage/trunking applications, range anxiety is not an issue as recharging infrastructure is available in the DC. Electric trucks for trunking operations have recently been launched in Europe by Terberg and in the US by Balqon Corporation. These HGVs move semi-trailers within a depot, port, airport, yard or intermodal facility. The Terberg YT202-EV (Figure 52) has an 180kW engine (241hp), can tow loads of up to 34 tonnes and has a 260 kWh battery pack (Terberg, 2014). In the US, The Balqon MX30 can travel at speeds of up to 105 km/hr., tow loads of up to 25 tonnes, has a range of up to 201 km fully loaded and can also be used for urban applications (e.g. street lighting maintenance), reducing fuel consumption 74% (Balqon, 2013) .

The main issue with e-trucks is that batteries have a much lower power density than fossil fuels. Figure 53 shows that rechargeable Li-ion batteries, such as the lithium iron phosphate batteries used by Terberg and Balqon vehicles, have a weight energy density of around 90-175 kwh/tonne, while diesel energy density is 12,584 kWh/tonne (the latter is based on the value reported by Carbon Trust (2011). Regarding volume, Li-Ion batteries deliver only 200-350 kWh/m^3, against 11,000 kWh/m^3 from diesel fuel (Carbon Trust, 2011). Obtaining a similar energy intensity to the one provided by diesel powertrains requires heavier and larger energy storage devices which can reduce vehicle payload (National Research Council, 2010) and increase energy consumption. As a result, battery packs of HGVs tend to deliver short ranges. Possible solutions to the range of anxiety problem include powertrain hybridisation, battery swaps and road induction lanes; however, the last two have not been commercialised targeting road haulage vehicles. Induction recharging is a costly option; however, very recently a trial in Milton Keynes (UK) has been conducted where electric buses are recharged via induction coils (Arriva, 2014). Batteries are fully recharged overnight and top-ups are provided several times during the day.

Fuel Cell Powertrains follow the same principle as explained previously for APU FCs. Hydrogen for automotive purposes is usually pressurised and stored at 350 or 700 bar (70Mpa) to occupy less space. This requires stronger, larger and heavier fuel tanks than conventional diesel fuel tanks, increasing costs and reducing potentially vehicle's payload. The only commercial Class 8 HGV using this technology is the TSSI Tyrano TM, a hybrid electric/ PEMFC vehicle running on the Port of Long Island (TSSI, 2013). The vehicle has a range of 322 km, top speed of 105 kph and a peak power of 400 kW. Unfortunately, the system integrator (Vision Industries Corp, Inc.) filed for bankruptcy in 2014.

Figure 52. European e-Truck for port and warehouse movement of freight (2013).

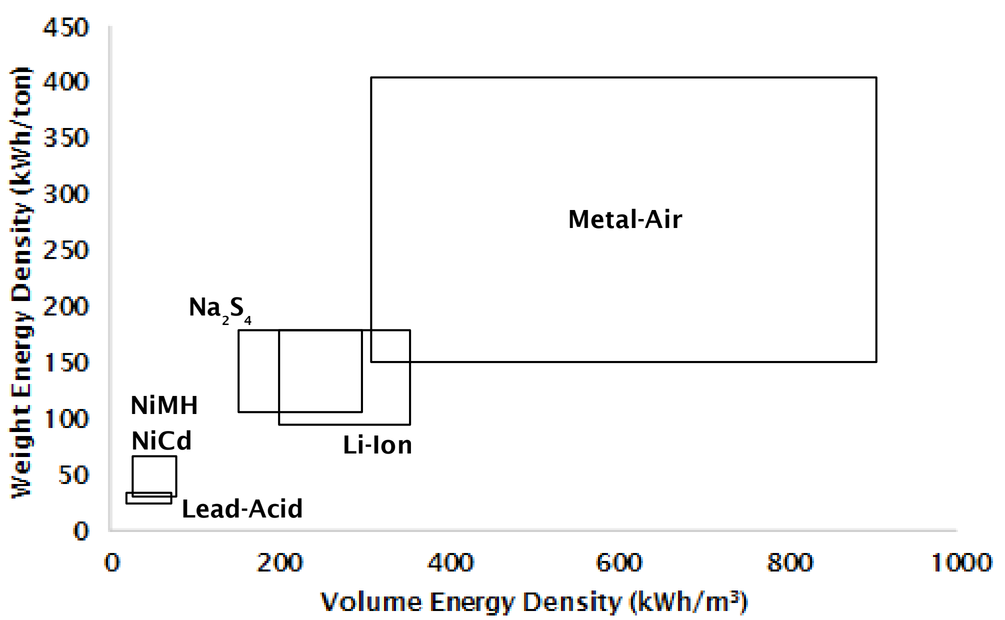
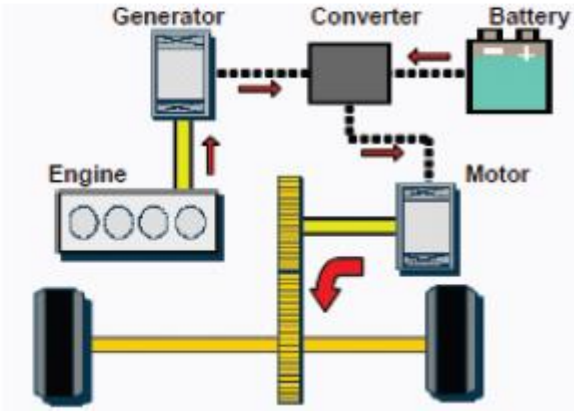


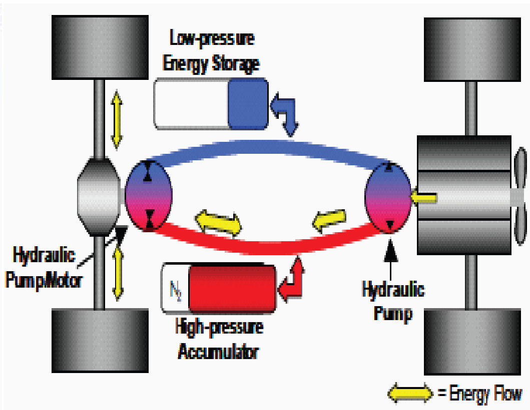
Figure 53. Energy density of batteries. Adapted from: Berecibar and Zhou (2013).

3.5.2.3.2 HYBRID POWERTRAINS

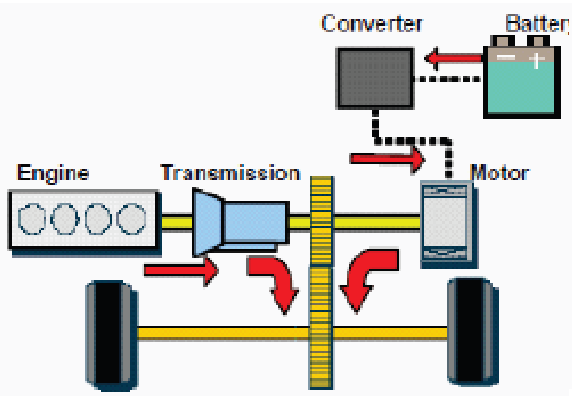
Depending on the degree of hybridisation, HGVs can be classified as full hybrids or mild hybrids (Figure 54). Full hybrids combine an engine with an electric motor. The ICE and electric (or hydraulic) motor can be installed in series, parallel or in power split configuration (Figure 54). Examples of the FCR that hybrid powertrain technologies can deliver are included in Table 18. Mild hybrids such as flywheels combine either an ICE or an electric motor with technologies that provide an auxiliary amount of energy available for limited periods of time (Table 19).



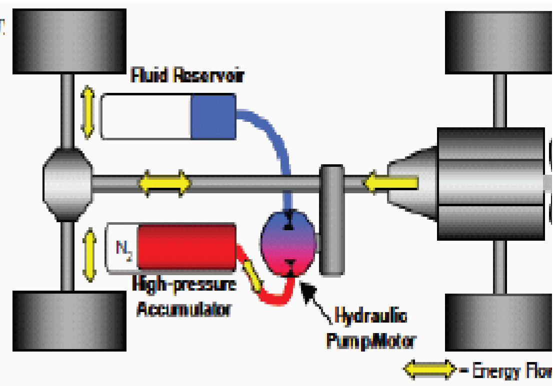
Series electric hybrid vehicle configuration.



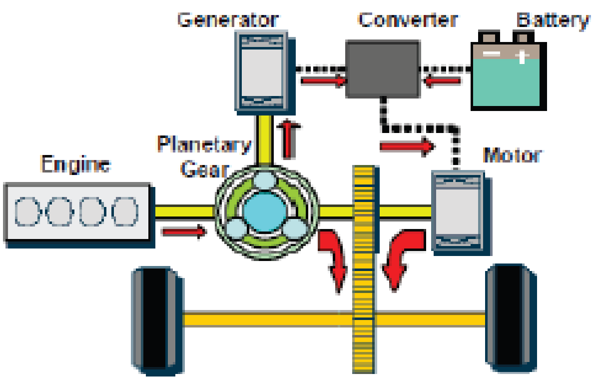
Series hydraulic hybrid vehicle configuration



Parallel electric hybrid vehicle configuration.



Parallel hydraulic hybrid vehicle configuration.



Power Split hybrid electric vehicle.

Figure 54. Configurations of HGVs hybrid powertrains. Source: National Research Council (2010).

Series hybrid electric vehicles combine an electric generator coupled to an ICE that provides power to the motor and recharges the battery. This allows the engine to work efficiently within the optimal zones according to the engine's map (National Research Council, 2010). Series hydraulic systems follow a similar architecture; however, the battery is replaced by a hydraulic accumulator; the electric motor by an hydraulic one; and the ICE by a hydraulic pump (National Research Council, 2010). These are typically used for commercial vehicles, mostly buses (Baker et al., 2009a).

A parallel hybrid's driveline is connected to an electric motor and to an engine simultaneously and both can share the power during acceleration (National Research Council, 2010). Hydraulic hybrids combine an internal combustion engine with a hydraulic motor that is typically used for launch assistance, improving acceleration and reducing fuel consumption. For this reason, these hybrids are adequate for urban deliveries or refuse trucks where the duty cycle counts with frequent stop/start cycles. UPS purchased 41 of these vehicles for delivery in 2012, expecting a 50% increase in fuel economy and 30% decrease in carbon emissions (UPS, 2012) .

In conventional series and parallel hybrids the engine is used to recharge the battery and this cannot be recharged from the grid. Plug-in hybrids, on the other hand, can also recharge the battery from the grid and tend to have larger battery packs and range than the first ones.

Power split hybrids are a combination of series and parallel powertrains. The Engine is coupled to a planetary gear arrangement, allowing the transmission of mechanical or electrical power (National Research Council, 2010). At the beginning of a trip, until the engine reaches its efficiency zone according to its engine map, the electric motor provides the power; reducing fuel consumption and GHG emissions. At cruise speed, the motor and engine can both work in parallel (simultaneously) to provide extra power. During deceleration and braking, the motor generates electricity from the kinetic energy. In other parts of the duty cycle, the ICE can propel the vehicle and recharge the battery at the same time. Hydraulic power split follows a similar configuration.

Hybrids present the greatest benefits in urban duty cycle, rather than in motorway driving (Table 18). In addition to delivery HGVs, these technologies are also found in refuse trucks and urban buses. These have very low speeds and many more stops than delivery trucks which present the ideal conditions to maximise the benefits of hybrid low carbon powertrain technologies. Hybrids have much smaller batteries than EV. Reducing the size of the battery pack further is possible through other technologies such as electrified catenaries, wireless induction systems and mild hybridisation. Known as tram trucks (trolley trucks) catenary powered vehicles are being trialled by Siemens in the US and Germany (Siemens, 2014), where the motors of rigid HGVs are powered by a catenary and the ICE is only used when disconnecting from the catenary to overtake other vehicles.

Table 18. FCR from different alternative powertrains.

Technology Full Hybrids	FCR	Study (or DC)	Comments
Series Electric	20% 7%	Baker et al. (2009a)	Medium Duty Long haul
	20% 10% 7%	Hill et al. (2011)	Urban Regional Long haul
Series Hydraulic	40%-50%	Cooper et al. (2009)	Refuse Trucks
	10% 15% 0%	Hill et al. (2011)	Urban Regional Long haul
Parallel Electric	20%-35%	Cooper et al. (2009)	Refuse Trucks
	25%-35%	Law et al. (2012)	Urban
Parallel Hydraulic	20%-25%	Cooper et al. (2009)	Refuse Trucks
Power Split Electric (Dual Hybrid) with Electrified accessories	8%-12%	Law et al. (2012)	Regional / Long haul

Mild hybridisation technologies (Table 19) include mainly the use of flywheels (kinetic energy recovery systems), regenerative braking and stop/start systems that use an electric motor mounted to the crankshaft to start the engine. This allows the vehicle's engine to switch off when the vehicle stops and are capable of regenerative braking (Baker et al., 2009a). Typically in regenerative braking, the motor is used as a generator and energy is stored in the battery. Flywheels or kinetic energy recovery systems (KERS) store and release energy from/to a vehicle driveline supplementing the engine's output (Atkins et al., 2013). Kinetic energy is captured in a flywheel (a magnetic wheel contained in vacuum) when braking and is released to provide extra power or replace engine output for a few brief seconds. This means that urban duty cycles can benefit more than motorway driving as more braking is required. Mechanical flywheels can release the mechanical energy into the driveline through a continuous variable or advanced clutched transmissions (Torotrak, 2014). In electro-mechanic flywheels, on the other hand, electricity is generated by a traction motor mounted in one of the axles and is used to charge the flywheel. When the energy is required the system works in reverse (GKN Hybrid Power, 2014). Also, the energy can be used to power auxiliary systems such as lights and air conditioning. Despite the fact that there are no trucks using these technologies at the moment, several trials are being conducted around the world, including one in Southampton where electric flywheels are being fitted into buses (Southampton City Council, 2014). Even so, the energy density of flywheels is in the range of 10-20 kWh/m^3 or 10-15 kWh/ton (Berecibar and Zhou, 2013), much lower than most battery technologies that appear in Figure 53 and substantially lower than liquid fuels.

Table 19. FCR from mild hybridisation powertrains.

Technology Mild Hybrids	FCR	Study (or DC)	Comments
Flywheels	15% 7.5% 5%	Hill et al. (2011)	Urban Regional Long haul (Also in Buses)
	17%	Atkins et al. (2013)	
Start-Stop	6% 3% 1%	Hill et al. (2011)	Urban Regional Long haul

3.5.3 FUEL TECHNOLOGIES

Lower carbon fuel technologies refer to sources of energy that can substitute conventional fossil fuels (petrol or diesel) delivering acceptable vehicle performance with lower WTW GHG emissions. These include alternative fossil fuels, biofuels and energy carriers (Figure 55).

3.5.3.1 BIOFUELS

More stringent UK energy legislation, including the elimination of the fuel duty differential in April 2012 and the amendments to the Renewable Transport Fuel Obligations (RTFO) Order 2011, is forcing logistic firms to rethink their fuel strategies. The EU directive 2009/28/EC states that biofuels must deliver GHGs savings of 35% by Jan 2017, 50% between Jan 2017 and Jan 2018 and 60% from Jan 2018[6] (European Commission, 2013a) compared to fossil fuels. As a result, some current biofuels will not be legally classified as biofuels and they will not be entitled to obtain Renewable Transport Fuel Certificates (RTFCs) as presented in

[6] If the fuel is produced in a new chain of installations

Table 20.

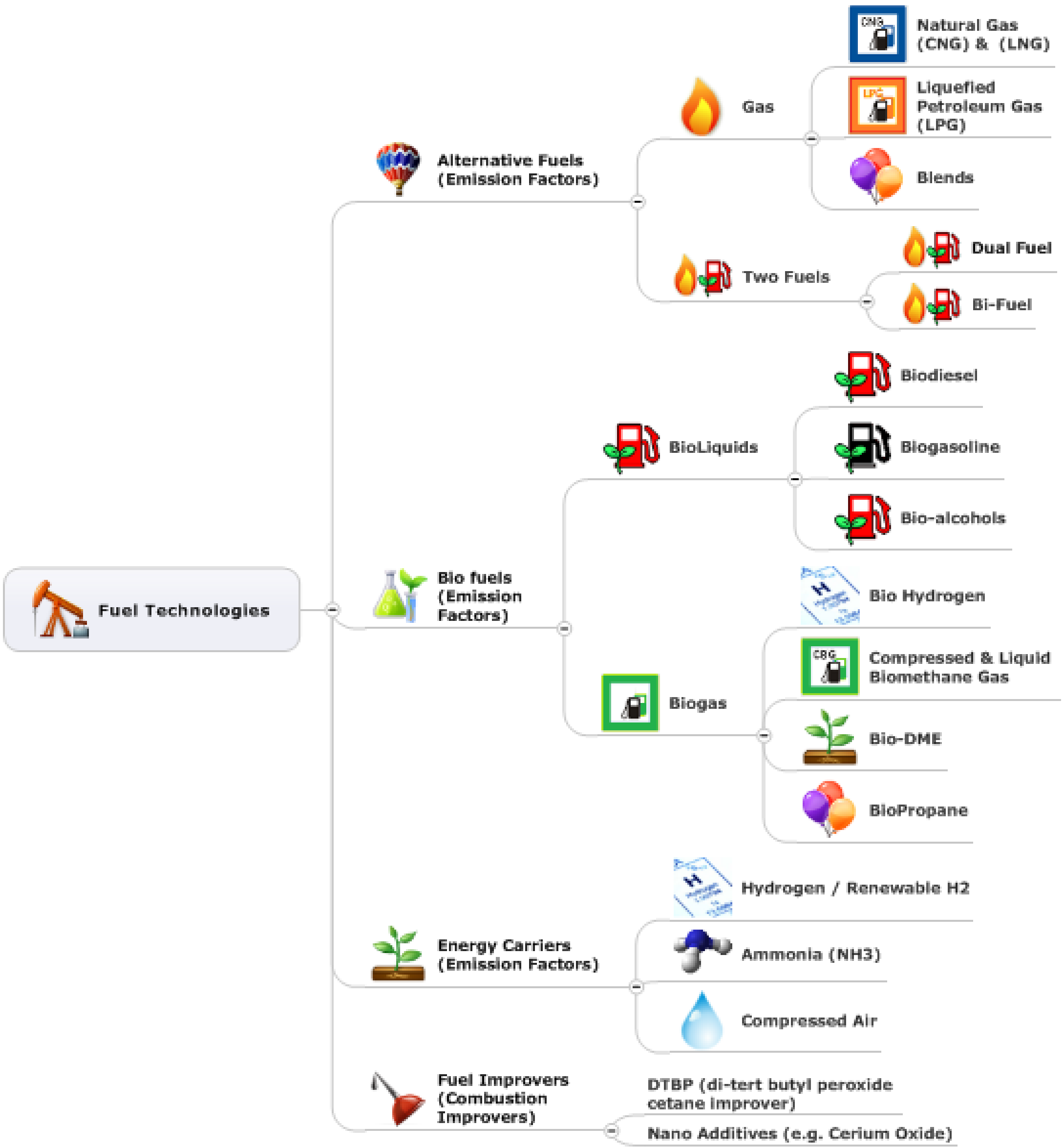


Figure 55. Classification of low carbon fuel technologies.

From the Table, it can be seen that first generation biodiesel will be phased-out from 2018, except for waste pathways (tallow and used cooking oil). Similar regulations have been developed in the US where the EISA 2007 Renewable Fuels Standard (RFS2) mandates an increase of renewable fuel consumption of biofuels by 2022 (National Research Council, 2014).

Table 20. Carbon intensity and GHG savings from different fuel pathways according to the UK renewable transport fuel obligation (RTFO) guidance year 8. Adapted from: DfT (2015a).

Feedstock	Default carbon intensity [g CO_2eq. / MJ fuel]	Default GHG emission saving [%]	Deadline by
Bioethanol, ETBE, TAEE			
Farmed wood	25	70	
Sugar beet	40	52	From 2018
Sugar cane	24	71	
Waste wood	22	74	
Wheat	70	16	Jan/2017
Wheat straw	13	85	
Biodiesel (methyl ester)			
Rapeseed oil	52	38	Jan/2018
Palm oil	68	19	Jan/2017
Soybean	58	31	Jan/2017
Sunflower	41	51	From 2018
Tallow - except category 3	14	83	
Used cooking oil	14	83	
Biodiesel (hydrotreated vegetable oil)			
Palm oil	62	26	Jan/2017
Rapeseed oil	44	47	Jan/2018
Sunflower	32	62	
Biogas (as compressed natural gas)			
Dry manure	15	82	
Municipal organic waste	23	73	
Wet manure	16	81	
Fischer-Tropsch diesel			
Farmed wood	6	93	
Waste wood	4	95	
Pure vegetable oil			
Oilseed rape	36	57	From 2018
Biomethanol, MTBE			
Farmed wood	7	91	
Waste wood	5	94	
DME			
Farmed wood	7	92	
Waste wood	5	95	

In the US, Renewable fuels can reduce WTW CO_2 emissions between 5 and 90% depending on the feedstock, the production process and the distance between source and consumption points (Baker et al., 2009a). In the UK, some pathways can yield GHG savings of up to 95% as shown in Table 20. Howey et al. (2010) suggested that biofuels grown in the EU could meet 46-80% of the transport demand by 2020. In contrast, Schenk et al. (2008) argue that if all arable land would be dedicated to produce biofuels, this would cover less than half of the world's energy demand. This means that improvements on energy yield are necessary which highlights the importance of second generation biofuel technologies as a solution for improving production from crops.

The approach taken in this research is to focus on using fuel technologies that use biofuels obtained from waste streams, as they offer higher GHG emission savings than most crops grown specifically for biofuel production. This is more likely to avoid direct and indirect effects such as indirect land use changes. Nevertheless, the magnitude of indirect land use changes for conventional biofuels is not clear yet (Renewable Fuels Agency, 2008). King (2008) indicated that the use of biofuels may lead to increased CO_2 emissions and food prices (Figure 56). To tackle this challenge, the EU proposed not to subsidize biofuels produced from crops used for food and feed that do not lead to substantial GHG savings (European Commission, 2012c). Waste generated by food supply chains, and more specifically from quick service restaurants (QSRs) present opportunities for energy recovery, either as sustainable fuels for transportation or as fuels for heating and power generation.

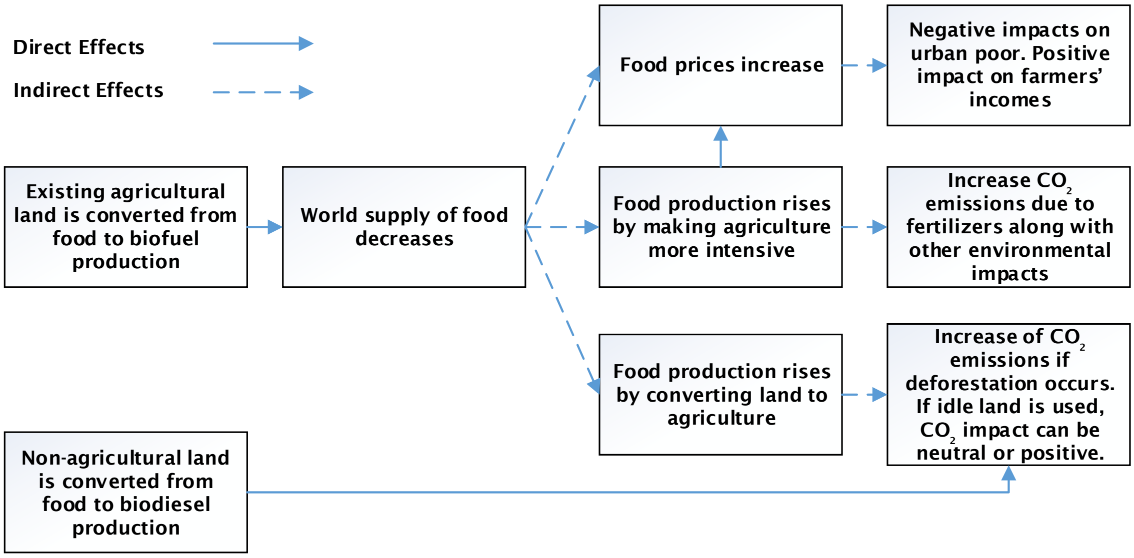


Figure 56. Indirect effects of biofuels. Adapted from King (2008).

3.5.3.1.1 BIOLIQUID FUELS

Bioliquid fuels include biodiesel, bioethanol and other bio alcohols such as bio-methanol and bio-isobutanol. As most UK fleets run on diesel, this section focuses on biodiesel.

BIODIESEL

Biodiesel presents better environmental credentials than diesel because it is "renewable, biodegradable and nontoxic" (Fazal et al., 2011). First generation biodiesel is produced from animal fat and/or vegetable oil through a transesterification process in which fat and methanol produce Fatty Acid Methyl Ester (FAME) and glycerine as a by-product. Biodiesel has very similar properties to conventional diesel and it is compatible with conventional diesel powertrains. It presents better lubrication; however, there are some disadvantages such as enhanced corrosion and material degradation (Fazal et al., 2011). Under low temperatures FAME presents challenges such as waxing. This may lead to the clogging of lines and filters, which imply shorter service intervals (oil and filter changes) and therefore, higher maintenance costs (Fazal et al., 2011). Biodiesel used in diesel engines reduce hydrocarbons, CO_2, PM_x and SO_x emissions while increasing NO_x emissions (Baker et al., 2009a, Fazal et al., 2011). Higher FAME biodiesel blends might require the adaptation of conventional diesel engines as there might be some compatibility issues with existing injection systems (Baker et al., 2009a). As the same engine technology and distribution network can be employed, there are less technical and financial challenges than with other alternative fuels such as biomethane or bioDME (bio dimethyl ether).

All UK HGVs can operate with biodiesel B7 (7% biodiesel content) and some manufacturers guarantee them with B100[7] (up to Euro V vehicles) with small service changes when they are fitted with unit injectors (AEA, 2011); however, since January 2014, all brand new trucks in Europe must meet Euro VI emission standards and according to personal communications with the main vehicle manufacturers (Iveco Paccar, MAN, Mercedes, Scania, Volvo) engine's manufacturers do not guarantee powertrains using more than 7% of FAME biodiesel (first generation) or 30% of hydrotreated vegetable oil (HVO) biodiesel (second generation).

Crops used to produce second generation biodiesel present a higher energy yield per hectare than 1st generation pathways and also some crops can be cultivated in less fertile soils avoiding competition with food. The conversion process is more efficient because the whole plant can be processed instead of using only oils, sugars and starch. Fischer et al. (2010) proclaimed that yields of herbaceous and woody cellulosic 2nd generation energy yields are 40-80% higher than crops of biofuels of first generation. On the other hand, the authors also warn about potential environmental pressures, changes in energy yields due to climate change, increased transportation costs and conflicts for using genetically modified feedstocks.

[7] FAME according to EN14214 quality standard

Second generation biodiesel can be obtained through BTL (Biomass-To-Liquid) or HVO (hydrogenation of vegetable oil) processes. In the BTL process, biomass is converted into liquid via pyrolysis. In the HVO production, vegetable oils and animal fats are hydrogenated and isomerised, yielding hydrocarbons with excellent combustion properties and good storage stability (European Expert Group, 2011) as they are free of aromatics, oxygen and sulphur and have high cetane numbers (Aatola et al., 2008). According to Aatola et al. (2008), HVO avoids the main problems of FAME oil such as deposit formation, storage stability, fast wear of the engine oil and poor performance in cold temperature.

According to Choren (2011), their synthetic HVO fuel can deliver CO_2 savings between 60-90% on WTW basis and PM_x emissions savings of 30-50%. Despite some progress, there are only 5 companies producing second generation biofuels at a commercial scale in Europe and the total production seems rather low (Table 21). Neste Oil claims their HVO product delivers 40-60% GHG savings compared to conventional diesel with similar reductions in hydrocarbons and NO_x emissions (Aatola et al., 2008). However, real field tests with a Mercedes-Benz Euro 3 engine OM 906 LA, revealed PM_x emission savings of just 20% (Krahl et al., 2007). With Euro 6 vehicles, the savings in air quality pollutants may be much lower.

Table 21. Commercial BTL plants in Europe. Adapted from: Bioenergy2020+ (2013).

Country	Company	Feedstock	Liquid Fuel	Output (tonnes/y)
Spain	Amyris	Sugars	Diesel-type Hydrocarbons	N/A
Italy	Beta Renewables	Lignocellulosic biomass	Ethanol	50
Netherlands	BioMCN	Glycerine	Methanol	200,000
Netherlands	Neste Oil	Oils and Fats	Diesel-Type Hydrocarbons	800,000
Norway	Borregaard Industries	Lignocellulosic biomass	Ethanol	15,800
Finland	Neste Oi	Oils and Fats	Diesel-Type Hydrocarbons	190,000

3.5.3.1.2 BIOGASES

BIOMETHANE / NATURAL GAS

Biomethane is typically obtained by upgrading to 95% biogas from Anaerobic Digestion (AD) or landfill gas recovery of organic waste. This can be done by venting or capturing the CO_2 by-product. Biomethane has the same chemical composition as methane. While natural gas (NG) is a fossil fuel, biogas has a biogenic origin. Biomethane vehicles have the advantage that they produce lower PM_x, NO_x and GHG emissions than their diesel counterparts (Baker et al., 2009a). Spark ignition engines running on NG are 100% compatible with biomethane, and they have a similar torque to conventional diesel trucks (compression ignition) with 10-15% lower efficiency (National Research Council, 2014). As a result, the comments made in this section regarding methane (NG) apply as well to biomethane vehicles as both fuels have very similar chemical composition.

The main challenges that NG fleets face are the lack and cost of refuelling infrastructure, more expensive vehicle purchasing costs, a reduced offer of engines, a potential decrease on vehicle payload due to heavier and larger fuel tanks, and a shorter vehicle range. Other uncertainties include the quantification of reserves, public acceptance and safety and sustainability concerns (National Research Council, 2014).

Combustion of NG releases 28% less CO_2 per BTU of heat than diesel (National Research Council, 2014); however, as NG engines have SI technology and this is less efficient that CI (used on diesel HGVs), this results in just 10-15% lower GHG emissions for CNG vehicles compared to diesel ones and 20-25% compared to gasoline (Baker et al., 2009a). The National Research Council (2014) warns against the impact that unburned methane and leakages along the upstream supply chain may have against WTT GHG savings. This is even more relevant for shale gas, as leakages are between 3.6-7.9% of the methane produced by venting or leaking to the atmosphere from the well, pipelines and storage facilities (Howarth et al., 2011). The National Research Council (2014) suggests that when losses are considered, the real GHG emissions savings are just 5%. There are also public concerns regarding the potential pollution of water resources due to the extraction method (hydro fracking) used to extract the gas.

NG can be compressed (200/250 bar) or liquefied (cryogenic storage at -162°C), which influences the range of the vehicles. The energy density of LNG is around 2.4 higher than CNG (Brightman et al., 2011, National Research Council, 2014) and for this reason, for the same volumetric fuel tank, the range of LNG is larger than CNG HGVs. According to the National Research Council (2014), with a 378.5 L fuel tank, a diesel truck has a range of 1,047 km in the USA, while a LNG around 611.5 km and a CNG just 274 km. The range anxiety problem and the lack of refuelling stations are being overcome by UK fleets by using bi-fuel or dual-fuel trucks (Figure 57). The first ones are HGV with one engine capable of running on two different fuels, typically methane or biomethane plus diesel but not both simultaneously (typically SI engines). On the other hand, dual fuel HGVs' engines burn a mixture of diesel and methane at the same time (typically in CI engines). In dual fuel HGVs, methane is injected in the vehicle manifold to improve combustion. Usually, HGV can be retrofitted and some manufacturers such as Mercedes and Volvo guarantee such upgrades. Truck manufacturers that have dual fuel models (diesel and natural gas) include Iveco, Mercedes, Renault and Volvo. Hardstaff Group is a UK company that fits these systems and supplies gas, and they acknowledge that dual-fuel methane vehicles are best suited for long haul operations (Hardstaff Group, 2012). In higher speed driving, the percentage of gas to diesel is higher, leading to greater GHGs savings (Hardstaff Group, 2012). Dual fuel hydrogen-gas HGVs were presented by Iveco in 2011 (Iveco Hydromethane) in Canada and have not reached the European market so far.

The purchasing cost of NG trucks is around 20-25% more expensive than their diesel counterparts (Baker et al., 2009a). In the UK, this translates to £15,000 to £35,000 more depending on vehicle size (Brightman et al., 2011). In the US, the extra cost of the tanks represents between $40k to $50k per vehicle; however, due to the low price of NG (partially due to the exploitation of shale gas) the payback period of such technology is around 2 years (National Research Council, 2014). As a result, the demand for such vehicles is increasing and according to the National Research Council (2014), there are already 11 million NG vehicles worldwide (including cars) and they expect that NG trucks will achieve a 36% market share in the US by 2020. Higher market penetration will depend greatly on operating costs and the differential between diesel and NG. According to OECD/IEA (2011), the differential makes NG more favourable with higher oil prices because of lower gas prices and taxation.

Deploying a private CNG refuelling station can cost between $600k and $1 million in the US depending on the filling speed and the number of vehicles to be supplied, and double for a LNG station (National Research Council, 2014). Brightman et al. (2011) estimated that the average costs in 2010 for a UK CNG, a LNG and a LCNG refuelling station supplying 10,000 kg/day was around £700,000, £350,00 and £800,000, respectively.

Figure 57. Dual fuel Diesel/CNG vehicle. In the centre two fuel CNG tanks are visible.

In the US, there are 632 public and 1200 private CNG refuelling stations and just 40 non private LNG ones (National Research Council, 2014). According to the Gas Vehicle Hub (2015) map, there are just 5 CNG (two working with bio content) and 10 LNG (seven of them working with bio content) publicly available stations operating in the UK (as per July 2015), with five further planned by Gasrec (Gasrec, 2015). In a personal interview conducted in 2014 with ENN management (the second biggest NG supplier in the world), the company communicated its intention to deploy mobile LNG refuelling stations across the UK, Belgium, Netherlands and Germany in 2015. The company is especially interested in locations near the ports where they can unload their cryogenic LNG tankers. These mobile refuelling stations could deploy infrastructure very rapidly if the market conditions were right. CNG Fuels has just obtained planning permission to deploy the first high pressure local transmission system CNG filling station in the UK, an installation that can supply more than 500 CNG HGVs per day (CNG Fuels, 2015).

Scania and IVECO have models that run on natural gas only, as well as Kenworth and Peterbilt in the US. Among the organisations that are involved in evaluations of CNG/LNG, CBG/LBG or dual fuel HGVs in the UK, are Gist/M&S, Howard Tenens, Eddie Stobart, Sainsbury's, Coca-Cola, Wiseman and Warburton's and John Lewis Partnership among others. Independently audited biomethane fleet trials conducted for 12 months by Coca-Cola Enterprises and CENEX with fourteen 26 tonne GVW HGVs reported GHG, PM_x and NO_x emissions savings of 60.7%, 97.1% and 85.6%, respectively (Cenex, 2011). These trials found that noise levels were also reduced. The results indicated that the total cost of ownership (TCO) of operating biomethane trucks was 15.3% more expensive than diesel ones[8]. Vehicle costs were higher (+53.3%); however, they expected the price differential to narrow down with the introduction of Euro VI diesel trucks in 2014 and higher CNG vehicles sales. Maintenance costs were also higher (+6.8%) with a lower reliability (an availability of 99.2% versus 100% of the diesel vehicle). On the other hand, fuel costs were much lower (-12.8%)[9], and this was including the installation costs of a liquid biomethane gas (LBG) refuelling station. In addition to lower GHG emissions, another advantage of the fuel technology was that operators can also benefit from dual RTFCs.

Howard Tenens decided to use dual fuel vehicles (diesel and natural gas) to meet its commitment with sustainability (Cope, 2011). With a range of 630 miles, HGVs were expected to deliver CO_2 savings of 15%. The company considered this technology as a stepping stone until biomethane becomes widely available. Due to the lack of natural gas infrastructure, the company deployed 3 refuelling stations at different sites in England, with more on plan, at a cost of £3 million. As the company realised that this was a niche technology, they decided initially to open their refuelling stations to other logistics providers in order to create a critical demand that could benefit the company in the long term. The creation of a critical mass market from CNG/LNG vehicles could also increase the chances of CBG (compress biomethane) and LBG (liquid biomethane) succeeding. Personal communication with the company in June 2015 indicated that two of these three facilities have now been closed.

Another company that has used biomethane is Sainsbury's. Within the "Running on Rubbish" initiative, Sainsbury's HGVs 500 km round-trip from their DC in Bristol to the company's environmentally friendly store in Dartmouth, saved 38 tonnes of CO_2 per vehicle per annum (Sainsbury's, 2008).

NG and biomethane feedstock can be used to produce other fuels and energy carriers such as DME, methanol, ethanol, GTL, ammonia and hydrogen. However, the conversion processes are energy intensive and they yield a lower net energy balance than using NG or biomethane directly. When NG or biomethane

[8] Assuming DERV price of £1.14 / litre (exc. VAT).
[9] Assuming a 10 tonne capacity station and 168 tonnes of biomethane consumed per annum.

are converted into electricity instead, a benefit can be observed as the efficiency of electric motors is higher than ICE.

DME AND BIO-DME

Dimethyl Ether (DME) is a fuel typically obtained from NG processing via methanol as intermediate product (National Research Council, 2014). However, this pathway does not produce any GHG savings except from the avoidance of NG leakages (DME has a lower GWP than NG, it does not boil-off). DME liquefies at 6 bars (or below -25°C), which means that it is easy to store and transport. It has similar properties to liquid petroleum gas (LPG) and a higher energy density than CNG. Greszler (2013) reported several advantages of DME when compared to NG such as lower costs of fuel tanks and refuelling stations (similar infrastructure as LPG ones).

When DME is produced from biogenic feedstock it presents GHG emissions savings over 90% (Table 20, page 76). BioDME is a second generation biogas obtained from biomass through gasification. BioDME vehicles use diesel adapted engines (the main adaptation required relates to specially designed fuel injectors) and it provides similar power, lower noise levels (BioDME, 2012) and virtually no soot, making the use of particulate filters unnecessary (National Research Council, 2014). BioDME has almost half of the energy content of diesel, and to obtain a similar range, vehicles need larger fuel tanks. This could reduce vehicle payload. Despite promising results and expectations, at the moment, this technology is not commercially available. In 2011, Volvo started a field test of 10 BioDME HGVs in Sweden (BioDME, 2012).

HYDROGEN AND BIOHYDROGEN

Hydrogen is the most abundant element in the universe; however, on Earth it is found mainly as part of organic compounds and water molecules. Hydrogen production is a highly energy intensive process and its WTW emissions depend on the feedstock used and the carbon intensity of the production process. Usually Hydrogen is obtained by the steam reforming of methane; this pathway represents 95% of all hydrogen produced in the USA (National Research Council, 2014). The electrolysis of water is also a feasible pathway and when the energy needed comes from renewable sources the carbon intensity of this pathway are almost negligible.

As less energy is released by hydrogen than the energy required for producing it, hydrogen is considered as an energy carrier and not as a fuel in the strict meaning of the word. Hydrogen can also be obtained from biomass using a wide range of technologies such as gasification, pyrolysis, supercritical extraction, liquefaction, hydrolysis, reformation and biological production (Holladay et al., 2009). Potential biogenic feedstocks available in the food industry include starch, food industrial waste, cellulose (wood and paper) and waste sludge in water treatment plants (Holladay et al., 2009).

Hydrogen can run in hydrogen internal combustion engines, also mixed with other fuels in bi-fuel and dual fuel HGV engines (e.g. hydrogen-methane) or it can be used in fuel cells to power electric motors. There are still a few technical challenges to overcome before seeing an increase in the market share of hydrogen vehicles. The main one is that it is quite complicated to store and transport it. Leakages are likely to happen with the added risk that when burning hydrogen it does not smell and produces a flame difficult to see. Secondly, there is a very poor refuelling infrastructure. There is a chicken-and-egg circle; there is no hydrogen demand because there is no infrastructure and there is no infrastructure because there is not enough demand (Farrell et al., 2003). This increases the costs of hydrogen and its refuelling infrastructure (Lebutsch and Weeda, 2011).

The Highways Roadmap (2008) estimated that hydrogen could reduce oil consumption in road transport by 40% by 2050. According to King (2007), hydrogen is key to achieving a 80% GHG emissions reduction in transport by 2050. The literature shows that most people do not perceive hydrogen as a safety concern (Haraldsson et al., 2006, Hickson et al., 2007, O'Garra, 2005, Schmoyer et al., 2006, Thesen and Langhelle, 2008, Velazquez Abad, 2010). However, a study in the Netherlands found that having hydrogen refuelling stations at less than 300 m was not accepted by the majority of the respondents (Achterberg et al., 2010). Another UK study found just the opposite, with a positive YIMBY (Yes In My Back Yard) response (Thesen and Langhelle, 2008). However, studies are full of non-response bias as large percentages of respondents did not have enough knowledge about the technology. According to H2stations.org (2015), there are just 14 hydrogen refuelling stations in the UK, mainly as part of small vehicles and bus demonstration trials. Some of these are located at University campuses and are not accessible to commercial fleets. In the US, there are just 10 refuelling stations mostly in California (National Research Council, 2014).

Grundon Waste Management (2010) conducted three trials with a device that injected a small amount of hydrogen into the engine's air induction tract of refuse trucks. The trial was supposed to deliver FCR around 3-5%; however, the supplier ceased operations due to several technical challenges that they were unable to solve. In the UK, another company (H_2gogo) that aimed at reducing GHG emissions by injecting small amounts of hydrogen in the combustion chamber abandoned its attempts by 2011. The only class 8 vehicle found running with fuel cells and hydrogen was the Tyrano TM (TSSI, 2013) whose manufacturer also filed for bankruptcy. This shows that the commercialisation of HGVs using hydrogen is still far away as many technical challenges still need to be resolved.

LPG (AUTOGAS) AND BIOPROPANE

Propane is a liquefied petroleum gas obtained as a by-product of NG processing and petroleum refining. In the US, Commercial autogas (also known as LPG) is made of 90% propane and 10% other gases such as butane, ethane and propylene. In European markets, the mix of propane/butane varies from 100% propane / 0% butane in the UK, to 20% / 80% in Greece (Matvoz, 2015a). Propane is the third most popular vehicle fuel in the world (US DoE, 2015a). In the US, there are 3,126 fuelling stations (US DoE, 2015b) and around 26,941 in Europe from which 1,644 are in the UK (Matvoz, 2015b).

Based on values from DECC (2014c), the energy content of LPG is 46.97 GJ/tonne (over 6% higher than conventional diesel in weight); however, due to its lower density, LPG has an energy content of 23.48 GJ/m^3 which is 34.65% lower than mineral diesel (assuming 42.94 GJ/tonne and 936.82 kg/m^3 for diesel). Assuming the average prices for LPG reported by Matvoz (2015b), the cost of LPG is around 34.71€/GJ, while diesel is around 41.96€/GJ. Being 17.27% cheaper and enjoying a well-developed refuelling infrastructure, LPG seems to be a very interesting proposition for some logistics companies. From an operational point of view, to carry the same energy, LPG HGVs must have a much larger fuel tank than diesel vehicles, which could have an impact on a vehicle's payload or alternatively for similar tank sizes / weight, they have a shorter range. LPG tanks contain the gas at a pressure of 1 MPa (~10 bar); roughly twice the pressure of an inflated truck tyre and due to their clean burning characteristics, engines have a longer service life (US DoE, 2015a). Compared to NG, LPG fuel tanks are cheaper and they can be built with a single wall. The LPG engine technology is similar to petrol (spark ignition); however, high octane enriched LPG has also been used in diesel homogeneous charge compression ignition (HCCI) engines using diethyl ether as an ignition enhancer (Miller Jothi et al., 2007). From an environmental point of view, taking DECC (2014c) emission factors as a guideline, LPG produces 12.95% lower GHG emissions than diesel (average bioblend). Several studies also report considerably lower NO_x, and PM_x emissions than diesel (Ning et al., 2012, Miller Jothi et al., 2007) and lower CO and NO_x than petrol engines (Bayraktar and Durgun, 2005).

Propane can also be produced from biogenic feedstock. DECC (2014d) identified the pathway to produce bio-propane as a co-product in second generation biodiesel production (HVO) and it quantified the total potential availability in 2.7 TWh worldwide. DECC (2014d) considers that if bio-propane was included in the Renewable Heating Incentive (RHI) it would indirectly steer the deployment of HVO production facilities in the UK. However, as the availability of feedstock of good quality is limited, the potential of HVO plants producing significant amounts of bio-propane is doubtful. Currently, there is just one commercial production plant worldwide and it produces small volumes of bio-propane. The company (KiOR) is based in the US and uses biomass catalytic cracking pyrolysis to produce this biofuel (DECC, 2014d).

3.5.3.2 WASTE-TO-FUEL OPPORTUNITIES

Rising food prices coupled to volatile energy prices and concerns related to environmental sustainability and energy security have led to an increased interest in exploring how to maximise the use of existing resources. Converting waste into fuel is one of the identified opportunities arising from food supply chains. This section uses a detailed investigation of a British fast food supply chain (FFSC) to understand the nature of the co-products and by-products produced, how these are currently treated, and the scope for their secondary utilisation in the context of logistics fleets. Energy produced from waste streams tend to present very low carbon intensities and great potential for the decarbonisation of fuels. Reducing fuel consumption is of critical importance in most countries from an environmental, economic and geopolitical perspective. In the UK, diesel (DERV) fuel costs rose by almost 83% (DECC, 2014b) and food prices by 40% (FAO, 2013) from 2002-2004 to 2014 (Figure 58). Rising costs increase the competitive pressures that food supply chains and distribution channels must face and justifies the interest on assessing any waste-to-fuel opportunity.

3.5.3.2.1 THE BRITISH FAST FOOD SUPPLY CHAIN

In 2009, the UK food chain produced 15 million tonnes of drink and food waste, almost half coming from households, 3.2 million from manufacturing and 0.6 million linked to the UK hotel and catering sectors (Defra, 2011a). According to Hollins (2013), UK hospitality and food service outlets only recycle, send to anaerobic digestion (AD) or compost 46% of the 2.87 million tonnes of waste generated each year. Designing products for a circular economy could allow UK supply chains to become virtually waste free whilst generating an income stream of $1.5 billion (equivalent to approx. £0.9 bn. as of 31/12/2013) per year or around $172 (£104 as of 31/12/2013) profit per tonne of food waste (Ellen MacArthur Foundation, 2013). To put this into perspective, Tesco alone generated 28,500 tonnes of food waste in the first two quarters of 2013, mainly from bakery products and fruit and vegetables (Houses of Parliament, 2013).

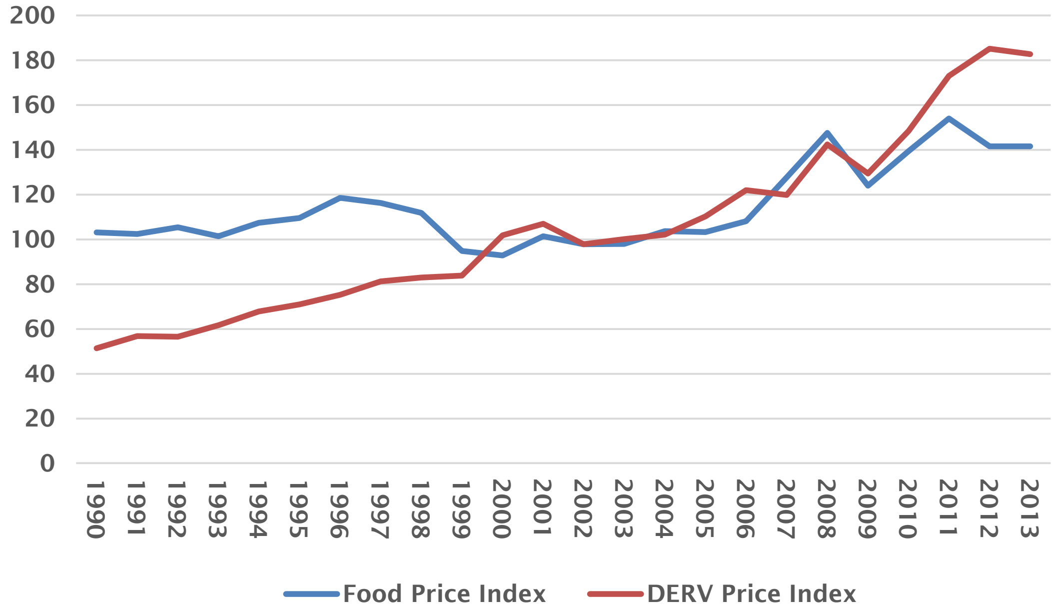


Figure 58. Food and diesel prices (Baseline 2002-2004). Adapted from FAO (2013) and DECC (2014b).

Quick service restaurants (QSRs) account for 12.1% of hospitality sector outlets in the United Kingdom (UK) (WRAP, 2011) and generate annual revenues in the region of £5.5bn (IBISWorld, 2013). They are responsible for generating 246,000 tonnes of waste annually with less than 57% of this being recycled, reused or composted (WRAP, 2011). In contrast, Hollins (2013) estimated the total food waste of UK QSRs in 76,000 tonnes (including fast food, take-aways, fish and chip shops and sandwich bars), representing £277 million per year (at £3,500/tonne) from which just 17,000 tonnes were unavoidable. Due to this inconsistency, an audit of waste was conducted as reported in Section 5.3 (Page 2085.3). This was very considered very relevant because with retail diesel costs having increased by almost 40% from 2004 to 2014 (DECC, 2015b), there is growing interest in whether waste arisings can be used as a supplementary fuel, given that biofuels from waste deliver substantial GHG emissions savings, avoid negative indirect land use changes and avoid competition with food production and prices, and therefore this can contribute to guarantee energy security for the industrial sponsor.

3.5.3.2.2 WASTE STREAMS

QSRs typically operate separate waste collections for paper and card, plastics, used cooking oil (UCO) and grease trap waste (GTW), kitchen food waste, glass and wood among other fractions. Waste arisings at QSRs also result from damage to products during handling, storage and transportation as well as from products discarded by consumers. A survey conducted by WRAP (2011) reported that mixed waste from UK QSRs generally consisted of kitchen food waste (51%), paper (15.1%), card (8.6%), dense plastics (4.8%), plastic film (6%) and glass (3%). It was estimated that UK QSRs produced around 16,300 tonnes of paper and 9,200 tonnes of card as mixed waste in 2009 (WRAP, 2011). Thermoplastics are widely used in the FFSC as packaging, and UK QSRs produced around 5,200 tonnes of dense plastic and 6,300 tonnes of plastic film in 2009 (WRAP, 2011).

In Europe, an estimated 14.6% of meat and 19% of fish are wasted between distribution and point of consumption (Table 22); Defra's estimation for the UK is considerably lower at 13% for edible meat and fish wasted (Defra, 2013a). The UK produces around 14 billion litres of milk annually (C-Tech Innovation Ltd, 2004) and over 1 billion litres (7%) are estimated to be wasted along with 26.5% of cereals, 23% of potatoes and 27% of fruit and vegetables between distribution and consumption (Gustavsson et al., 2011).

Table 22. Estimated percentages of food losses and wastes in Europe. Adapted from: Gustavsson et al. (2011).

Food Type	Agricultural Production	Post harvest handling and storage	Processing and packaging	Distribution: Supermarket Retail	Consumption	Total Losses & Waste
Cereals	2	4	5	2	25	34-38
Roots & Tubers	20	9	15	7	17	52.2
Oilseeds & Pulses	10	1	5	1	4	19.6
Fruit & Vegetables	20	5	2	10	19	45.7
Meat	3.1	0.7	5	4	11	21.9
Fish & Seafood	9.4	0.5	6	9	11	31.4
Milk	3.5	0.5	1.2	0.5	7	12.2

In Europe, the main oil crops are sunflower and rape seed (C-Tech Innovation Ltd, 2004) which are the main ingredients in the vegetable cooking oils used by most QSRs. British QSRs generate huge amounts of UCO. Examples of this include Kentucky Fried Chicken (KFC) collection of 7.75 m litres annually (KFC, 2012) and McDonald's 3.6 m litres (McDonald's, 2012). More efficient cooking technologies such as air fryers and healthier meal options may reduce the availability of UCO in the future, with Burger King and McCain having already introduced fries with 40% less fat in 2013 (Burger King, 2013). This excludes grease tap waste from wastewater interceptors and tallow separately collected from cooked burgers.

3.5.3.2.3 WASTE-TO-FUEL OPPORTUNITIES FOR BRITISH QSRS

A summary of the GHG savings that could be realised from using different biofuels made from QSR waste feedstocks is shown in Table 23. This is by no means a comprehensive list of waste-to-fuel pathways and it uses average values that do not necessarily represent the emission factors for specific pathways and supply chains.

Table 23 GHG balances for different fuel and biofuel pathways. Adapted from: Edwards et al. (2014).

Pathway Code	Feedstock	Fuel	Total WTT GHG (g CO_2eq. /MJ final fuel)	Total TTW GHG (g CO_2eq. /MJ final fuel)	Total WTW GHG (incl. combustion) (g CO_2eq. /MJ final fuel)	GHG Savings (%) vs. Baseline
COD1	Mineral Oil	Diesel	13.8	74.8	88.6	Baseline Diesel
COG1	Mineral Oil	Gasoline	12.2	74.9	87.1	Baseline Gasoline
GMCG1	Mineral Gas	CNG (EU-Mix)	11.8	57.5	69.3	Baseline Gas
OWCG1	Municipal Waste	Compressed Biogas	11.3	3.5	14.8	83% vs. COD1 79% vs. GMCG1
WWET1	Waste Wood	Ethanol (Gasoline)	19.3	0.2	19.5	77.6% vs. COG1
WOFA3a	Waste Cooking Oil (UCO)	FAME Diesel	13.6	0.2	13.8	84% vs. COD1
WOHY1a	Waste Cooking Oil (UCO)	HVO Diesel	13.0	-4.9	8.1	91% vs. COD1
TOFA3a	Tallow	FAME Diesel	26.2	0.1	26.30	70 % vs. COD1
TOHY1a	Tallow	HVO Diesel	29.7	-5.2	24.50	72% vs. COD1
WWSD2	Waste Wood via black liquor, diesel pool	Synthetic diesel	2.5	0	2.5	97% vs. COD1
WWDE2	Waste Wood via black liquor, road	Bio DME (Dimethyl ether)	2.1	0	2.1	98% vs. COD1
WWME2	Waste Wood via black liquor, road	Bio MeOH (Methanol)	2.2	0	2.2	97% vs. COD1

Biogas can be produced from organic waste feedstocks such as fish, meat, fruit, vegetables, dairy products, wasted oil, fat, paper and cardboard. In August

2011, there were 66 AD plants in the UK treating around 1 million wet tonnes of food and agricultural waste (Houses of Parliament, 2011); this increased to 78 by June 2012 (NNFCC, 2012).

Biomethane as a fuel for transportation competes against combined heat and power plants (CHP). When the fuel is generated through AD, the residue of the process (digestate) can also be used as a biological fertilizer reducing the need for synthetic fertilizers (Heaven et al., 2011, Banks et al., 2011). If the digestate complies with the requirements of the Publicly Available Specification BSI (PAS) 110, it is no longer considered as a waste and does not attract disposal costs.

The paper and wood industries share raw materials and present similar waste-to-fuel opportunities. Wood waste is mainly generated through wear-and-tear on wooden pallets. This waste can be converted into liquid biofuel or biogas through biomass-to-liquid (BTL) or biomass-to-gas (BTG) processes; such as the Fischer-Troops biodiesel (FT Diesel) and bioDME respectively. Both pathways are very promising with GHG savings of 98% for the wasted wood (black liquor) to BioDME pathway (BioDME, 2012, Edwards et al., 2014) and 97% for wood waste to synthetic diesel via the Fischer-Troopsch method (Edwards et al., 2014). The paper industry generates pulpwood waste, black liquor and coke from the paper Kraft process and there is also potential for producing methane from these wastes (Lin et al., 2011, Magnusson and Alvfors, 2012, Rintala and Puhakka, 1994), an example followed by Saica Natur, a large paper manufacturing company that installed a CHP plant to use the biogas obtained from their recycling processes (Saica Natur, 2012). Besides AD, energy efficient recovery pathways for paper, cardboard and wood waste (pallets) include combustion and incineration with heat recovery and at a smaller scale, gasification and pyrolysis of lignocellulosic waste. Gasification is more appropriate in applications where there is a use for heat while pyrolysis is typically used to transform biomass into liquid fuels (Panwar et al., 2012). The char produced during pyrolysis can also be gasified to produce syngas which is energy-rich in hydrogen, methane, monoxide of carbon and other compounds. This process converts the mix of gases (monoxide of carbon and hydrogen) into liquid hydrocarbons (Damartzis and Zabaniotou, 2011). Currently, the only Biomass-to-Liquid (BTL) initiative in the UK is a pilot plant producing biobutanol (Bioenergy2020+, 2013), a fuel that can be blended with petrol. As the majority of the HGV fleets in the UK run on diesel, there is very little scope for these pathways making any impact on in the short term.

UCO from the food industry is widely recycled in the UK and constitutes one third of all Fatty Acid Methyl-Ester (FAME) biodiesel feedstock (DfT, 2013b). In the

UK, there are 30 registered medium and large UCO collectors and biodiesel producers (organisations with more than 50 employees) with the capacity to process 250 million litres of UCO per year (Environmental Audit Committee, 2012). First generation biodiesel converts UCO into FAME biodiesel through transesterification; however, second generation biodiesels production processes convert UCO into hydrogenated vegetable oils (HVO) biodiesel, obtaining bio-propane as a co-product (DECC, 2014a). Sunde et al. (2011) found that HVO made from UCO outperforms FAME biodiesel and BTL biodiesel from woody material, with respect to environmental life cycle impact and costs. As shown in Table 23 (page 90), FAME biodiesel from UCO can deliver 84% GHG savings (WOFA3 pathway) compared to 91% for HVO biodiesel (Edwards et al., 2014). Unfortunately, there are currently no second generation biodiesel production plants operating commercially in the UK.

Most plastics and films come from fossil oils and can be recycled a number of times into new plastics avoiding the production of new virgin plastic. They can also be converted into hydrocarbon fuels (Kaminsky et al., 2004, Michaud et al., 2010). Each tonne of mixed plastic can yield between 700 litres (SITA UK, 2011) and 1,201 litres of consumer ready diesel (4R Sustainability Inc., 2011) depending on whether other oil distillates are also obtained in the process. In the UK, SITA plans to open 10 processing plants with the capacity to recover energy from 60,000 tonnes of mixed plastic waste per year, producing a diesel with a higher cetane number and at a lower cost than the conventional one (SITA UK, 2011). The GHG emission factor for recycled plastic is 0.6 kg CO_2eq./kg versus 2.5-4.5 kg CO_2eq./kg for new plastic (Hill et al., 2013). For this reason, it does not seem efficient to produce synthetic fuel from plastics that have not reached their end of life. This would reduce the availability of recycled plastic, forcing companies to buy virgin (raw) material. Another alternative to reduce emissions from plastic consumption, is increasing the proportion of bioplastics in packaging; however, this is not always technically feasible. Bioplastics can protect firms against rising prices of mineral oil derived plastics as some of them can also be digested to produce biogas, a preferred option over composting in respect to energy demand and depletion of natural resources (Michaud et al., 2010).

To illustrate the complexity that entails the evaluation of each waste-to-fuel opportunity, it suffices to look at the potential uses of spent coffee grounds (Figure 59); the residues left after brewing coffee, one of the many organic wastes from QSRs and coffee shops. The UK coffee consumption per capita of 3.04 kg (International Coffee Organization, 2012) is relatively small compared with other European markets such as the Nordic countries, where consumption is around 9 kg per person (Petracco, 2005). According to the World Coffee Portal (2014) 2 billion cups of coffee were sold in the UK in 2014 through 18,832 outlets, including branded shops, non-specialists such as QSRs and independent sellers. According to World Coffee Portal (2014), the leader was Costa with 149 million cups, followed by McDonald's with 126 million cups sold annually. Assuming that each cup contains at least 5 g of coffee this means that each chain generates around 745 and 630 tons of SCG respectively each year.

On average, spent Robusta coffee grounds contain 10% of lipids and Arabica coffees around 15-16% on a dry weight basis (Petracco, 2005). This means that from each kg of mixed SCG (assuming 12.5% lipids), 125 g of oil can be obtained. This percentage could be even higher, as experiments conducted by Al-Hamamre et al. (2012) showed oil yields of 15.3% in weight after 30 minutes of Soxhlet extraction with hexane. The quantities considered translate to roughly 93,125 kg and 78,750 kg of biodiesel per year for Costa and McDonald's respectively; using as a baseline the cups of coffee sold by each brand as reported by World Coffee Portal (2014). Kondamudi et al. (2008) reported conversion yields of 100% from coffee oil to biodiesel through transesterification. Although uncommon in the industry, this pathway is widely reported in the literature (Kondamudi et al., 2008, Burton et al., 2010, S.Caetano et al., 2012, Al-Hamamre et al., 2012, Vardon et al., 2013). Once the lipids are washed out from the grounds, the remains can also be anaerobically digested producing biomethane (Lane, 1983, Dinsdale et al., 1996, Neves et al., 2006). Alternatively, a syngas can also be obtained through pyrolysis (Xu et al., 2006). Besides transportation applications, SCG can also be used as a source of renewable energy in CHP by burning it in furnaces, or even as feedstock for ethanol production (Kondamudi et al., 2008). Other non-energy uses include garden fertilizer (Kondamudi et al., 2008), activated carbon (Sanchez, 2011), as an ingredient for clay bricks (Eliche-Quesada et al., 2011) and as a component in the production of succinic acid for plastic and detergent manufacture (ACS, 2012). In a similar fashion, Jensen et al. (2013) describe the value offerings that can be obtained from bread buns waste.

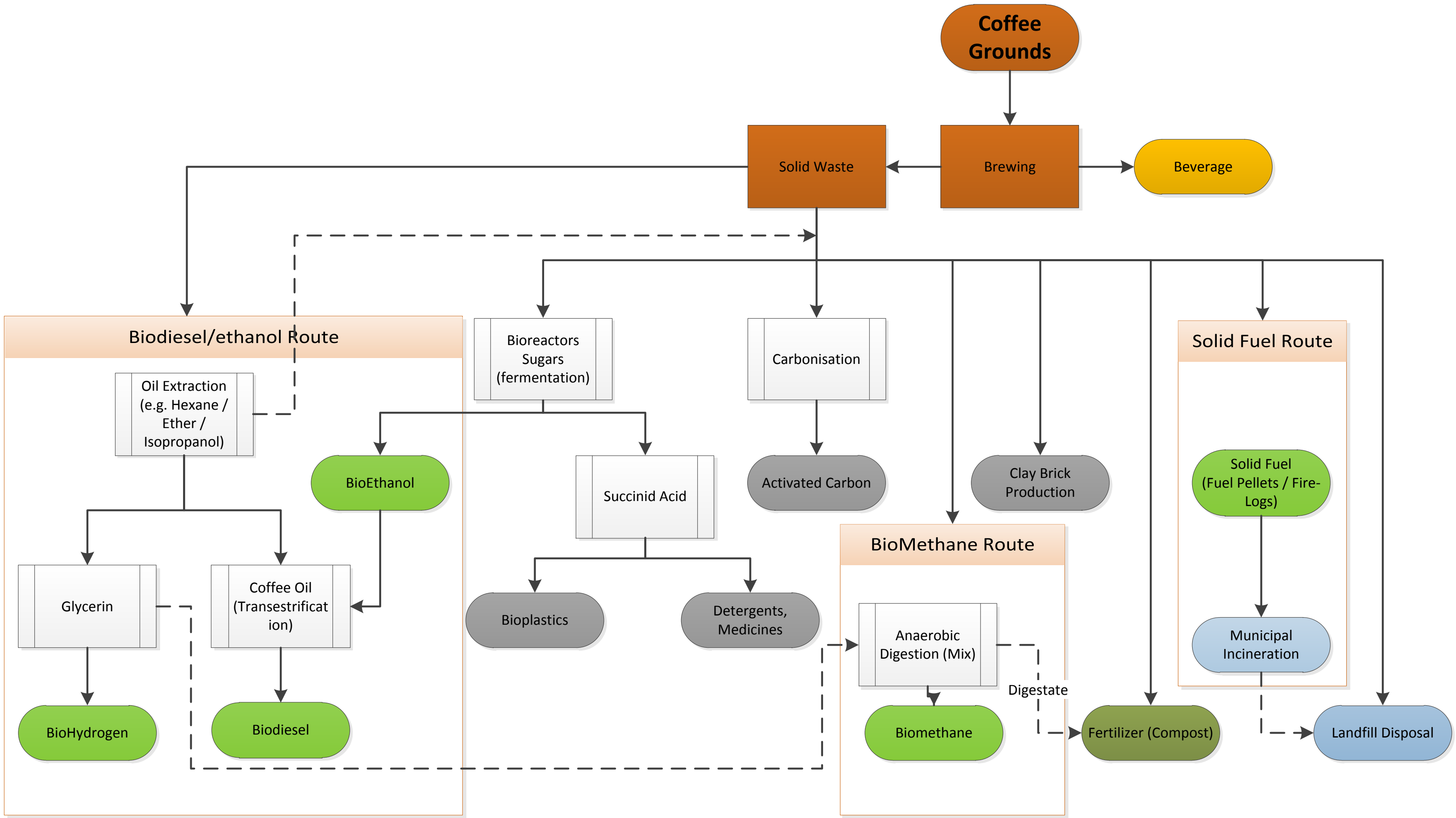


Figure 59. Capturing value from spent coffee grounds with an emphasis on fuel production.

3.5.4 TRANSPORT REFRIGERATION TECHNOLOGIES

Low carbon road transportation refrigeration technologies refer to technologies that can reduce energy consumption from conventional mechanical trailer refrigeration units (TRUs); using refrigerant gases with lower global warming potential (GWP); and other alternative refrigeration technologies. The findings of the literature and evidence have been categorised in three main groups (Figure 60). In the first group, there are the conventional mechanical refrigeration systems where the refrigerant gas is contained in a closed circuit. In the second group, there are the cryogenic refrigeration systems where a liquefied refrigerant gas is kept at cryogenic temperature or a substance acting as such is vented to the atmosphere. The third group includes other technologies that do not fit in the other 2 groups. Key subcategories here relate to refrigerant gases with low GWP, insulation technologies and refrigeration technologies in research and development that may lead or not to real world applications in the coming years.

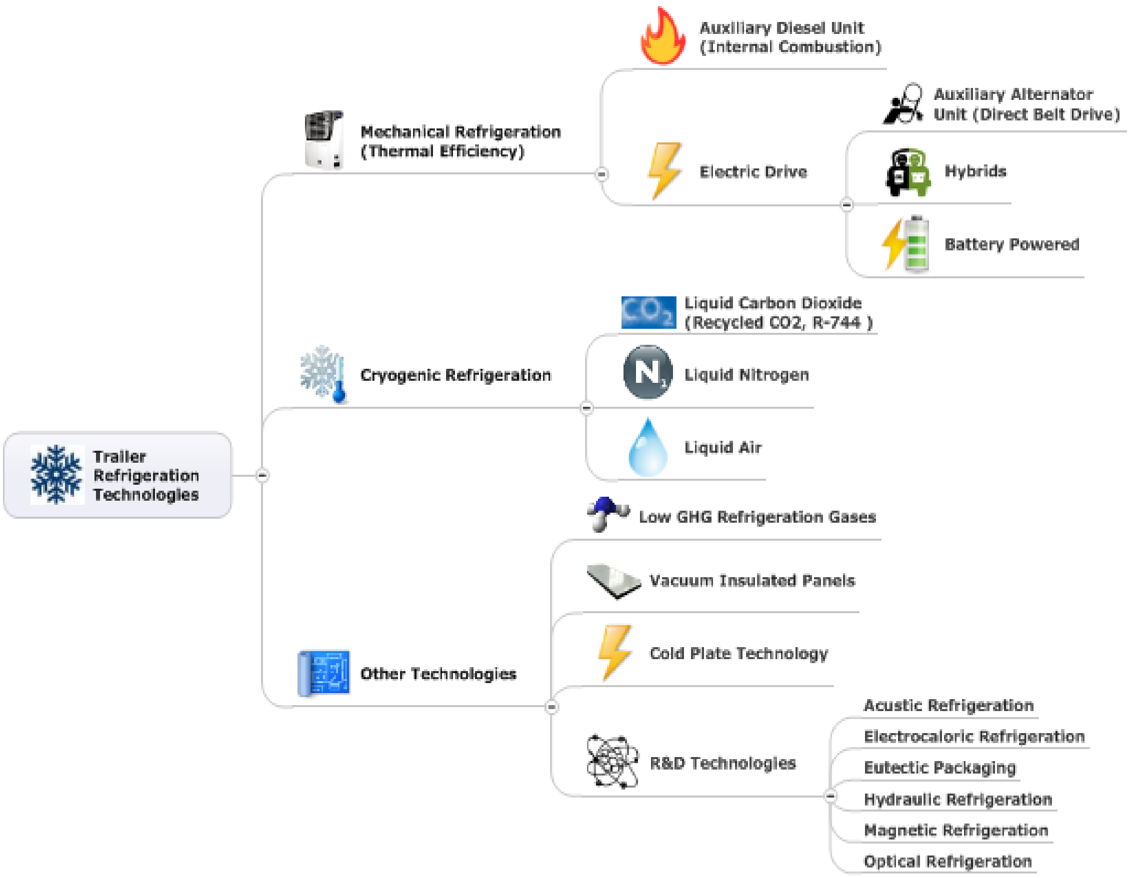


Figure 60. Classification of transport refrigeration technologies.

3.5.4.1 MECHANICAL TRANSPORT REFRIGERATION UNITS

Transport refrigeration units (TRUs) emissions are not regulated in the EU despite the fact that they produced 6 times more NO_x and 29 times more PM_x than Euro 6 HGVs each year (Centre for Low Carbon Futures, 2014). Typically, TRU's GHG emissions can be calculated from their energy consumption and the amount of refrigerant gas leaked. Tassou et al. (2009a) calculated that chilled refrigeration for small rigid lorries, large rigid lorries and semi-trailers consume around 1.5, 2.5 and 4l/hr. of diesel (Table 24). Applying Defra GHG carbon reporting guidelines and its emission factors (Defra, 2013b), a TRU working an average of 3,000 hrs. per year would emit 32 tonnes of CO_2 eq. Average fuel consumptions for frozen produce (-20°C) is between 2 l/hr. (rigid lorries) to 4 l/hr. (semi-trailers) (Table 24), which can represent over a fourth of the total fuel consumption for articulated HGVs running a 300 km delivery trip, lasting 6 hrs. As TRUs run on red diesel, its carbon emission factor is higher than the standard DERV used by the tractor units (which has around 5% biodiesel on it) or than biodiesel. This stresses the importance of low carbon transportation refrigeration technologies.

Table 24. Refrigeration duties and fuel consumption of self-contained mechanical transport food refrigeration units. Source: Tassou et al. (2009a).

Body inside length/inside volume/type	Minimum refrigeration capacity long distance transport (W)		Required refrigeration capacity, multi-drop distribution (W)		Fuel consumption (l/h)	
	−20 °C k = 0.4 W/m² K	0 °C k = 0.7 W/m² K	−20 °C k = 0.4 W/m² K	0 °C k = 0.7 W/m² K	−20 °C k = 0.4 W/m² K	0 °C k = 0.7 W/m² K
6.2 m/33.42 m³/rigid lorry	3765	3876	5630	4554	2.0	1.5
10.4 m/61.15 m³/rigid lorry	6155	6353	9897	7920	3.0	2.5
13.4 m/78.79 m³/semi-trailer	7730	7986	13,500	10,078	4.0	3.0

The most common system for TRUs is mechanical refrigeration through a refrigerated transport vapours compression system (Tassou et al., 2010). Semi-trailer HGVs tend to have APU (gensets) and to a lesser extent vehicle alternator units or hybrid units. The first ones are units that have a diesel engine built into them that uses white or red diesel; however, the second ones draw their power from the main tractor unit engine. Tassou et al. (2009a) believe that the future of TRU are hybrid systems where electric power is produced by a diesel generator but also the TRU can be plugged into the grid when the vehicle is stationary (e.g. parked in the warehouse). Electric units use electric power either directly from the grid (e.g. hybrid TRUs) or from an alternator that can be mounted in the engine compartment and driven by a belt connected to the crankshaft (Tassou et al., 2009a). The advantage with electric TRUs (Figure 61) is that as electric motors are more efficient than ICEs; they produce lower GHG emissions; they are quieter; as they have fewer mechanical parts, they are easier to maintain; more reliable; and as they have less joints, they have fewer leakages. This results in a longer operating life and lower GHG and AQ emissions. The particular challenge with alternator TRUs is that they need the tractor unit engine to be running to draw the power from it and therefore, they cannot work standing alone. This makes this technology better suited for city logistics and operations where the trailer returns to the depot overnight. One of the logistics leaders of refrigerated food logistics in the UK reported that alternator TRUs deliver GHG savings of 50% with further reductions in NO_x, CO, HC and PM_x emissions of 62%, 70%, 93% and 96% respectively compared to standard diesel powered TRUs (3663, 2014). As a result, 95% of its fleet now integrate this technology.

Other technologies based on mechanical refrigeration include the use of fuel cells and electric battery packs. Fuel cell APUs (PEMFC) for trailer refrigeration are being developed in the US where a trial with four trucks is expected to deliver savings of 45 L of fuel per day and vehicle in addition to lower emissions of AQ pollutants and noise (National Research Council, 2014). The potential for mobile SOFC in transport refrigeration is rather limited as the most powerful ones have a total power of 3 kW, which is not enough power to keep food frozen.

Figure 61. Three-phase alternator refrigeration unit.

Despite not being a refrigeration technology per se, solar trailers (Figure 62) have been trialled in the past decades as a low carbon alternative for powering transport refrigeration units. A photovoltaic array mounted on the roof of a trailer can generate enough power to meet the hotel loads required by HGVs. Bahaj (2000) demonstrated that it was also feasible to produce enough energy to power a multi-temperature chilled food refrigerated delivery trailer, even during months of very low irradiance. The 35m^2 roof of the trailer was able to generate 4.4 kW of maximum output which was enough for chilling (+7°C) fresh food. Multi-drop multi-temperature frozen food transport requires much lower temperatures (-20°C) and due to the high thermal load (the difference between the external temperature and the set point) much more power is necessary (around 10 kW for MB trailers as per DIN 8959). Photovoltaic panels can make a significant contribution in reducing energy consumption but they cannot provide an autonomous solution yet, as the efficiency of the cells, the costs and energy density of batteries need to improve.

Figure 62. Solar semi-articulated trailer trial. Source: Bahaj (2000).

Thin film technology provides even lower efficiencies and does not represent a realistic alternative. One of the key barriers of a 'solar trailer' is the long payback period which has been estimated to be around 15 years (Bahaj and James, 2002). This figure may now be overly pessimistic as more recent findings suggest that reductions in non-silicon costs and silicon usage drive annual module cost reductions of 13-17% (Ernst & Young LLP, 2011). The VIP semi-trailer manufactured by Krone included several low carbon innovations, one of them being solar panels installed on the roof. These panels reduce the power demand of the electric functions of the TRU (Krone GmbH, 2012). An additional advantage of solar trailers, is that vehicles parked during the day, could generate additional streams of revenue by selling the energy surplus to the grid, taking advantage of the UK Feed-in Tariffs (FiT). Vehicle-to-Grid (V2G) technology (Figure 63) has commercial potential; however, it requires the development of smart grids and a well-defined regulatory framework if it is to work in the EU. This could contribute towards the stabilisation of the national grid (energy balancing) by providing good quality energy in relation to frequency and voltage (Tomic and Kempton, 2007). This could shorten the payback period of the investment, making 'solar trailers' a more economically feasible alternative.

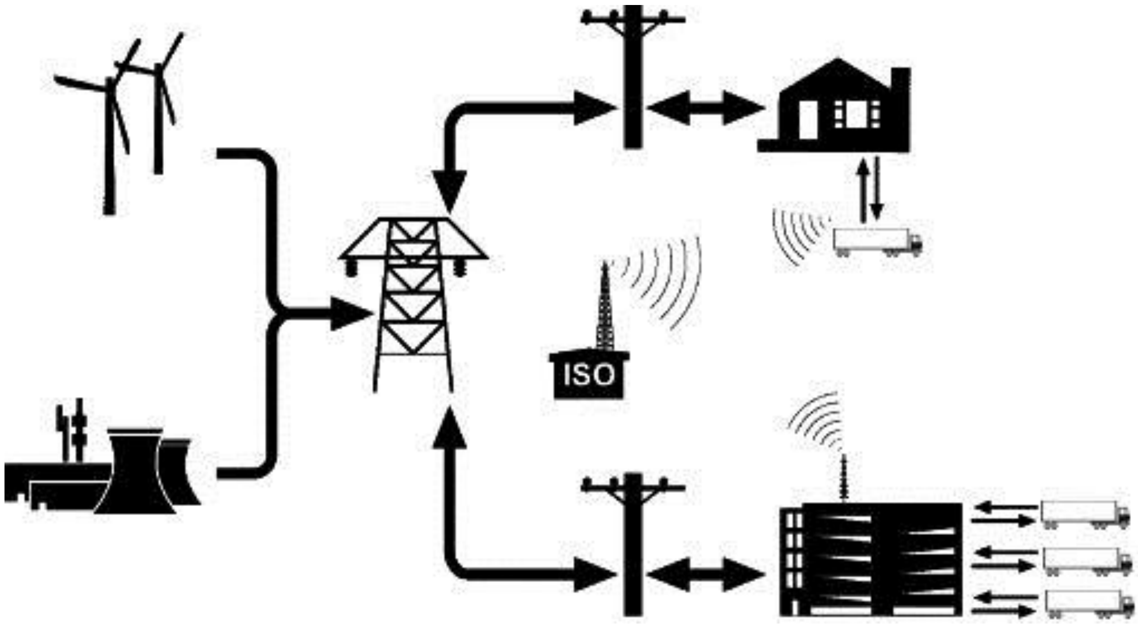


Figure 63. Vehicle-to-grid scheme. Adapted from Tomic and Kempton (2007)

3.5.4.2 CRYOGENIC REFRIGERATION

In cryogenic liquid nitrogen (LIN) refrigeration systems, LIN stored in tanks at cryogenic temperature is either sprayed along the trailer or multi-temperature compartments (like Naturefridge) or it is passed through a heat exchanger (like Frostcruise). The first one (called direct approach) is 30% more efficient than the heat exchange (called indirect approach) but neither extracts any power from the evaporation process (Centre for Low Carbon Futures, 2014). In the first case, the fluid vaporises quickly and reduces the temperature of the container uniformly cooling down the cargo faster than conventional systems (Tassou et al., 2009a).

Nitrogen refrigeration does not produce emissions at point of use and is very quiet (under 60dB (A)) which allows operators to potentially access previously restricted low-emission urban areas during out-of-hours periods. TRUs which stay within the 60dB(A) without manual intervention can get PIEK certification and this indicates that the equipment is considered as suitable for use in night time deliveries without causing noise disturbance (Piek, 2015). LIN TRUs do not have an engine or evaporator, and therefore fewer mobile parts reduce maintenance costs up to 65% (Logistics Manager.com, 2008). This influences the whole life cycle cost because around half of these comprise fuel, downtime, repair and servicing costs and service delivery failures (DfT, 2010a). Other benefits include reduced top freezing and more consistent set point temperatures compared to conventional systems (EcoFridge, 2009). If Nitrogen is generated renewably, it eliminates the carbon footprint of food refrigerated transport (ecoFridge, 2009b); however, unless the energy used for producing the LIN comes from a renewable source with renewable energy guarantees of origin (REGO) certificates, the GHG emissions (all scopes) can be much higher than conventional diesel units. LIN production and compression is an energy intensive process. Producing 1 litre of LIN requires 0.6 kWh of electricity (Linde Cryoplants Ltd, 2012). Naturefridge (previously known as Ecofridge), on the other hand, publishes energy requirements of 1.1 kWh per m^3 (NatureFridge, 2012). If the LIN is bought in bulk, the carbon miles of transporting the product to the refuelling point increase GHG emissions slightly. From a financial point of view, it seems that LIN cryogenic refrigeration is expensive and from an environmental point of view, it makes sense only when the LIN is produced with renewable energy. A typical installation is illustrated in Figure 64. The capital costs of a LIN production plant is around £,4,000,000[10] (Linde Cryoplants Ltd, 2012) plus the extra cost for each refrigeration unit. This may result in increased costs even if the LIN is produced internally instead of bought in bulk. When LIN is purchased externally, the risk associated with limited sources of supply has to be considered as well, in addition to concerns related to safety. Manipulation of cryogenic liquids requires special training and equipment. Also when unloading freight, it is necessary to leave the doors open for a few minutes before accessing the interior of the semi-trailer. LIN tanks may be fitted under the trailer; however, this could reduce vehicle volume payload. DDTs may not have enough space to fit these tanks.

Carrefour (France), Safeway (US), Woolworths (South Africa) and Asda (UK) have been customers of Ecofridge (EcoFridge, 2009); now trading under the name Naturefridge. ASDA conducted a 5 year trial (ended in 2012) with 7 nitrogen-cooled chill ecoFridge units (DfT, 2010a). ASDA reported carbon savings of almost 83 tonnes during the first 10 months of the trial (EcoFridge, 2009). The grocer operates around 2500 trailers (DfT, 2010a) and if the trials were satisfactory they could reduce carbon emissions by 14 tonnes per truck per year. Unfortunately, technical reports have not been published so far.

[10] This cost is an extrapolation from a £400,000 cost of an installation 10 times smaller

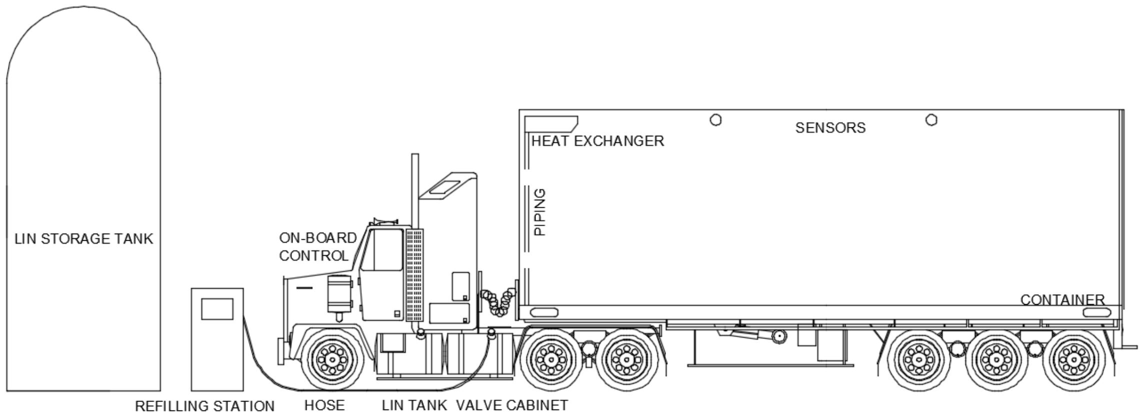


Figure 64. A possible LIN / liquid air cryogenic transport refrigeration system.

In 2012, Linde Gases announced the launch of "Frostcruise" a LIN cryogenic cooling technology. The manufacturer conducted a refrigeration trial with chilled produce (+2˚C) in a 46 m^3 trailer and it showed very low operating noise (60-65 dB) with estimated GHG savings of 15% in summer and 12% in winter (Linde Gases, 2012). LIN tanks are heavier and bulkier than diesel ones. Frostcruise systems are being operated by GIST (a cold logistics company) for Marks & Spencer and Starbucks (Centre for Low Carbon Futures, 2014).

In cryogenic CO_2 refrigeration systems, the liquid CO_2 is used by the refrigeration unit instead of being sprayed in the interior of the box, and later is vented to the atmosphere. This process is carbon neutral as long as the gas is obtained sustainably (e.g. as a by-product of anaerobic digestion). According to Tassou et al. (2009b) a 38t frozen food HGV working around 10 hrs. needs around 505 kg of CO_2. If the same vehicle with a genset would consume 3 L/hr., GHG savings would be around 78 kg per day. On the other hand, costs would increase from £30 (assuming £1.01/L red diesel) to £50.5 (assuming £0.1/kg CO_2). This shows that costs will be one of the main challenges for the uptake of this technology.

According to Thermo King, its cryogenic CO_2 CryoTech system compares positively with LIN, as it offers one-third of the carbon footprint of other LIN systems (as they use recycled CO_2), it does not present safety concerns or delays when entering the box, it generates airflow that keeps humidity protecting fresh produce (MarshallWeb, 2012) and it has a noise level of just 58 dB(A). This system is suitable for multi-temperature trailers with up to 3 compartments and according to the manufacturer, it refrigerates four times faster than conventional TRUs (Thermoking, 2015).

Liquid air cryogenic refrigeration is a new development promoted by the Centre for Low Carbon Futures, Dearman Engine Company, Ricardo and co-funded by the Technology Strategy Board (Centre for Low Carbon Futures, 2014). Nitrogen constitutes 78% of the atmosphere, and therefore LIN and liquid air have very similar characteristics. At atmospheric pressure, LIN liquefy at -196°C and liquid air at -194°C, and it can be stored in insulated and unpressurised tanks (Centre for Low Carbon Futures, 2014). This technology seems to present a very strong business case as the payback period could be within 3 months for rigid refrigerated lorries and under 3 years for semi-articulated; while delivering considerable GHG and air quality emissions reductions (Centre for Low Carbon Futures, 2014). The study bases some of the environmental benefits on the fact that liquid air can be obtained as a by-product of LIN production (at least up to 2019) and therefore, at a negligible environmental impact. The promoters of this technology assume that there is a well-developed LIN infrastructure within 100 miles of 28 of the 30 biggest cities of the UK. This means that logistics firms located outside these 28 areas will produce much higher GHG emissions due to the delivery of liquid air.

This technology is based on a new liquid engine developed by Dearman Engine Company that reduces tailpipe emissions 100% in refrigeration applications and when it works in combination with a novel split cycle ICE developed by Ricardo (that incorporates LIN to raise fuel efficiency of HGVs) it can reduce FC by 15-30% in heat-hybrid powertrains (Centre for Low Carbon Futures, 2014). The Dearman engine is a piston engine that draws power from the vaporisation and expansion of liquid air or LIN by using a heat exchange fluid that allows very fast rates of heat transfer inside the engine (Centre for Low Carbon Futures, 2014). This allows cooling but also gas pressure drives the Dearman engine which can be used to drive a conventional refrigeration compressor or auxiliary power (Centre for Low Carbon Futures, 2014). The first on-vehicle demonstration trial of TRUs using this technology started in the summer of 2015.

3.5.4.3 REFRIGERANT GASES

According to DECC (2014c) conventional mechanical TRUs have a hermetic refrigerant gas container that leaks between 7.5% (R-410A) and 15% (R-404A gas) of its content each year. To understand the implication of these leakages, it is necessary to explain how these gases contribute to GHG emissions.

Radiative forcing (RF) is used to quantify variations in the Earth energy balance as a result of anthropogenic changes. IPCC (2013) defines RF as the 'change in net downward flux (shortwave + longwave) at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium…' IPCC (2013) defines GWP as a metric used to quantify and report the relative contribution of emissions of different substances to climate change. It represents the radiative efficiencies of each substance in a particular time horizon (typically 20, 100 and 500 years) and their forecasted lifetimes in the atmosphere. In a simplistic way, it represents an index of the energy added to the climate system by a substance compared to the same amount of the CO_2 gas. Taking as a reference the RF of CO_2, all the other substances represent multiples of an equal mass of CO_2. The GWP of CO_2 is 1 and it represents 1.68 W/m^2. In contrast, the typical refrigerant gas used in transport refrigeration units (TRUs) known as R-404A has a GWP 3,922 times higher than CO_2 (100 years' time horizon) and an atmospheric lifetime of 40.36 years (IPCC, 2013). Appendix 5 (Page 329) includes a list of refrigerant gases and blends with their respective GWP.

Taking as an example a Carrier Vector 1,400 TRU containing 8.3lts of R-404A (Carrier, 2011), leakages will represent around 1.245 l each year. As its GWP is 3,922 this equates to almost 4.9 tonnes of CO_2eq. per year. On top of this, almost a further 3 tonnes must be added to account for the emissions generated by disposing the unit at the end of its lifetime.

Fluorinated Gases (F-Gases) were proposed as alternatives to ozone depleting substances being phased out under the Montreal Protocol (CFCs, HCFCs and halon gases). F-gases are greenhouse gases (GHGs) with greenhouse warming potential (GWP) [11] ranging from 124[12] (HFC-152a) to 22,800 (SF_6) and include three groups: hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). F-gases account for 2% or the EU's overall GHGs emissions but these have risen more than 60% since 1990 (European Comission, 2012b). The European Commission (2012d) aims to reduce emissions of F-gases by 72-73% by 2030 and by 78% by 2050. There are also blends of F-gases with GWP between 650 and 11,700, such as R-407C and R-410A (that replaced HCFC-22 mainly in stationary air conditioning) and R-404A and R-507A (that replaced R-502 and HCFC-22 in commercial refrigeration). A ban for recycled HCFC-22 came into force in 2015. The other blends will be phased down by 2020. Hydrofluorocarbons (HFCs) are the main type of F-gases and these are used as refrigerant gases in air conditioning, commercial refrigeration systems and transport refrigeration units (TRUs). Due to their impact on global warming, HFCs are covered by the Kyoto Protocol. In the Logistics

[11] Appendix five reproduces the GWP of different F-gases and refrigerant blends.
[12] Considering Defra "GHG Guidelines for Company Reporting 2014".

industry, HFCs are released through the leakage of refrigerants in vehicles and refrigerated warehouses and trailers.

The EU Commission has proposed to replace the existing EU Regulation (EC) No 842/2006 on F-gases with a new legal framework, following the path of the EU Low Carbon Economy Roadmap 2050 (European Comission, 2012c). The proposed regulation aims to reduce F-Gas emissions by two-thirds of today's levels by 2030 starting by phasing-down the sale of HFCs from 2015. Existing legal requirements, such as the control of leaks, proper servicing of equipment and the recovery of gases at the end of the equipment's life are maintained and strengthened in the new proposal (European Comission, 2012c). The proposal is also related to the Directive 2006/40/EC on mobile air conditioning that entered into force on the 1^{st}/Jan/2013. The aim of this directive is to reduce the footprint of the automotive industry. The 2006/40/EC directive has just banned the use of HFC-134a (GWP of 1,430) in newly type-approved vehicles, a refrigerant that replaced CFC-12 in stationary and mobile air conditioning machines (European Comission, 2012a). HFC-134a can be easily substituted by HFO-1234yf (GWP of 4). Safety concerns regarding the flammability of this gas has been reported by one vehicle manufacturer and the Commission is investigating this. The Commission concluded that phasing-down F-Gases was the best alternative, as it showed the "the highest additional environmental benefit, stimulate innovation to the highest degree and would come at a low cost to the economy and society as a whole". The Commission believed that by implementing this proposal, the society would benefit from avoiding the most dangerous effects of global warming. According to the Proposal, there will be a ban on the sale of brand new commercial refrigerators and freezers for the storage and distribution of products in food service from 2017 for refrigerants over 2,500 GWP and over 150 GWP by 2020. The proposal will affect refrigerated trucks and trailers as now containment measures have been extended to them; this means that TRUs will have to be checked for leakages every 3-12 months, depending on their CO_2 footprint. The EU Commission aim is to discourage the use of F-Gases with high GWP where alternatives exist (European Commission, 2012d).

Iso-butane (HC-600a) is expected to become the main refrigerant for domestic refrigeration, Ammonia for industrial use and propane (R290) which has a GWP of 3.3 and CO_2 for TRUs (European Commission, 2012b). Ammonia has zero GWP and Ozone Depleting Potential (ODP); however, it is toxic and slightly flammable. Hydrocarbons such as HC-600a have ultra-low GWP; however, they are also highly flammable. Carbon dioxide has a GPW of 1 unit (as it is the value of reference); however, as a refrigerant it requires much higher pressure than conventional systems. The GHG savings of using CO_2 as refrigerant in mechanical TRUs have been reported in the order of 28% compared to previous units and around 5% compared with the next most efficient model of the same manufacturer (Carrier, 2015).

3.6 REVIEW OF SELECTION AND SIM-HEURISTICS TOOLS

There are a handful of tools that can help fleet managers calculate fuel savings and carbon emissions from different vehicle specifications. They do so by aggregating the improvements of low carbon technologies selected by the user. These tools however neither select low carbon technologies by themselves nor consider multiple goals, which is the objective of the framework developed in this thesis.

The 'Carbon Intervention Modelling Tool' developed by Heriot-Watt University (2011) for the FTA is a decarbonisation prediction tool that estimates how much CO_2 can be reduced from freight transport operations by applying one or more decarbonisation measures. Users can calculate the carbon savings resulting from the options they choose from a range of energy efficiency measures, energy carbon reduction approaches and some operational alternatives related to vehicle loading, routing and modal shift for the years 2013 and 2015. This tool does not take into consideration the costs of these technologies.

The UK DfT developed the 'Freight Best Practice Fuel Ready Reckoner' that allowed fuel savings to be estimated for different fuel saving techniques (DfT, 2010b). The user could understand the cumulative savings of each option alongside the inter-relations between technologies. The model indicated total fuel savings per annum; however, it was the user who had to select the technologies until identifying the combination that yielded the greatest savings. This model also calculated air quality emissions but only to Euro V and capital expenditure were not included in the analysis.

The 'Low Emission Toolkit' was developed by the 'Low Emissions Strategies Partnership' of UK local authorities and helped to estimate the transport emissions associated with new developments. It also compared energy efficient vehicle technologies on an individual vehicle basis, calculating emissions and benefits of vehicles (Strategies.co.uk, 2013). The model included eight LCT in addition to driver behaviour improvements; fairings, shaped trailers, spray suppression, low rolling resistance tyres, single wide tyres, auto tyre pressure adjustment, predictive cruise control and vehicle platooning. In a similar approach to the one applied by Baker et al. (2009a), this model looked at costs, technology maturity and limitations related to the lack of infrastructure. This model also required the user to input the desired technologies in order to compute the likely carbon savings; however, not all eight technologies could be selected for all HGVs. This model used the payback period; an invesment technique that suffers from several flaws, as it will be described in Section 4.5.1.1 (Page 168).

The Lumped Parameter Model (US EPA, 2015) is an application that estimates the CO_2 reduction of various technology combinations or packages for light-duty vehicles and it accounts for synergies between technologies (Figure 65). Unfortunately this tool cannot be applied to HGVs, it does not consider different driving cycles and it does not provide an economic assessment of the technologies chosen by the user.

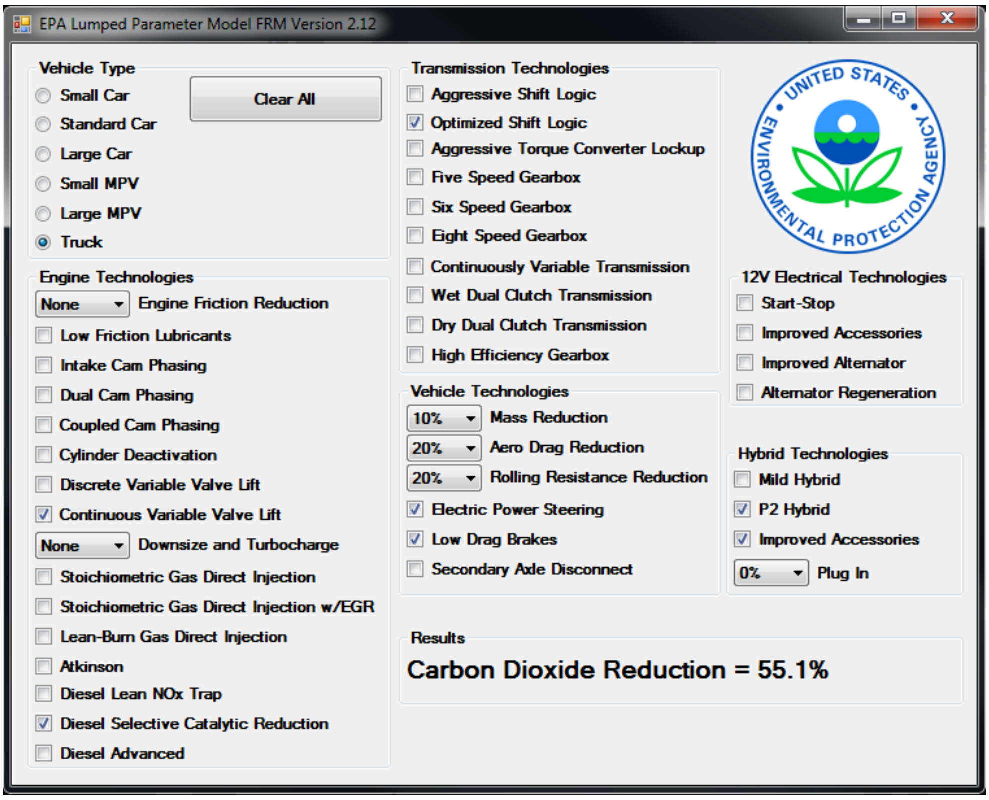


Figure 65. Lumped parameter model. Adapted from US EPA (2015).

3.6.1 SIMULATION SYSTEMS

A simulation is an experiment performed using a model (Fritzson, 2011). In the context of this research, simulations are performed using virtual models of HGVs. Virtual vehicle systems are therefore computer representations of the behaviour and characteristics of a real world system. According to Fritzson (2011) simulations are some of the most common techniques for answering questions about systems and present several advantages over conducting live experiments: i) they are cheaper and safer to run compared to physical model experiments; ii) they provide faster observations of small changes in the development of the system; iii) they suppress disturbances (it is easier to isolate particular effects);

iv) it is relatively easy to manipulate the model parameters and suppress second-order effects.

Simulation models need to be validated to analyse how accurately they represent the real vehicle. Despite being quite precise, different simulation tools present different results for the same vehicles and driving cycles. Examples that illustrate these differences are found in Figures 66 and 67. Kousoulidou et al. (2013) simulated a 12 tonne HGV with four different simulators (AVL Cruise, VECTO, PHEM and Autonomie) under 3 different driving cycles (urban / suburban / motorway) (Figure 66). They found that in most cases the results of different simulators remained within ±4% of the reference value (measured on road tests) during most parts of the cycles. These results were close to the standard value accepted for low carbon technology test SAE J1321 (±2%); except in the case of the simulation tool 'Autonomie' under urban conditions. Franco et al. (2015) identified that GEM returned CO_2 emissions 17% higher than VECTO for most driving cycles (Figure 67).

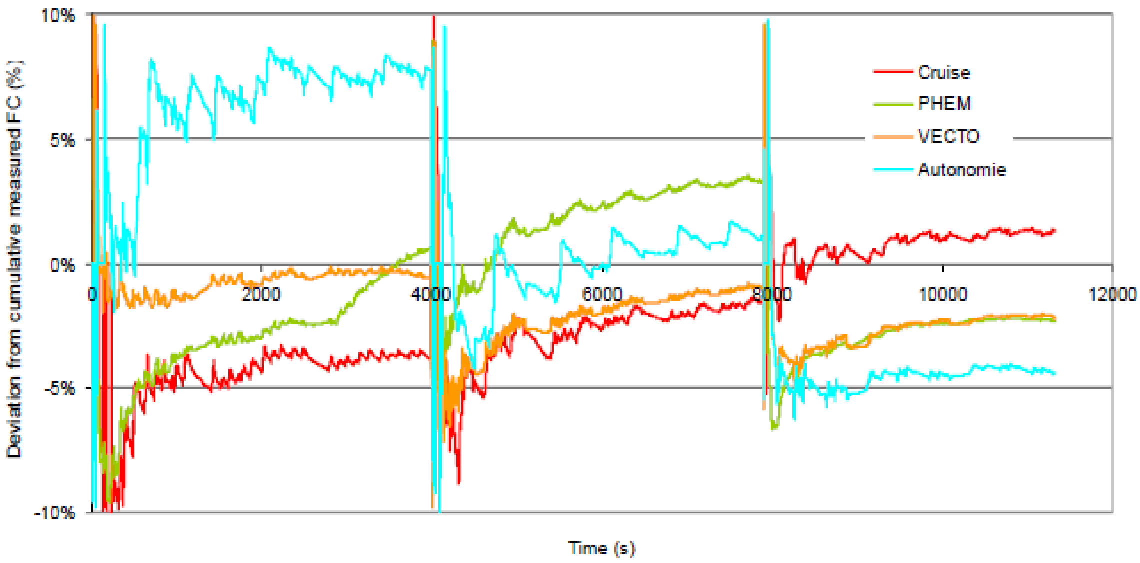


Figure 66. Deviation of simulated cumulative fuel consumption for several simulation. Source: Kousoulidou et al. (2013).

The reasons for the differences in the results between simulation tools depends on the type of architecture that these simulators operate under. Franco et al. (2015) classify this architecture in terms of forward and backward models. In VECTO (the 'backward looking modelling approach'), the vehicle load required is calculated from the elements that appeared in the road-load equation (driving resistance, efficiency of powertrain and power consumption of auxiliary systems) and the fuel consumption is interpolated from an engine map. In GEM (the 'forwards looking modelling approach'), fuel consumption is calculated as an interaction of algorithms combining the driver model and control algorithms for specific vehicle components. Backward models (such as VECTO) cannot accommodate 'black-box' systems to test alternative blocks representing different technologies. Backward models take the driving cycle as the actual vehicle speed, while forward models (such as GEM) take the driving cycle as the target speed and use a control loop or driver model to provide a throttle signal input to the powertrain (Franco et al., 2015). This means that forward models represent better drivers' driving behaviour and the characteristics of the vehicle kinematics which will show differences in vehicle acceleration between different vehicle models and virtual drivers. These models can integrate other subsystems and as a result, they are more suitable for testing different technologies and more complex powertrains. This means that less powerful vehicles following the same driving cycle (which indirectly represents speed limits, congestion, acceleration and driver's behaviour) will take a longer time to complete the trip. Forward systems are more complex and require a larger number of inputs. This in turn can potentially reduce the accuracy of the results (Kousoulidou et al., 2013). Forward simulators contain equations of motion, kinematics (multiple degrees of freedom) and must replicate mechanical, electrical, electronic, hydraulic, pneumatic, thermal components and the interactions (synergies) between these.

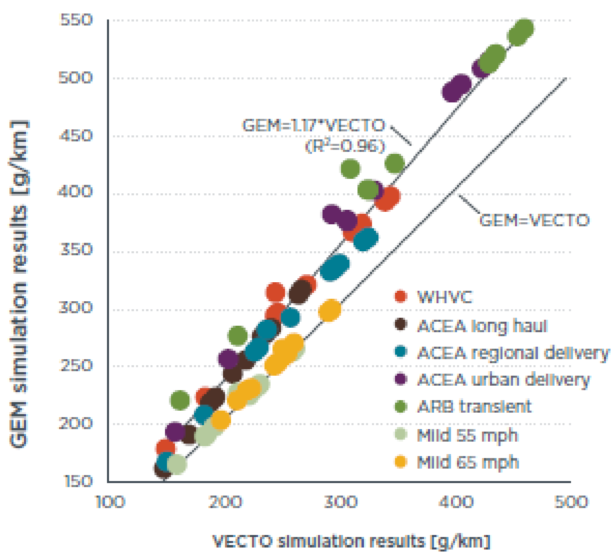


Figure 67. Comparison between GEM and VECTO for different driving cycles. Source: Franco et al. (2015).

There are nonetheless additional layers of complexity. While GEM and VECTO for example are longitudinal vehicle dynamic block models that ignore lateral forces involved during steering and cornering, as these are considered to be minimal, both present different modelling approaches; other models such as IPG Truckmaker and AVL Cruise (Figure 68) take longitudinal, lateral and vertical dynamic forces into account. Some simulation environments also reproduce a gradient and can import 3D digitized roads. This is very important as the gradient is a key factor influencing energy consumption as seen in Equation 2 and 3 (Page 33). These roads can be obtained from companies such as Google (Google Earth), Ordnance Survey, ArcGIS, NAVTEQ and Nokia Here or from companies such as TÜV (3D-Track) for a much more precise topology and roughness details. Commercially available 3D road models can have a resolution of 10 mm (horizontal) x 1 mm (vertical) (Witschass et al., 2008).

The framework developed in this research uses the FCR of different HGVs based on the simulated impact of certain low carbon technologies and real world trials. The accuracy of the heuristic model depends on the validity of the FCR calculated by the simulation tools or found in the real world trial experiments (following very strict rules). As the framework used commercial software for simulations, the personal validation of the simulations' results was not necessary as these had been widely covered in the literature (Kousoulidou et al., 2013, Hausberger et al., 2012, Franco et al., 2015) and independently validated by the customers of such software applications. Fritzson (2011) gives some recommendations for model verification and validation and these were followed for validating the results of the mathematical models:

- Critically review the assumptions behind the model.
- Compare results with experiments whenever possible
- Perform sensitivity analysis. When the simulation results are relatively insensitive to variations on the model parameters, this suggests that the model is valid.
- Check that the model is consistent, checking that dimensions and units are compatible (e.g. Newtons with kg m/s^2).

Currently, the US and the EU are researching the use of simulators as tools for vehicle type approval to calculate GHG and AQ emissions. Examples of these developments include GEM in the US and VECTO in the EU. The European Commission (2015) intends to propose legislation in 2015 which would require the certification, reporting and monitoring of CO_2 emissions from new HDVs using VECTO. The reason for this is that simulators present advantages compared to chassis dynamometer and driving resistance tests and compared to on-road testing with portable emissions measurement systems. Hausberger et al. (2012) found that using simulations for vehicle certification allows the reproduction of tests more consistently as experiments can be repeated in the exact same way each time. It is also easier to conduct the experiments (once the software is developed) as there is no need to drive the real vehicle to the test location and therefore tests are cheaper.

The system is highly sensitive to fuel saving measures and can be applicable to almost all HGVs categories and technologies. Chassis dynamometer tests also presents a good repeatability consistency; however, these are not sensitive to fuel saving measures as some technologies cannot be properly assessed (e.g. aerodynamic improvements). These are still expensive as the costs of dynamometers for regulatory testing are around £200-£300k and around £44-55k for in-service testing (EMStec, 2002). The study also found that on-road testing is too cumbersome and its repeatability poor. As it will be commented in the results section, the trial conducted to verify the fuel savings of spray suppression mudflaps confirmed this. On road, tests require identical conditions to be created for each run which is difficult to replicate when weather conditions, traffic congestion, vehicle loadings and driving behaviour are considered. These factors, confirmed in the trial conducted as part of this research (section 4.3), make on-road testing very unreliable. The Euro VI emission test uses an engine test bed for type approval; however, the EU also uses on-road testing to verify that the vehicle meets the type approval conditions in the real world and currently, it is considered as an appropriate approach for measuring in-service CO_2 (Hausberger et al., 2012). Nevertheless, it seems that this is likely to change in the near future as VECTO is being developed for such purpose.

A review of vehicle simulation tools is shown in Table 25. Some of these systems are based on object-oriented languages such as Modelica and require the programming of different vehicle subsystems, while others require no programming at all (or very little) such as IPG Truckmaker, AVL Cruise, Ricardo Ignite, Autonomie and Siemens LMS. In general, most of these tools tend to allow the integration of third party models (generally at least with Matlab/Simulink) to add blocks and strategies from ‘black box’ subsystems. Not all the tools can display 3D animations; a feature that seems useful to understand the transient dynamic behaviour of the vehicles (e.g. braking, manoeuvres).

The simulation packages that appear in Table 25 are very different from emission calculation tools such as COPERT, EMFAC, MOBILE, MOVES, ARTEMIS, HBEFA, VERSIT+ or EMV. These focus on macroscopic emissions (mainly air quality emissions) rather than individual vehicle emissions. Simulation packages are not policy analysis tools, such as TREMOVE, GLOBEMI, NEMO, and TREMOD; however, their results can become an input on these analysis. These tools cannot run micro-simulations of single vehicles (sometimes interacting in a realistic 3D environment with other vehicles). Similarly, simulation systems such as the ones enumerated must not be confused with micro-simulation software such as AIMSUN, PARAMICS or VISSIM which focus on optimising complete traffic systems where hundreds or thousands of vehicles interact with the aim of improving traffic flows and where energy efficient technologies cannot be modeled.

3.6.2 HEURISTICS COMBINATORIAL AND MULTICRITERIA DECISION MAKING APPROACHES

Metaheuristic algorithms are one of the most practical approaches to solve combinational optimisation problems (Yagiura and Ibaraki, 2001, Laguna, 2011). The model developed in this research could evaluate a large number of technology combinations (currently it considers just 25). Combining 100 different technologies requires the evaluation of a total of 2^{100} (1.26×10^{30}) combinations. This would be a very intensive computational task that can benefit from heuristics to find an optimal (or near optimal) solution in a timely fashion. Heuristic approaches have been used for function optimisation of multiple parameters (Mitchell, 1998) and optimisation of engineering problems (Togun and Baysec, 2010, Laguna et al., 2013) including a technology selection that impacts on performance and economic parameters (Patel et al., 2006).

Heuristic methods such as genetic algorithms (GA) can evaluate a large number of combinations within a reasonable time; however, due to their probabilistic nature there is no guarantee that the solution found corresponds to a global optimum instead of a local optimum (Mitchell, 1998). Other evolutionary algorithms such as Tabu search (TS) guides a local heuristic search procedure to explore the solution space beyond local optimality (Glover, 1996) by using adaptive memory and associated memory-exploiting mechanisms (Martí et al., 2006). Scatter search (SS) is another heuristic optimisation method that uses strategies (rules) for diversifying and intensifying the search rather than relying on randomisation (as genetic algorithms do). Details of how this technique works and its pseudocode procedure were described in detail by Martí et al. (2006). SS can be combined with TS to take advantage of its adaptive memory (Martí et al., 2006). Despite all being evolutionary programs, TS and SS provide better quality solutions than GA (Martí et al., 2005).

Table 25. Examples of vehicle simulation packages.

Software Package	Requirements	Developer	Connectivity	Website
ADVISOR	Matlab / Simulink	Alliance for Sustainable Energy, LLC	Matlab / Simulink	http://sourceforge.net/projects/adv-vehicle-sim/
ASM Truck	Matlab / Simulink	dSpace	Matlab-Simulink	https://www.dspace.com/en/inc/home/products/sw/automotive_simulation_models/produkte_asm/vehicle_dynamics_models/asm_truck.cfm
AUTONOMIE (LMS Imagine.Lab Sysdm)	Matlab / Simulink	Siemens / Argonne National Laboratory	GT-Power / AMESim / TruckSim / AVL-DRIVE	http://www.autonomie.net/index.html
AVL CRUISE	Standalone	AVL	Matlab-Simulink / IPG Truckmaker/ C / Fortran / AVL BOOST DRIVE InMotion / KULI / Flowmaster / AmeSim / ASCET / OPAL-RT / TruckSim / Excel	https://www.avl.com/cruise
Dymola Vehicle Dynamics	Standalone (based on Modelica)	Dassault Systèmes	Matlab / Simulink / Truckmaker / Excel	http://www.3ds.com/products-services/catia/products/dymola
Dynacar	Labview RT	Tecnalia	Inertia / NI VeriStand	http://www.dynacar.es
GEM	Standalone	EPA	Matlab / Simulink	http://www.epa.gov/otaq/climate/gem.htm
GT-Suite	Standalone	Gamma Technologies	Simulink / CFD Software (STAR-CD / FLUENT / AVL FIRE / CFX / OpenFOAM)	https://www.gtisoft.com/products/p_GT_SUITE.php
IGNITE	Standalone	Ricardo	Matlab-Simulink / WAVE	http://www.ricardo.com/en-GB/What-we-do/Software/Products/IGNITE/

Software Package	Requirements	Developer	Connectivity	Website
IPG TRUCK MAKER	Standalone	IPG	Matlab-Simulink/AVL Cruise/ADAMS / Sherpa Engineering / C / AVL Concerto / Dymola	http://ipg.de/simulationsolutions/truckmaker/
SYSTEM MODELER	Standalone (based on Modelica)	WOLFRAM	Mathematica	http://www.wolfram.com/system-modeler/
TruckSim (only vehicle dynamics)	Standalone	Mechanical Simulation Corporation	Matlab-Simulink / Labview / ASCET / C / AVL Cruise / dSpace / OPAL-RT, ETAS Labcar RT, Fujitsu-Ten CRAMAS, A&D	https://www.carsim.com/products/trucksim/
VECTO	Standalone	TU Graz / JRC	Under development	http://bookshop.europa.eu/en/development-of-a-co2-certification-and-monitoring-methodology-for-heavy-duty-vehicles-pbLDNA26452/

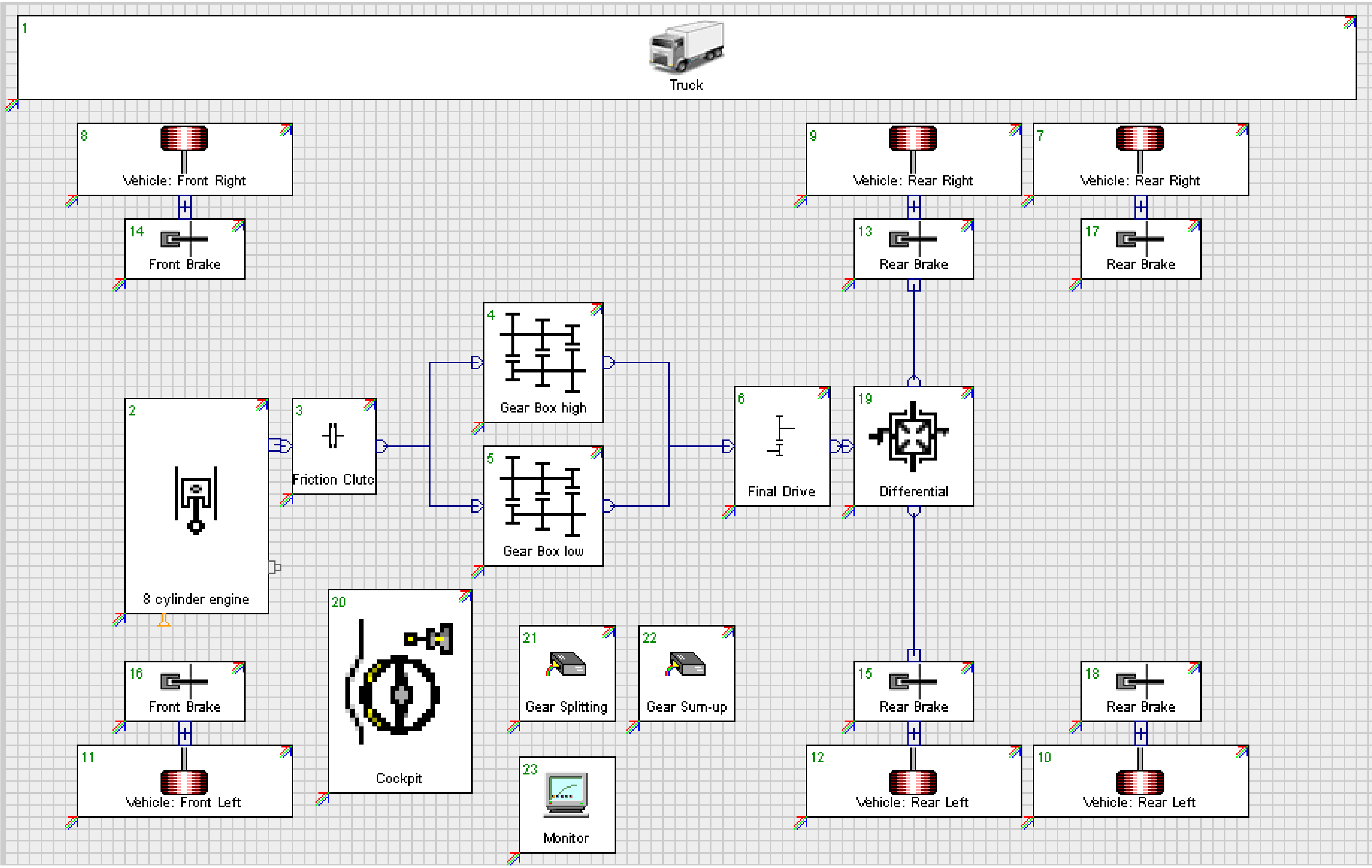


Figure 68. Interface of a truck model in AVL Cruise.

The heuristics method in this research is combined with a multicriteria decision analysis (MCA) approach for selecting the optimal solution based on several targets. MCA techniques are designed to avoid cognitive biases in decision making by using an approach which focuses on different criteria according to their relative importance (H.M. Treasury, 2013). MCA is a range of decision support tools and methodologies that can be used to solve complex problems with multiple goals and conflicting objectives (Kahraman et al., 2015, H.M. Treasury, 2013). It can help decision makers to develop coherent decisions among alternative choices (H.M. Treasury, 2013). MCA can combine quantitative and qualitative measures to produce a ranking of preferred choices.

The evaluation of quantitative criteria includes different techniques such as financial analysis, cost-effectiveness analysis, cost-benefit analysis and decision trees. The financial analysis focuses on assessing financial costs and revenues and includes a payback period, net present value (NPV), expected rate of return, etc. The net present cost is based on the NPV and it is the technique applied in the heuristics model presented in this thesis for the cost minimisation objective function. Cost-effectiveness analysis is also another quantitative technique that can consider non-financial targets. This technique is used to assess the least-costly choice to achieving the objective and it is used when this objective cannot be valued (H.M. Treasury, 2013). The cost-benefit analysis (CBA) aims to value the expected impacts of an alternative in monetary terms based on the willingness-to-pay principle of winners and willingness-to-accept from losers. As a result, this is more suitable for public policy decision making. The last two approaches are not suitable for the problem being addressed in this research, as there is no information regarding the monetary impacts that the risks associated to different levels of technology maturity, safety and infrastructure limitations can have on operational results and therefore financial costs. Also, there is no a mandatory target regarding GHG emissions that logistics firms must follow. This also eliminates decision trees as it is not possible to model expected values of these qualitative criteria as their impact cannot be quantified. This justifies the use of multicriteria analysis techniques where the results of the financial analysis produced by the heuristic model are incorporated as one of the criteria to be considered.

There are several MCA techniques and their main difference is the way in which they combine the data for the weighting of each objective. MCA techniques are used to find a single preferred alternative, to rank a number of alternatives, to short-list a range of possibilities or to distinguish acceptable from unacceptable alternatives (H.M. Treasury, 2013). Generally speaking MCA techniques assess the extent to which criteria are met within several alternatives. Examples of these include multi-attribute utility theory (MAUT), analytic hierarchy process (AHP) and fuzzy sets. MAUT is a prescriptive theory developed by Keeney and Raiffa (1976) that allows decision makers to evaluate several objectives by building a performance matrix, determining independence among criteria and estimating the value of options. H.M. Treasury (2013) argues that by taking uncertainty formally into account and by not assuming mutual independence of preferences a simpler linear additive model as used in most MCA is not possible, which makes this technique more demanding and complex.

The Analytic Hierarchy Process (AHP) is a MCA technique developed by Saaty (1987) and widely used in multicriteria decision analysis. This approach uses pairwise comparisons to determine relations and trade-offs between qualitative and quantitative (tangible/intangible) objectives. In the context of low carbon emissions, HGV trade-offs are very important as technologies that may reduce energy consumption the most tend to be more expensive and present a higher risk (e.g. hydrogen fuel cells, electric vehicles). French (1986) criticised the internal consistency of AHP, the difficulties of adding new options and the fact that a 'lack of clarity of the underlying axioms make them not empirically testable'. Nevertheless, AHP seems to be a popular technique that has been used in engineering and many other complex decision problems, including technology investment decisions (Triantaphyllou and Mann, 1995, Wong and Li, 2008, Bard, 1986, Tummala et al., 1997) and more specifically automobile purchases (Ma et al., 2009, Dae-Ho, 2001, Luqman et al., 2015). AHP is described in more detail in the methodology chapter.

Defining the most critical objectives and the importance of each target depends on the subjective judgements of the decision makers and these can be prone to cognitive distortions. The final scores given to each criteria must be agreed among a group of experts; typically through group discussions. Croskerry (2002) found that having clear and unambiguous data leads to fewer mistakes. Arkes (1991) suggested that elaborate rational thinking leads to better decision making. In contrast, more recent research indicates that complex strategies can be less accurate than heuristic cognitive thinking, despite considering less information (Gigerenzer and Gaissmaier, 2011). The range of biases is certainly extensive and special attention must be paid to detect red flags (what Campbell et al. (2009) call distorting attachments) when scoring objectives and weighing the performance of each alternative in regards to each criteria.

Other MCA techniques such as Fuzzy linguistic approaches have not been pursued in this framework because, as Noci and Toletti (2000) describe, fuzzy

sets are elements with smooth boundaries in which belonging to a membership group is gradual rather than abrupt. In this framework, the criteria of technology maturity is rather abrupt, which means that a LCT package presents a specific risk profile that indicates that all the technologies integrated in the HGV may be commercially available or they are at clearly stated levels of immaturity (e.g. being trialled or at research stage within university labs). A similar concept applies to the safety and limitations criteria. H.M. Treasury (2013) arguments that fuzzy MCA models are difficult to apply for non-specialists, do not have clear theoretical pillars to model preferences and have not shown critical advantages that are not available in other conventional models.

KEY FINDINGS OF THE LITERATURE REVIEW AND REVIEW OF EVIDENCE

- **Global Warming is accepted as a reality by most of the scientific community.**
- **Transportation and freight have a major impact of GHG emissions.**
- **There are no tools that can provide vehicle specifications to decision makers optimising multiple objectives.**
- **Low carbon technologies for HDV studies are geographically dependent as vehicles present design and driving cycle and operational differences.**
- **The road load equation is a good guideline to consider the principles that are involved in the fuel cost reduction from different technologies.**
- **Larger vehicles increase the vehicle fuel consumption while reducing GHG emissions per unit of payload (e.g. tonne-kilometre).**
- **Diesel powertrain technologies can still improve their efficiency but they have a theoretical limit.**
- **Refrigeration technology potential focuses on alternator and cryogenic refrigeration units. No research has been done focusing on the decarbonisation of the fuel used in conventional TRUs.**
- **Technology maturity is key as several manufacturers in the areas of fuel cell vehicles, advanced biofuels and cryogenic refrigeration have filed for bankruptcy in the last 5 years.**
- **The extensive literature highlighting waste-to-fuel energy pathways suggests that the food supply chain can benefit from managing such resources.**
- **The decarbonisation of fuel has a great potential; however, the lack of demand and lack of clear policy has led to the deployment of few production facilities worldwide and a lack of refuelling infrastructure.**
- **Alternative fuels such as propane and CNG have the potential to reduce GHG emissions providing acceptable range for most fleets.**
- **The popularisation of NG fleets can have a positive impact on the uptake of biomethane vehicles.**
- **A gap has been identified in the literature regarding the lack of tools that can help identify the optimal combination of low carbon technologies and select vehicle specifications that match the objectives of specific logistics firms or other decision makers.**
- **Simulation systems are being developed in the USA (GEM) and EU (VECTO) to validate HDV's emissions, as alternative to dynamometers and engine benches tests.**

- **Simulations allow repeated testing, eliminating interferences from non-controllable factors and reducing trialling costs; however, their accuracy depends on the modelling approach.**
- **Heuristic methods are convenient for the evaluation of millions of non-linear, non-smooth combinatorial solutions.**
- **Multi criteria decision analysis is a proven technique for technology selection when conflicts or trade-offs between quantitative and qualitative criteria have to be assessed.**
- **Analytic hierarchy process is a fairly simple technique to determine objectives, their relative importance (through pair-wise comparisons) and measuring the performance of each alternative in respect to all criteria.**

4. RESEARCH METHODOLOGY

Chapter Aims:

To describe and substantiate the methodology selected for the data collection and data analysis of the mathematical models used

Develop a research framework, combination of different methodologies, for the resolution of the low carbon technology selection problem

In the previous chapters, the context of the research has been introduced. The purpose of this chapter is to explain the data collection and production processes followed, as well as describing an innovative framework for aiding decision makers in the selection of the optimal combination of low carbon technologies for refrigerated heavy goods vehicles according to their corporative aims. The research methodology follows four main stages as illustrated in Figure 69.

In the first block, an extensive literature review of low carbon technologies was conducted to produce the background knowledge that allowed to undertake the empirical work of the next block. Some of the low carbon technologies and vehicles data came from triangulations from Journals and conference papers; theses; commercial; independent and Governmental reports; and personal communications from suppliers. Other technology data came from observations from the simulations undertaken and via statistical analysis of real world field trials. In this block also operational data was collected from the industrial sponsor via internal software systems dealing with routing and scheduling (e.g. average stops per delivery), telematics (e.g. real mileage per vehicle, trips per day, average fuel consumption) and enterprise resource planning (e.g. quantities delivered). It was also very important to review different standards in regards to low carbon technology testing methods (opting finally for the SAE J1321 standard) and carbon lifecycle auditing (opting for the BSI and PASA standards). Waste collection data was supplied by the industrial sponsor and analysed statistically.

Further supply chain data including the localisation of suppliers and customers was also provided by the industrial sponsor. This data was combined with geographical information systems (GIS) to produce geographical datasets. To build the simulations from block two a review of dynamic analysis methods was necessary to understand the relevance of driving cycles and how these could be built from raw telematics datasets. Before developing the optimisation models a review of the operations research techniques suitable for technology selection were conducted. The last stage on this block consisted on asking the industrial sponsor its priorities in regards to the procurement of vehicles. The data needed to generate the pair-wise comparisons of preferred criteria were discussed among different senior members of the sponsoring organisation. Most data collected were quantitative except for the risk profiles of each technology and the preferences stated by the industrial sponsor resulting from their internal discussions that were both of qualitative nature. A more exhaustive descriptive list of the types of data and data collection methods used in block one to generate the inputs needed in blocks two and three appear in Figure 70. In Appendix 6 a flowchart with the data collection flows is also illustrated.

The second block produced data from simulations, a field trial and a carbon audit of waste-to-fuel pathways. The engineering data and operational data obtained in block one were used to model vehicles and technologies in simulators (e.g. IPG Truckmaker and Autodesk MotionFlow). The data produced in the simulations was used as an input in block three. Based on the standard SAE J1321 Type II, the statistical analysis of the fuel savings delivered by spray suppression mudflaps were updated in the quantitative mathematical model from block three. Waste feedstocks and supply chain mapping were used to model the WTW GHG emission factors of the waste-to-fuel pathways most feasible for the industrial sponsor. Cluster analysis was used to give an indication of the areas with higher potential for consolidating and processing waste. This in turn was used to calculate distances and therefore produce the inputs related to carbon miles for transporting waste and fuels.

In block three, a quantitative model was created to find the optimal combinations of low carbon technologies that meet a specific objective function based on different scenarios and the inputs generated through primary and secondary data collections. Primary data was generated by simulating technologies and by conducting real world field trials with vehicles provided by the industrial sponsor. Carbon emission factors were calculated by analysing statistically waste data collections managed by the industrial sponsor and modelling flows through a waste-to-fuel lifecycle analysis. In this block, two contrasting approaches to find the quantitative optimal solution were developed. The first approach consisted of developing a VBA application to review all possible combinations of LCTs and selecting the one optimising the objective function. The second approach used a metaheuristics algorithm to find the optimal solution. The performances of both approaches were compared to ascertain that the quantitative results of both were the same. The inputs used in this block and the methods used to produce datasets are illustrated in Figure 71.

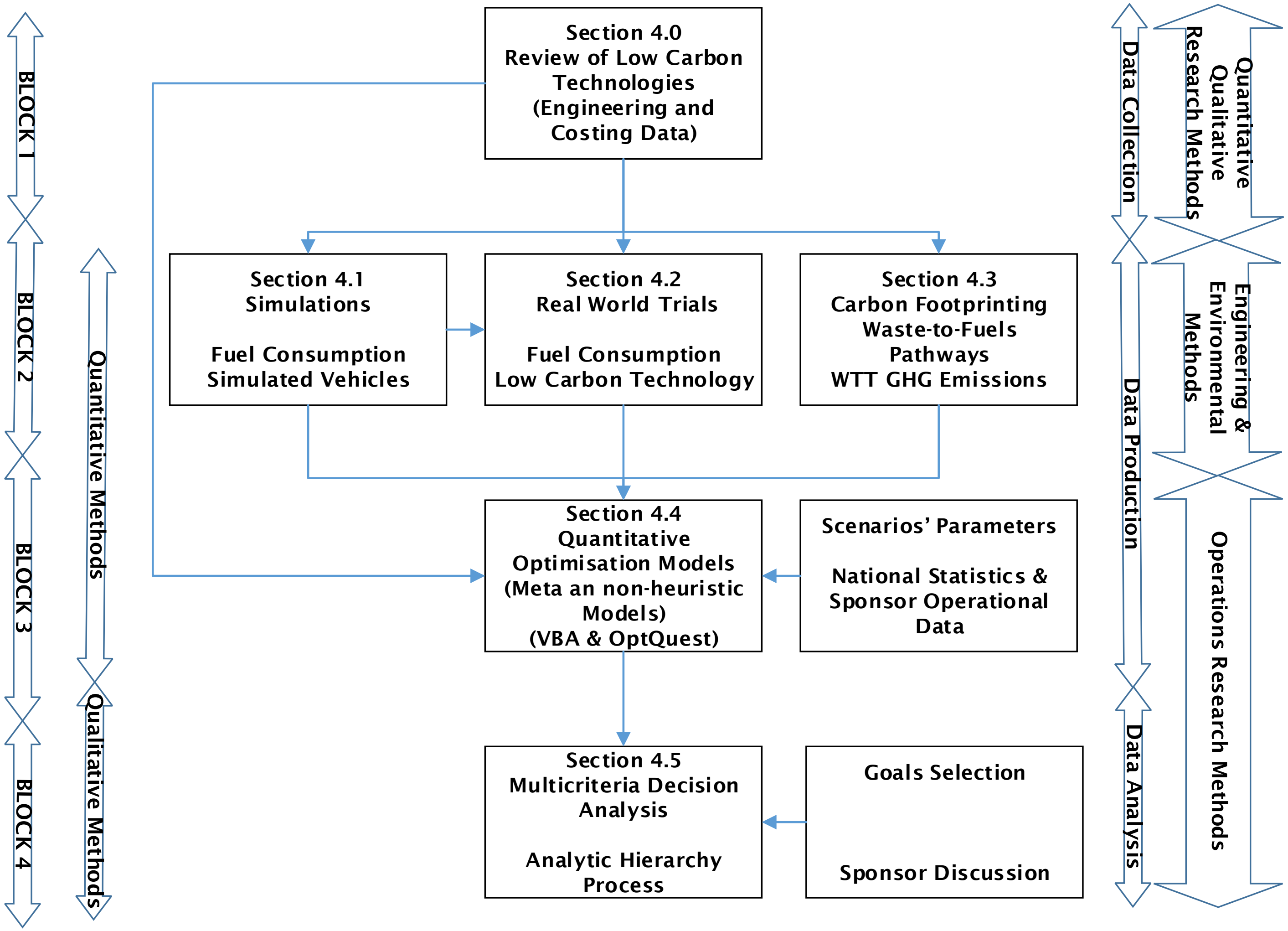


Figure 69. Structure of the methodology chapter.

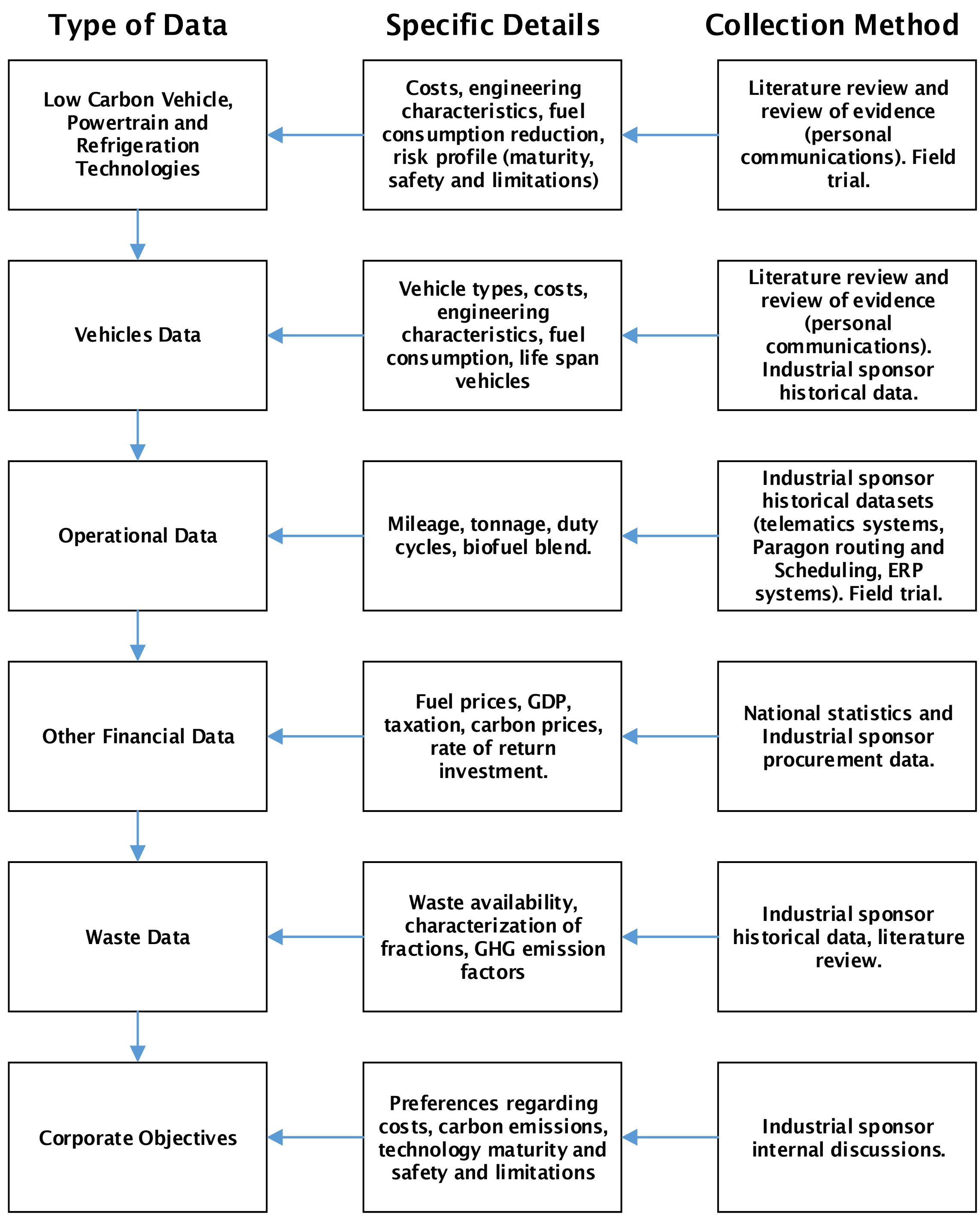


Figure 70. Details of the data collection process followed.

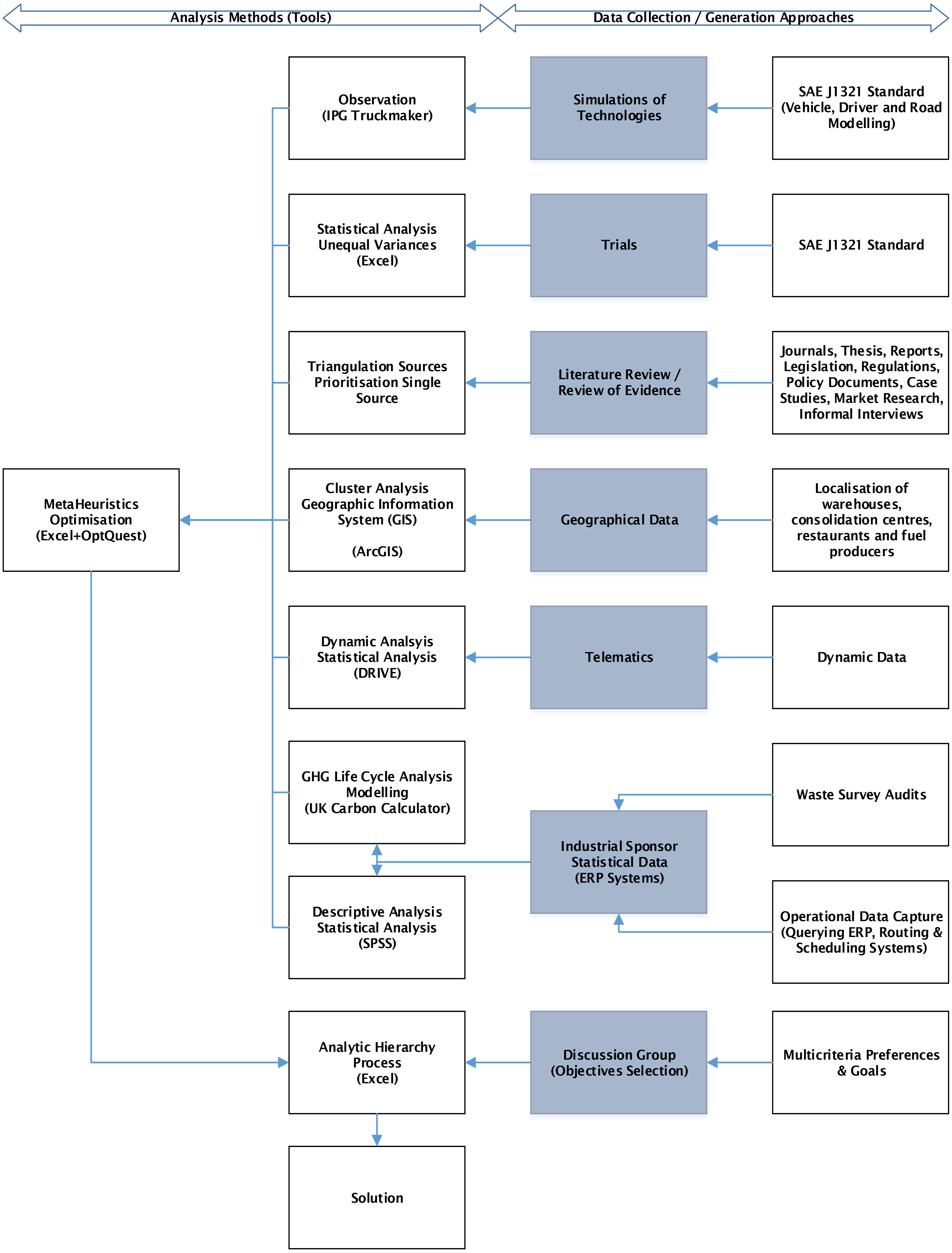


Figure 71. Methodological Approach to produce input data used in the metaheuristics model.

In the fourth and last block, the outcome of the objective functions were used in a multicriteria decision analysis process to determine the most recommended vehicle configuration based on an specific combination of low carbon technologies according to the goals preferred by the industrial sponsor.

All the research methods presented here existed previously; however, these were not applied in the same way to answer the research questions highlighted in Chapter 1. The result is a framework that can help to simplify the evaluation and selection of thousands of potential vehicle configurations.

4.1 BLOCK 1- LITERATURE REVIEW OF LOW CARBON TECHNOLOGIES

There exists a huge amount of technologies that claim to have a favourable impact on fuel savings. Some technologies seem to obey reasonable engineering principles while others inner workings were too secretive. Taking the fuel consumption reduction reported in the commercial literature at face value was an approach that the industrial sponsor was not willing to take. The reasoning to conduct a thorough literature review and a review of evidence was to find whether commercial claims were backed up by independent research findings published mainly in Journal papers and by Governmental and independent research organisations reports. Triangulating all sources it was possible to discriminate technologies whose benefits were just guaranteed by the manufacturer. From the data sources found, a higher weight was given to Baker et al. (2009a) and Hill et al. (2011) as their findings related to UK heavy duty vehicle fleets. This is important as the findings of the literature are geographically and operationally contextual. The fuel savings of technologies reported in the literature depend on vehicle regulations (e.g. shape, size, weight, legal speed, etc.), the particularities of the fleet (e.g. driving cycles, number of stops, etc.), testing standards (e.g. SAE, BSI) and weather conditions (e.g. rain, temperature, wind speed).

Literature reviews and market research have provided descriptions of low carbon technologies; their advantages (e.g. fuel savings) and disadvantages; purchasing and maintenance costs; risks associated to the different levels of technology maturity; engineering principles and potential incompatibilities with other vehicle technologies and subsystems. It was common to find the costs of technologies and sometimes some of these reports also included a payback period of different technology packages. As it will be described in 4.5.1.1 (Page 168) this approach presented several flaws.

The main challenge when evaluating the literature was appreciating the different testing methodological approaches of each study (e.g. simulations vs. bench tests vs. real world trials); the different fuel consumption testing standards (e.g. SAE J1321 vs. bespoke trials); the specific conditions under each test (e.g. weather); the types of vehicles (e.g. shapes, weight); and other information regarding the fuel used (e.g. blend of fuel might have a higher fossil content in winter than in summer which impacts on energy density and therefore fuel consumption). By applying Equation 2 (Page 33), it can be demonstrated that even small changes in any of the parameters can have a large impact on energy efficiency. Examples of these included vehicle weights, aerodynamic shapes, rolling resistance and speed road gradients. As a result, combining different sources is not a good approach unless there is certainty that all elements involved in the test are exactly the same. To avoid this flaw and to be consistent, the fuel consumption reduction of each technology and their costs comes mainly from Hill et al. (2011); a single data source; except for the results of the simulations and trials conducted in this research and the update of some technology prices than when projected into 2015 from the 2010 baseline were considerably inaccurate.

Simulating all technologies and conducting individual tests for each one of the possible cases is beyond the scope of this research. In consequence, only a few technologies have been simulated for a particular type of HGV to validate whether the results found in the literature were relevant to the industrial sponsor's operations. FCR studies focussing on US Class 8 trucks are not always representative of similar tonnage for N3 vehicles from the EU (see Table 4, page 40). The reason being, is the different directives regulating vehicle characteristics (e.g. length) and speeds; the latter affecting driving cycles.

4.1.1 TECHNOLOGY MATURITY AND SAFETY AND LIMITATIONS

The review of evidence has been helpful to evaluate the risks associated with each technology. The technological risk assessments are based on the methodology and findings of Baker et al. (2009a) for HGVs (Tables 26 and 27). This study evaluated low carbon technologies in the year 2010. As technologies evolve rather quickly, some of the risks have been updated according to the most recent market developments. This updated data were produced from a market research. For example technologies such as cryogenic refrigeration systems that were just being trialled in UK fleets in 2010 (level 6), by 2015 were commercially available (level 7). It was also interesting to find that technologies with first prototypes in

HGVs (level 4) had been withdrawn from the market by 2015, not having found commercial success.

Technology maturity is used here as a proxy for reliability. It is assumed that commercially available mature technologies are more reliable, while technologies that are in a developmental stage are likely to be less so. Reliability here is synonym for risk. It is assumed that being the first at trialling a technology is more risky than procuring the incumbent technology and therefore it is more likely that the technology may fail. In turn, this may affect on-time deliveries, leading to potential penalties, remediations and damages for the logistics operator.

Table 26. Level of risk related to the maturity of the technology (RITM). Adapted from Baker et al. (2009a).

RITM Level	Description
1	University Research Laboratory (Potentially extremely unreliable)
3	Technology Available but not in HGVs (Potentially very unreliable)
4	First Prototype in HGVs (Potentially unreliable)
6	In Fleet Trials (Moderately reliable)
7	First Entry into Market (up to one year). (Fairly reliable)
8	Technology in the market for more than 1 year and less than 2.
10	Predominant technology in market place (Very reliable)

The outcome of the technology risk assessment is integrated into the metaheuristic financial model (Block three) as a constraint that limits the technologies that can be chosen in the solution. The solution that minimises the net present costs is made of a number of low carbon technologies, each one with its own risk level. The technology maturity risk profile and the risk derived from its safety and limitations determine the overall risk profile of the solution of the quantitative metaheuristics model. The risk profile is the same as the risks level of the riskiest technology chosen. The reason for this, is that if there would be a breakdown, the whole vehicle would have to get serviced and this would compromise the vehicle availability. In this case, solutions with unsafe technologies (levels 1-4) are excluded in the metaheuristics model for obvious reasons.

The risk associated with safety and technology maturity is used mainly as a proxy for infrastructure deployment. All the technologies are safe and the differences regarding safety are very small, as safeguards are fitted on the vehicles, otherwise if there would safety concerns, the technologies would not be approved for vehicle use. Most technologies have a level 5-6, meaning that they are safe and either slightly more limited or with the same limitations as incumbent technologies.

Table 27. Level of risk associated with the safety of the technology and risks related to limitations (RISL) (e.g. poor infrastructure or service). Adapted from Baker et al. (2009a).

RISL Level	Description
1	Worst, do not use this technology (Very dangerous)
2	Several major safety issues need to be addressed / Several limitations restricted areas of application (Dangerous)
3	A few safety issues that need to be addressed / A few limitations restricting application areas (Slightly dangerous)
5	No new safety issues, but a few limitations (Somewhat limited)
6	No additional safety concerns or limitations with using this technology (Not Dangerous or limited)
7	No new safety issues, and fewer limitations / more advantages in using the new technology (Not Dangerous, Less limited)
9	More advantages than disadvantages, and it's safer
10	Best, this technology is much safer to use than the incumbent technology and has far fewer limitations

Each one of the solutions from the metaheuristics model has an associated risk profile. Depending on the aversion to risk and the relative importance of risk versus costs and GHG emissions the analytic hierarchy process (Block 4) yields the recommended vehicle specification. A stochastic risk analysis was considered initially. The idea was that by using Montecarlo simulation and including probability risk distributions into the model, this would reflect the risk of each technology accurately; however, as there was no detailed information regarding the quantitative impact that each risk would have, this approach was discarded. For example, if some LCT were being trialled, this would not mean that they would work; and even if they would deliver the fuel savings expected, it would not be possible to estimate their reliability as there would not be enough data available. In consequence, costing the impact of those risks quantitatively (e.g. breach of time windows due to vehicle breakdown) was not possible. It seems clear that to consider stochastic risks (e.g. via Montecarlo simulations) requires the availability of historical reliability data to define realistic risk curves. It is also important to have a clear understanding of the economic implications that each breakdown represents (e.g. cost of reparations, cost of out of service, costs of time windows, etc.), as well as evaluating supply chain risk (e.g. availability of parts). The stochastic cost analysis of risks, despite being an interesting aspect, was beyond the scope of this research.

4.1.2 DETERMINING TECHNOLOGY & FUEL COSTS

The prices of vehicles, trailers and conventional refrigeration units owned by MB were provided by company, as well as other costs such as refrigerant gases, red diesel and biodiesel prices. For consistency, as the FCR used in the metaheuristics model came from Hill et al. (2011), the costs of the technologies come from the same source; however, some amendments have been made for the technologies that were tested or added into the financial model and not existing or whose prices were considerably different to the 2010 baseline study (e.g. tyre pressure management system (TPMS), spray suppression mudflaps, 3 phase alternator refrigeration units, cryogenic refrigeration systems and insulation panels). The costs of those were updated according to manufacturers' and suppliers' personal communications. The costs of low carbon technologies in other geographical markets varied and as a result, the findings from this model are not immediately transferable to foreign markets. Costing information is abundant in the literature of energy efficient HGVs. The latest USA costs found were reported by Meszler et al. (2015), and include an exhaustive list of technologies. Information regarding maintenance costs were provided by the industrial sponsor and supplemented by list prices from HTC Theale, the company that services the industrial sponsor's fleet. The costs of some alternative refrigerant gases, cryogenic CO_2 and LIN were obtained from personalised communications from suppliers (e.g. Linde, BOC, and Carrier). Information regarding taxation was obtained from UK Governmental sources, this included the current vehicle excise duty from the DVLA (2013); valid from April 2015. Vehicle registration, road user levy and trade licenses, insurance costs, MOT costs were obtained from Lowe and Clive (2015) and UK Governmental sources. As the tractor units had 2 axles and trailers 3 axles, the cost of the MOT testing was £196 for each year (DVSA normal working hour's fees).

Fixed costs included vehicle excise duty (VED), tax, insurance and the net present cost of the vehicle and trailer leased. Variable costs included the running costs of fuel consumption, tyre wear and maintenance. Drivers' costs representing the cost for the employer were excluded from the model as they were considered irrelevant for determining optimal vehicle specifications. Some of the cost assumptions considered in the model are shown in Table 28. The costs were obtained from Hill et al. (2011) and updated to 2015 prices, with additional quotations provided by Continental (2015), Frigoblock UK Ltd (2013), Centre for Low Carbon Futures (2014), GKN Hybrid Power (2015), MarshallWeb (2015), Kevothermal (2015), Spraydown (2013), Spraydown (2015). As the model assumed that MB's vehicles were leased, capital fixed costs in fact represented operating expenses.

Historical road biodiesel prices were provided by the industrial sponsor; however. In the metaheuristics model fuel prices during the life span of the investment vary. As a result, three energy price scenarios for each strategy were analysed where DERV fuel prices (central forecast) were taken from projections made by DECC (2014e); a prediction that reaches up to 2035. For longer time horizon fuel prices in the USA, forecasts up to the year 2,100 are produced by Argonne National Laboratory (2010), albeit these prices might not be relevant in a European context.

Table 28. Purchasing Costs of different technologies.

Low Carbon Technology		Areas for improvement	Urban	Regional	Long Haul
Vehicle Technologies	Reduced Aerodynamic Resistance	Aerodynamic Trailers	£2,500	£3,000	£3,000
Vehicle Technologies	Reduced Aerodynamic Resistance	Aerodynamic Irregular body shape	£817	£817	£817
Vehicle Technologies	Reduced Aerodynamic Resistance	Aerodynamic Fairings	£1,096	£1,096	£1,096
Vehicle Technologies	Reduced Aerodynamic Resistance	Spray Reduction Mud Flaps	£129	£129	£172
Vehicle Technologies	Reduced Rolling Resistance	Low rolling resistance tyres	£325	£325	£325
Vehicle Technologies	Reduced Rolling Resistance	New generation wide-base single tyres	£766	£766	£1,207
Vehicle Technologies	Reduced Rolling Resistance	Automatic tyre pressure adjustment	£915	£915	£1225
Vehicle Technologies	Vehicle Mass	Lightweighting Materials (500kg)	£348	£348	£1,486
Vehicle Technologies	Intelligent VT	Predictive Cruise Control	£1,300	£1,300	£1,300
Vehicle Technologies	Auxiliary Systems	Controllable air compressor	£130	£130	£176
PowerTrain Technologies	Exhaust Heat Recovery	Heat Recovery (in general)	£10,742	£10,742	£10,742
PowerTrain Technologies	Exhaust Heat Recovery	Electrical Drive Turbocompound	£6,499	£6,499	£6,499
PowerTrain Technologies	Transmissions	Automated Manual Transmission	£3,250	£3,250	£4,379
PowerTrain Technologies	Mild Hybrid	Flywheels Hybrid	£6,891	£6,891	£6,891
PowerTrain Technologies	Mild Hybrid	Stop-Start: Electric Hybrid	£594	£594	£873
PowerTrain Technologies	Mild Hybrid	Pneumatic Booster - Air Hybrid	£743	£743	£743
PowerTrain Technologies	Alternative PT	Full Hybrid: Series / Parallel Electric	£20,672	£20,672	£20,672
PowerTrain Technologies	Alternative PT	Series / Parallel hydraulic	£12,256	£12,256	£12,256
Transport Refrigeration	Mechanical Refrigeration	Frigoblock 3 phase alternator Unit (HK)	£4,000	£5,000	£5,000
Transport Refrigeration	Mechanical Refrigeration	Hybrid Carrier MT-1850	£2,911	£2,911	£3,234
Transport Refrigeration	Mechanical Refrigeration	Lower GWP Gas (CO_2) TRU	£950	£975	£1,000
Transport Refrigeration	Non Mechanical Refrigeration	Cryogenic LIN	£2,330	£2,330	£2,330
Transport Refrigeration	Non Mechanical Refrigeration	Cryogenic CO_2	£500	£500	£500
Transport Refrigeration	Non Mechanical Refrigeration	Cryogenic Air	£270	£270	£270
Transport Refrigeration	Other	Vacuum Isolated Panels	£4,183	£6,754	£8,590

All historic prices and future projections based on different baselines have been updated to the year 2015 according to the UK central GDP forecast projected by DECC (2014e). When prices were in foreign currencies, they were converted to British Pounds (GBP) at an exchange rate of 0.86134 €/£ and 0.67112$/£ (exchange rate on the 5.7.2014).

4.2 BLOCK 2 – PRODUCING EMPIRICAL DATA

Block 2 includes the methodology applied to the simulations, field trials and waste-to-fuels pathways modelling. To produce the outputs of this block, the inputs of block 1 related to low carbon technologies had to be combined with the industrial sponsor datasets to produce more tailored results. Collecting operational data was used to evaluate the waste-to-fuel potential of their supply chain and the carbon intensity of each pathway. Having had access to the entrerprise resource planning software (ERP) and telematics systems of the industrial sponsor made the statistical analysis of such data possible. Information regarding loading factors was available in the routing and scheduling system (Paragon Routing). Information regarding distance travelled was also found in the routing and scheduling system; however, this information was finally collected from the telematics system as this reflected MB's trip distances. The analysis of some of the operational data was presented in Chapter 2 (Table 2) and it was the result of the analysis of two years' worth of daily freight movements. The sample was filtered by eliminating all trips with a travelling distance shorter than 10 km, as these trips were considered to be movements around the yard. Also, all the trips that showed a fuel consumption lower than 15 l/100km or higher than 50 l/100km or lower than 20 l/100km or higher than 55 l/100 km for rigid lorries and semi-articulated vehicles respectively, were not included in the statistical analysis, as these were assumed to be telematics reading errors. To calculate averages, the aggregated sum of the value measured was divided among the sample number. The descriptive statistics were conducted with SPSS 20. Information regarding the driving cycles' analysis methodology is presented in Section 4.2.1.2 (simulation of driving Style).

4.2.1 SIMULATION OF VEHICLES

Simulations were conducted to quantify the fuel consumption reduction benefits of various vehicle technologies (aerodynamic fairings, spray suppression mudflaps, lightweight materials and speed limiters) and a refuelling strategy (filling the fuel tank with the minimum amount of fuel possible for each trip). This made possible the verification that the results found in the academic and commercial literature were relevant to the industrial sponsor's operations and its vehicles.

The simulator (IPG Truckmaker) registers hundreds of engineering variables (e.g. power, lateral dynamics; rolling resistance, etc.). However, for the purpose of this research, only fuel consumption, travelling time and distance were relevant. As environmental variables and driving behaviour can be controlled in a simulator, the difference between the fuel consumption of the control and test vehicles was attributed to the low carbon technology or strategy tested. The reason for choosing IPG Truckmaker were multiple: i) a free license was provided. ii) baseline vehicles were available and building bespoke HGV models did not require programming skills iii) it could import 3D roads. iv) it produced high quality 3D graphics; v) It accepted external libraries and specialised software such as AVL Cruise and Matlab; vi) the software was independently validated by many vehicle manufacturers and accepted in the EU for ADAS vehicle type approval. Other software packages (see Table 25, pages 112-114) were also evaluated and they seemed less powerful and less easy to use.

Due to financial constraints in the funding of this research and the time limitation of a doctorate degree, simulations were a best approach to test these technologies more economically and faster than conducting live trials. As mentioned in the literature review, governments around the world are developing simulation systems (e.g. VECTO, GEM) for vehicle type approval, which could be used in the near future to calculate the GHG emissions from low carbon technologies fitted in HGVs. A commercial software tool was used to conduct these simulations (IPG Truckmaker). IPG Truckmaker is fully compliant with ECE 13-H; an standard for vehicle homologation that allows the use of dynamics simulation software (UNECE, 2014). This means that calibrating the IPG Truckmaker simulation system while conducting this research was not needed, as this had been privately validated by the software developer (Glide, 2015) and used by many vehicle manufacturers for homologation purposes, including Daimler Trucks since 2011 (Wüst and Lutz, 2012). The accuracy of different simulators appears in Figure 66 (page 107) and this shows that results, despite not being 100% accurate, are in line with what would be expected in a real world trial following SAE J1321. This indicates that the use of simulators is an appropriate methodology for calculating GHG emissions (National Research Council, 2010). The methodology of the simulation of HGVs required three main elements: a virtual vehicle; a duty cycle (represented by driving behaviour and a driving cycle); and a digital road. The methodology followed for simulating HGVs is presented in Figure 72.

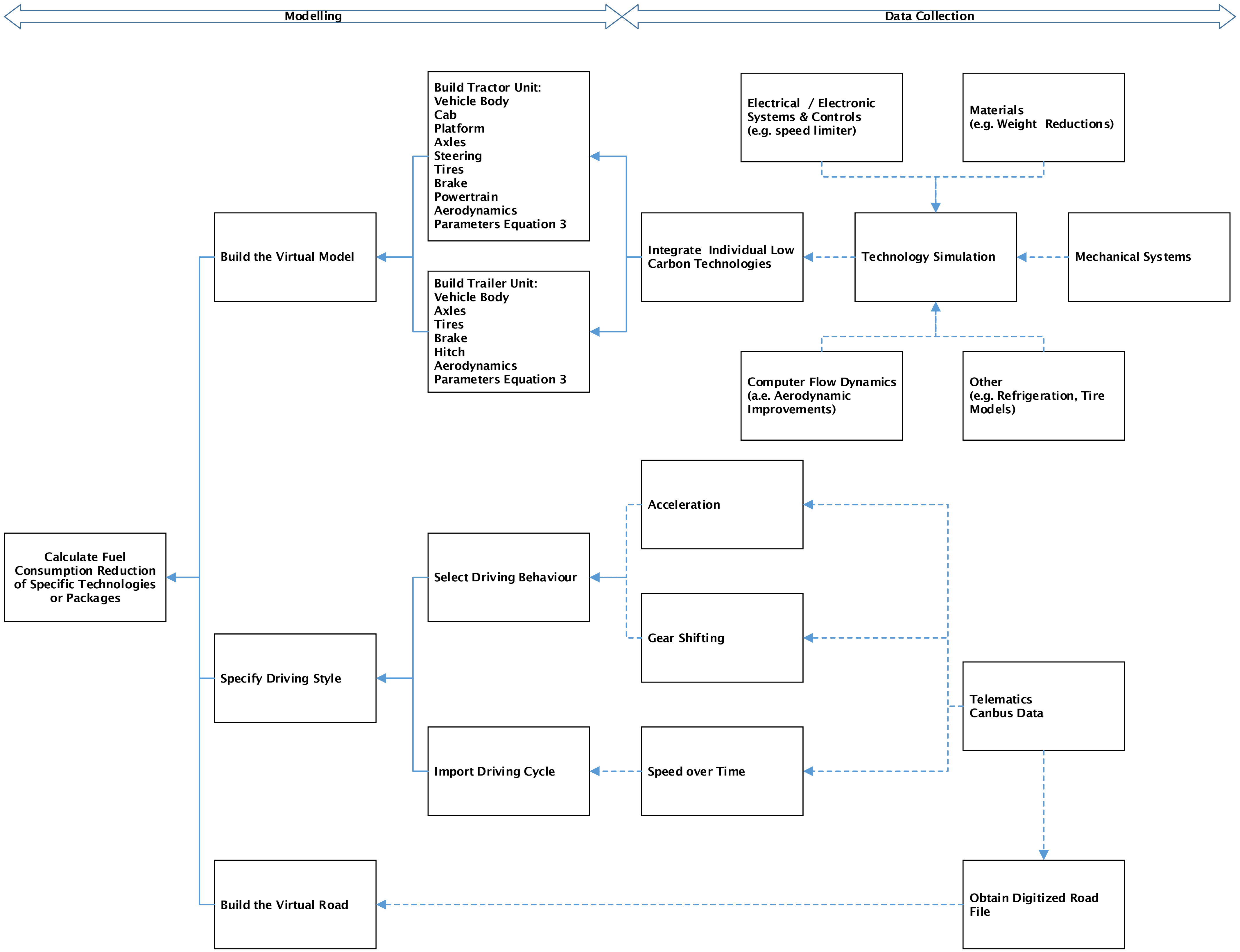


Figure 72. Research Methodology for the simulation of vehicles.

The simulation of the fuel consumption reduction of each low carbon technology add-on (and strategy) consisted of two runs for each scenario. In the first run, a control baseline HGV with no improvements was virtually sent from the distribution centre in Basingstoke to Bristol and also to Penzance (Cornwall). In the second run, a test vehicle with a technological improvement add-on replicates the same route. The difference in the fuel consumption between the control (baseline) and test (the one with the add-on) vehicles was attributed to the specific technology tested.

From the telematics data, it was possible to build the virtual roads by converting the GPS values into a Google Maps KML file, a format that can be read by the simulator. Using Google Maps did not allow the proper representation of roundabouts which lead to vehicles exiting the road due to their turning angle. As a result, the intended final outcome of representing truthfully a 3D road from Basingstoke to Bristol and another from Basingstoke to Penzance (both being real routes of the industrial sponsor) was not achieved accurately. If more resources would have been available, instead of using Google Maps to build digital roads, high resolution commercial digitized roads such as the ones produced by NAVTEQ, Nokia Here or TÜV (3D-Track) would have been a better alternative to represent the fuel consumption reductions of vehicles on each route.

To simulate the effect of a speed limitation device, the maximum cruising speed of the vehicle was limited. This means that regardless the real driving cycles extracted from the telematics datasets, the vehicles' speeds in the simulated trips did not exceed a set-up value. As the destination point has to be reached anyway, travelling time increased with lower maximum speeds.

Another experiment consisted of simulating light weighting materials. This was done by reducing the tractor unit mass by 500 kg, as a 10% weight reduction of the tractor units appears often in the literature for urban, regional and long-haul HGVs (Cooper et al., 2009, Hill et al., 2011) . This requires a reduction of the value on the 'Mass [kg]" parameter in the vehicle body tab in IPG Truckmaker. Unloading the vehicle load required a script such as the one that appears in Table 29. In this example, after 4 hrs., the load of the trailer is equal to zero. This is illustrated on the upper right corner of Figure 73, where the green line (speed) drops after 14,400 seconds to zero, to represent a half an hour stop to unload the cargo.

Table 29. Script that simulates the unloading of freight after a given period of time.

Eval Time>=14400 ? Tr.Load.0.mass=0

A refuelling strategy was also tested. The idea was to see whether filling the tank with just the amount of fuel needed for each single trip would have a significant impact on the vehicle fuel consumption, due to a lower tractor unit mass. To simulate the impact of filling the tank at different levels, the tractor weight was decreased according to the amount of fuel contained. With a script, the weight of the fuel tank was updated dynamically (Table 30). In this particular experiment, the weight of a full 400 litre fuel tank (332.8 kg) is updated according to the fuel remaining in the tank as a result of the fuel level minus the absolute instantaneous fuel consumption. This could potentially yield some fuel savings as it will be shown in the results chapter (Section 5.1.2.1, page 194).

Table 30. Script to replicate the change fuel tank mass according to fuel consumed.

val Qu::fuellevel=400	; Fuel level in L
Eval fuellevel=(fuellevel-PT.Engine.Consump_Abs)	; Fuel available
Eval Car.Load.0.mass=(fuellevel * 0.832)	; Updated fuel tank mass

4.2.1.1 VIRTUAL VEHICLE MODEL

Simulations of HGVs were produced based on a semi-articulated DAF CF-85 virtual vehicle unit built with parameters obtained from the commercial literature and some vehicle characteristics found by default in an IPG Truckmaker for 4x2 Mercedes model. An illustration of the IPG simulation desktop environment appears in Figure 73. The detailed parameterisation of the tractor and trailer units used by the live case study appears in Appendix 7, respectively. The reason for simulating a DAF truck was because this was the preferred brand of the industrial sponsor and DAF has the biggest market share, representing slightly over a quarter of newly registered HGVs over 6 tonnes in the 12 months to February 2015 (SMMT, 2015).

Figure 73. Desktop environment for IPG Truckmaker.

4.2.1.2 DRIVING STYLE

Driving style is represented by the driving behaviour and the driving cycle (the green line Figure 73). A driving cycle represents vehicle speed as a function of time and when its characteristics are captured, it is possible to conduct emissions tests under reproducible conditions (Barlow et al., 2009). The driving cycle was replicated from data obtained from the vehicles' engine's control unit (ECU) as captured by the telematics systems fitted on the industrial sponsor fleet. The driving behaviour, however, represents the harshness of accelerations/decelerations of the driver and the speed at which s/he drives. Driving style was simulated in IPG Truckmaker according to the parameters illustrated in Figure 74. The g-g diagram represents the aggressiveness in driving style, determined by the longitudinal and lateral acceleration of a vehicle (Vaiana et al., 2014) , where good driving falls within the inner area; in this case. The g-g diagram (the red polygon in Figure 74) represents a non-aggressive driver compared with the distribution points reported by Vaiana et al. (2014) in Figure 75. The statistical analysis of driving cycles, revealed that the maximum acceleration was 1.38 m/s^2 and the maximum braking 3.8 m/s^2. It made sense to parameterise the driver style within the limits (this values appear in ft. /s/s in Appendix 8 at 4.55 ft. /s/s for acceleration and -12.55 ft. /s/s for deceleration).

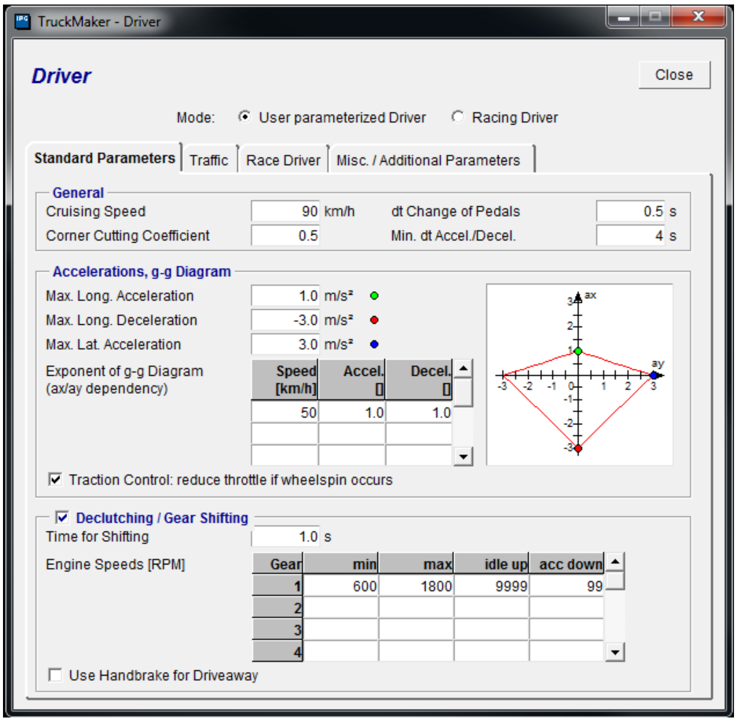


Figure 74. Driver behaviour section in IPG Truckmaker.

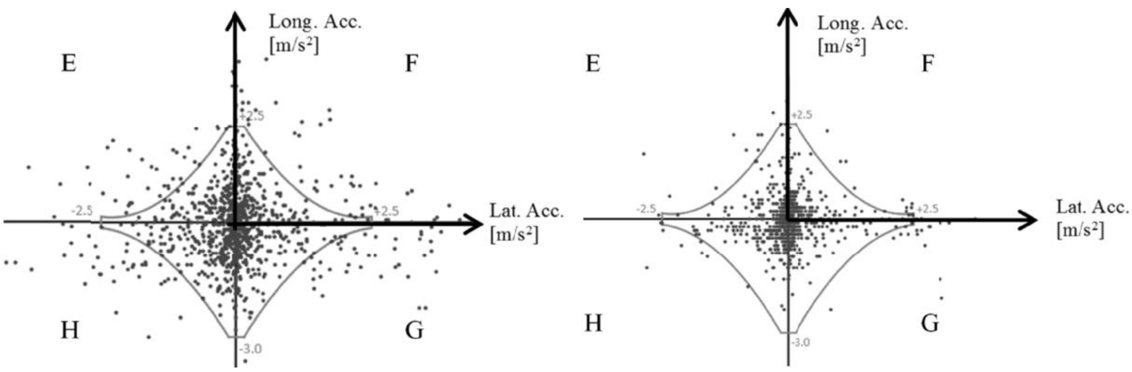


Figure 75. Distribution points within a g-g diagram for an aggressive driver (left) and a non-aggressive one (right). Source: Vaiana et al. (2014).

Building a statistically representative driving cycle for a whole fleet requires the processing of large datasets with the individual vehicles' driving cycles over a long period of time. To illustrate this complexity, Figure 76 shows the driving cycles (speed over time graphics) for the trips conducted by one single vehicle from 21st April 2013 to 1st May 2013. From the observation, little can be concluded and for this reason, creating a statistical representative driving cycle and analysing its characteristics was of great help to parameterise driving style. This process is also important, as the resulting cycle can be used as an input in the vehicle simulator, but also in a dynamometer or in a real road test-truck, helping to improve the reproducibility of experiments, tests and trials.

Data to build an individual driving cycle can typically be collected from the ECU of a vehicle, its telematics unit or directly from a GPS device. If the vehicle speed, acceleration and distance are derived from the raw GPS signal, then data must be filtered and corrected to eliminate spurious readings. As stated by Duran and Earleywine (2012) these errors can occur due to signal loss, outlier data points, speed drifting and white noise in the signal. The reliability of the data was improved with DRIVE; a tool developed by NREL capable of producing representative, testable custom drive cycles from large real-world datasets of vehicles telematics data based on GPS signal values (Duran, 2013). This is a very useful tool to create statistically representative driving cycles for a logistics company. In Figure 76, the driving cycles of a single vehicle for 8 days are illustrated in a single graphic. This Figure shows that evaluating driving cycles visually is not intuitive at all.

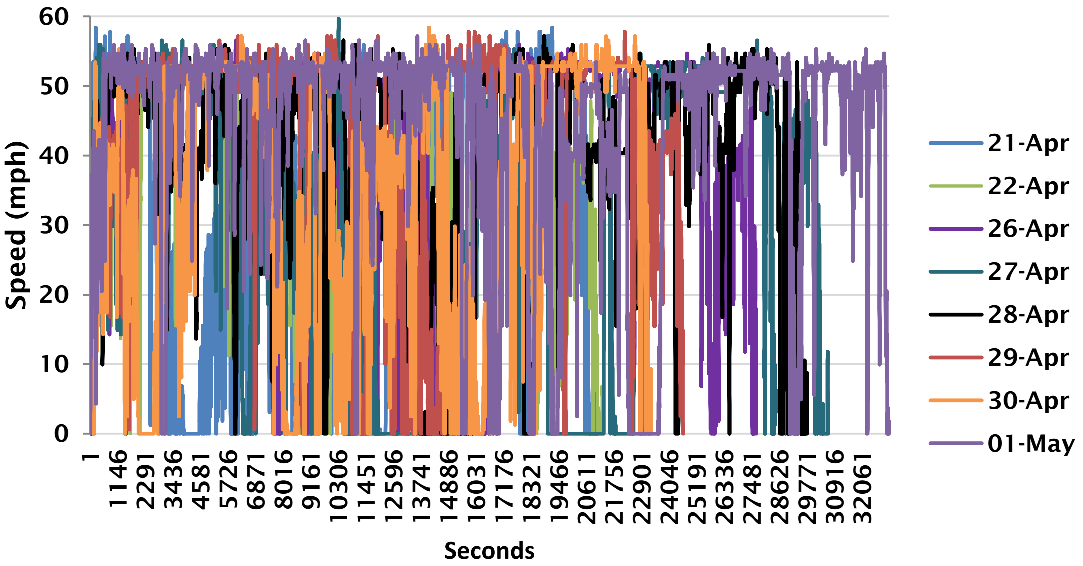


Figure 76. Driving cycles for one single DAF CF85 from 21st April to 1st May 2013.

Analysing driving cycles required the collection and analysis of dynamic data. Dynamic analysis refers to the use of instrumenting software products to monitor and collect data (Wieringa and Heerkens, 2007). Each HGV included a Mix Telematics FM 3306/3316 unit that can capture readings at 1 Hz (1 reading per second). However, the supplier does not offer to the industrial sponsor this service for two main reasons: 1) capturing so much data is expensive, as the data is sent via GPRS to a server; ii) for geofencing, geolocation and the typical driving behaviour analysis conducted with the telematics systems by MB, such level of detail is completely unnecessary. The ECU follows the SAE J1939 Fleet Management System (FMS) standard (equivalent to the European ISO 11898) and it is connected to the telematics unit via a CAN gateway. The J1939 protocol is accepted by all EU truck manufacturers (European Automobile Manufacturers Association, 2012) and registers vehicle parameters that are meaningful when evaluating fuel consumption.

The parameters that are available include among other values; time, date, GPS coordinates, speed, rpm of the engine, clutch engaged, cruise control speed and exhaust brake; some of these and their characteristics appear in Table 31. The information available is captured from the ECU by the telematics system and transmitted by GPRS to a server (Web Services Portal). The server can be interrogated from a desktop to request the data using an API or client following the SOAP 1.1 or SOAP 1.2 protocols (Simple Object Access Protocol). This is a protocol for the exchange of information through Web Services and it relies on XML information Set and HTTP or SMTP protocols for message negotiation and transmission. This information can be analysed in a later stage with statistical software (e.g. DRIVE or any other similar commercial or bespoke tool).

From the telematics data, it was difficult to infer the number of deliveries and stops done as a result of the European Working Time Directive. Vehicle weight has a significant impact on fuel consumption and just by looking at the telematics it was impossible to infer the weight of the freight unloaded at each delivery point. This information was obtained from the routing and scheduling software (Paragon Routing). When conducting live trials this can also be controlled via visual observations. Paragon was used to calculate the average number of delivery stops and to obtain the weight unloaded in these.

The telematics systems used by the fleet of the industrial sponsor reads trip data of the vehicles (e.g. coordinates, speed) and engine parameters (e.g. RPM) at irregular intervals; often triggered by alarms (e.g. events of harsh acceleration). Producing datasets that can be used by the simulation system and with enough granularity to allow meaningful statistical analyses required regular and frequent readings (e.g. one reading per second). As the telematics service 's supplier was unable to provide the ECU data at the frequency of 1 Hz, a system was developed to connect directly to the ECU (Figure 77). With this system it was possible to visualise vehicle data in real time with an iPad, storing this data and send this via email as a file for further statistical analyses . The interface components of the telematics data capture system included a power supply (A) to convert the 24VDC of can-bus to the 12VDC needed by the OBD2 transmitter (E); fuses (B) to avoid damaging the OBD2 circuit; a resistor (C) to improve the quality of the signal (if needed); an OBD2 connector (D); an OBD2 to Wi-Fi device to capture and transmit data to an IOS device (an iPad in this case); and a 12 pin FMS connector (F) that connected to the can-bus network of the vehicle. As a redundancy safety measure, a datalogger was connected to the connector (F) to store data.

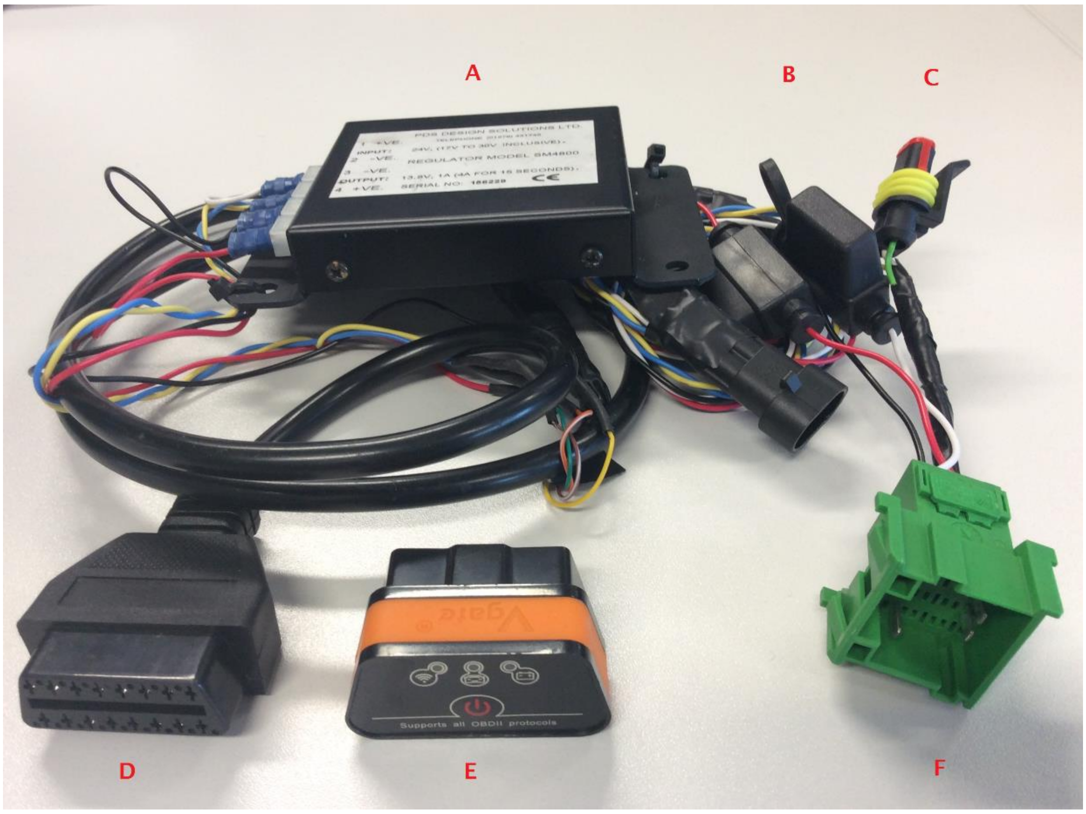


Figure 77. Telematics can-bus data capture system developed for this research.

4.2.1.3 SIMULATION OF AERODYNAMIC TECHNOLOGIES

To simulate the aerodynamic improvement of aerodynamic cab roof fairings, tractor mounted gap reduction and turning vanes a different technique was used. Instead of simulating the whole vehicle subsystems, with computer flow dynamics it was possible to focus just on the shape of the vehicle.

A different simulation technique was used to assess the aerodynamic coefficient obtained by a baseline vehicle and by a test vehicle. This was calculated using computational fluid dynamics (CFD). A semi-articulated DAF CF-85 obtained from DAF Bodybuilder Information Plus (DAF Trucks, 2015) with and without aerodynamic cab roof fairings, tractor mounted gap reduction and turning vanes was analysed. A tractor and trailer were modelled in 3D from DAF drawings and exported to a format compatible with Autodesk Flow Design. The modelling of aerodynamic drag is complex and despite the fact that CFD simulations can assist in this task, wind tunnel testing is a far more accurate approach. Wind tunnels are typically small and scaled models need to be produced to fit in them.

Table 31. Relevant parameters and reading frequencies transmitted by truck systems via CAN (SAE J1939 / ISO11898 compliant). Adapted from: European Automobile Manufacturers Association (2012) and DAF Trucks (2012).

Parameter Group Number (PGN)	Subject Parameter Number (SPN)	Name of the Signal	Repetition rate in ms.	Comments	Further Comments
65257	250	Engine total fuel used	1000	4 bytes, 0 to 2 105 540 607,5 L	Might be set to “not available” if SPN 5054 is available
65276	96	fuel level 1	1000	1 Byte	
61444	513	Actual Engine – Percent Torque	20	1 % / Bit, -125 % offset	
61444	190	engine speed	20	2 Byte, 0-8031,875 rpm	
65217	917	High resolution total vehicle distance	1000	4 bytes, 0 - 21 55 406 km; without TCO	
65132	1624	Tachograph vehicle speed	20/50	With digital tachograph	rep. rate tacho dependant
65262	110	engine coolant temperature	1000	-40° to 210°	
65269	171	Ambient Air Temperature	1000	0.03125 °C / Bit gain	
	182	Engine trip fuel	1000	0,5L/bit	
65266	183	Engine Fuel rate	100	0.05 L/h per bit, 0 to 3212.75 L/h	Calculated values given as indications, not as contractual
65266	184	Engine Instantaneous Fuel Economy	100	1/512 km/L per bit, 0 to 125,5 km/L	Calculated values given as indications, not as contractual
64777	5054	High resolution engine total fuel used	1000	0.001 L/bit, 0 to 4211081.215 L	Is implemented if technical possible
61443	91	accelerator pedal position 1	50	1 Byte	1 Byte
61443	92	Engine Percent Load At Current Speed	50	1 % / bit, 0 to 125 % operational range	1 % / bit, 0 to 125 % operational range

National Research Council (2014) suggests that wind tunnel and CFD can reduce the cost of development of aerodynamic technologies, as fewer prototypes may be needed and development time can be shorten. In spite of this, real world tests are more representative of individual fleets; however, repeatability and accuracy is a handicap. The outcome of either of these processes produces an aerodynamic coefficient (C_D) for the tractor-trailer combination that can be used in a simulator to calculate the fuel savings achievable from aerodynamically designed improvements.

4.3 BLOCK 2 - LIVE TRIAL

After the literature review, spray suppression mudflaps were identified as the lowest cost technologies and they seem to present an excellent return on their investment. The industrial sponsor had fitted a few of these in some vehicles; however, there was no evidence backing up the fuel savings claimed by the supplier. The opportunity of undertaking a real-world trial presented itself in association with Martin Brower UK Ltd who provided vehicles and drivers. The fuel consumption reduction of spray suppression mud-flaps was tested following the SAE J1321 Type II standard. Comprehensive details of this standard are described by SAE (2012). The methodology consisted in measuring the fuel consumption of two identical vehicles (a control and a test vehicle) for a minimum of 3 runs between origin and destination (in day one). During the second day of the trial, the test vehicle was fitted with a low carbon technology (a patented spray suppression mudflap) and both, control and test HGVs were asked to do another 3 runs. The statistical analysis revealed whether the technology tested delivered any fuel consumption reduction (FCR). Instructions regarding how the live trial was run appears in Appendix 9. Details of the data collected during the trial appear in Appendix 10 (forms D0, D1 parts 1 to 3, D2, D3, D4 parts 1 to 4, D5 and D6)

Real world trials can give the most accurate prediction of the fuel consumption reduction of low carbon technologies, as these can reproduce the real conditions in which the fleet operate. However, trials are prone to the influence of many environmental and human variables. To minimise these distortions, and provide statistically significant results, SAE developed the SAE J1321 Type II standard. This standard is a fuel-consumption test procedure that uses accepted data collection and analysis methods to calculate fuel consumption changes in trucks (and buses) over 4.5 tonnes (10,000 pounds) and it can be undertaken on public roads (SAE, 2012).

The standard defines identical vehicles as '… having the same; external surface contours (preferably the same make, model and year), tyres and wheels (preferably the same type, condition, mileage and same tyre model per tyre position) aerodynamic configuration, power-train, and are in the same operational and physical condition.' Including same load and cargo weight distribution. In this trial, both vehicles were nearly identical with fairly similar mileage. Details of the vehicles appear in Appendix 10 form D1 parts 1 and 2.

To measure all environmental conditions, a weather station was installed in the location where the test was managed (Theale, UK); details of this weather station and other measurement devices appear in Appendix 10 – Form D1 – Part 3. Readings of an intermediate location were taken from BBC Weather. To be able to publish a low carbon technology trial as SAE J1321 compliant, weather conditions must be similar between each day of the trial, between each run and between segments of each run. One of the main constraints is that trials must be conducted in dry conditions; other constraints appear in Table 32. The reason for this, is that wind and rain have a huge impact of the vehicles' fuel consumption and if these impacts are not controlled, the trial could lead to wrong conclusions.

Table 32. Environmental Constraints of SAE J1321. Adapted from SAE (2012).

Wind Data	Mean Wind Speed	Min Wind Speed	Max Wind Speed	Variation in Run Wind Speed	Variation in Segment Wind Speed	Variation in Test Wind Speed
Constraint (kph)	19.3	-	24.14	8	8	8
Temperature Data		Min Temp.	Max Temp.	Variation in Run Temp.	Variation in Segment Temp.	Variation in Test Temp.
Constraint (˚C)		4.44	37.77	1.11	1.11	1.11

Two skilled drivers with many years of experience were suggested by the industrial sponsor due to their excellent driving performance. Both were briefed regarding the objectives of the trial and they were requested to follow a range of rules, as specified in the SAE J1321. The aim of both professionals was driving as similarly as possible to reduce the influence of drivers' style during the trials. This is very difficult to achieve as reported by Cherrett and Pitfield (2001). Both drivers were interviewed after each run and their comments were noted to account for any detail that could have affected fuel consumption. The comments appear in Appendix 10 – Form D3. Unfortunately, the human factor had a negative impact as one of the drivers did not check the water level and had to do a quick emergency stop to refuel the water tank and both drivers accessed the motorway differently. The latter did not have a material impact as the statistical analysis of the fuel consumption of the vehicles is based on the differences of variances and as they followed the same route each time, the differences remained consistent.

The experiment comprised two phases. The first phase (calibration) consisted of three "calibration runs" of 163 km each (101 miles), with 2 identical vehicles running simultaneously and at a distance of no less than 800 feet (243.8 m) to minimize traffic interference between both vehicles. The first round of trips took place on the 25th September 2014 between Theale (RG7 4AG) and exit 17 from the M4 in Stanton St. Quintin (Post code SN14). The second day of the trial (30th November 2014) consisted of another 3 runs over the same route (Figure 78) and with the same vehicles; however, the test vehicle fitted "Spraydown" spray suppression mudflaps in the tractor and trailer, instead of the standard mudflaps. In total 1,956 km were run for this trial. The reason for choosing Theale as origin of the trial was logistical. The company that services the industrial sponsor fleet is located in Theale. This company's assistance was necessary to access some of the encrypted parameters of the vehicle that are required by the SAE J1321 standard; to meet the tight deadlines in regards to time between runs due to the amount of readings that had to be taken; and to unplug the fuel tanks and position them on top of the scales. This location was also convenient because it was relatively close to Martin Brower's distribution centre in Basingstoke and there was a large scale nearby that made possible to weigh the vehicles before starting the runs. The destination point was chosen because the SAE J1321 standard required a minimum distance of 100 kms for each run and St. Quintin was on the M4 motorway, a route followed by the industrial sponsor fleet when they go from Basingstoke to Bristol.

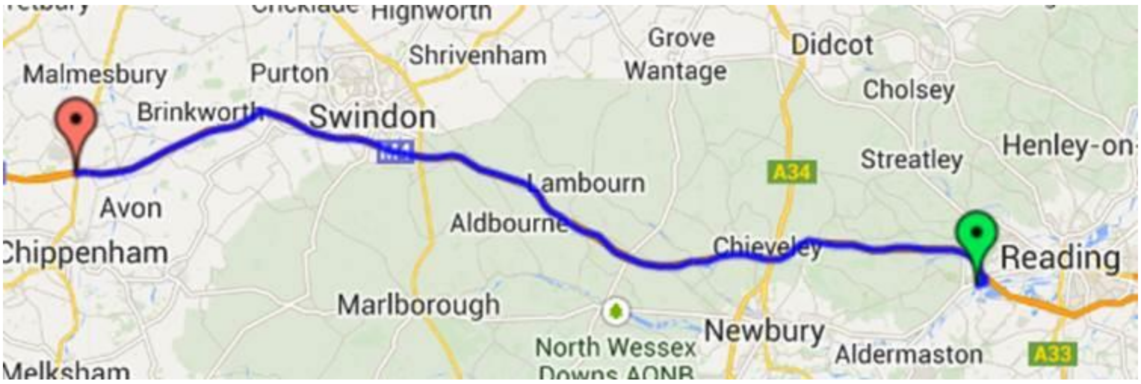


Figure 78. Route where the trials took place. From Theale to Chippenham.

SAE J1321 requires that in each run, the driving cycle of both vehicles must be the same and therefore, the difference in time between both vehicles to complete each run must be less than 0.5% of the longest run time for the first trip. For example, if the control vehicle took 2 h to complete the first run, the test vehicle had to complete its run within 36 s of difference. Time for each vehicle to complete all subsequent runs in the baseline segment were stricter and had to be within ±0.25% of the time (~18 seconds). Unfortunately, this was impossible to achieve on public roads due to congestion and weather variability.

The Control and Test Vehicles were fuelled from the same fuel dispenser during the entire trial to insure consistent fuel grade and quality. Before starting the trips on each phase, both vehicles circulated for 1 hour to warm up. Before departing, a series of vehicle maintenance checks and ECU readings were taken as established in SAE J1321. As a number of the parameters from the DAF ECU were encrypted, a DAF console 'Davie' was used to read them, as other can bus devices could not do so. Parameter readings were taken at the warm-up stage, between runs and at the end of the test day. These parameters included: oil pressure and leaks; brake air system leaks; coolant temperature and leaks, exhaust gas temperature; engine air filter restriction, electrical load, tyre pressures; brake dragging (i.e. temperature); exhaust smoke; observed ability to maintain selected test speed; transmission or differential leaks; intake manifold pressure (turbocharger boost) and other intake system losses; number and duration of DPF (Diesel Particulate Filter) regeneration events. During the trials no regeneration took place. After each run all vehicle diagnostic messages and warning signals were investigated and none of them represented a cause of concern.

To follow SAE J1321 strictly, the maximum time between runs should have been 30 minutes. If the 30 minutes window was exceeded, the vehicles had to be put through a warm up process. This happened often as the tasks required were too time consuming for the amount of people allocated to this trial and technical resources available in the workshop. However, the warm up was not executed as it would have made unfeasible to conduct each trial in a single day.

After arrival, two vehicles were weighed on a full vehicle scale and after arriving to the departure location, an engineer assisted with mechanical checks, measurements and adjustments to ensure that the cold tyre pressure of all wheels of each vehicle was inflated to vehicle or tyre manufacturer standard within a tolerance of ±1 psi (6,895 Pa). Furthermore, the fuel tank of each tractor unit had to be detached, weighed and re-installed (Figure 79).

The tank was positioned on top of a scale and its mass was weighed. Diagnostic messages and parameters also had to be read from the ECU and as the service shop had only 1 console, the second vehicle had to wait. This led to a departure that exceeded 30 minutes in the first run for the control vehicle and even longer for the test vehicle. In consequent runs, time slightly improved; however, with just only two people available to do all the work, it was impossible to meet the time constraints. Also, it is relevant to be aware that in an on-road trial, drivers are still subject to the working time directive and in one particular occasion, the break of the driver coincided with the departure time and further delays were unavoidable.

Figure 79. Detachment of fuel tank for gravimetric fuel consumption measurement during the spray suppression fuel reduction trial.

After each run, a range of vehicle parameters had to be read again and a new gravimetric measurement of the fuel weight had to be taken to calculate the fuel consumed of each trip. This was the most adequate approach to measure fuel consumption as the standard expressly prohibits taking readings of fuel consumption from the ECU. This is because can-bus data has a very low accuracy. Using very high resolution flow meters was beyond the budget available in this research and the accuracy of most of these is rather limited (error of $\pm$1%). The degree of error was found to be of the same magnitude as the fuel savings that spray suppressions were expected to yield. Weighing the fuel tanks before and after each run gave the fuel consumption in kg and this was converted into litres after measuring the fuel density each day. Information regarding the fuel consumption of each run appears in the results section.

The vehicle fuel consumption was statistically analysed to ascertain that the fuel consumption reduction achieved by the low carbon technology being tested (specially designed spray suppression mudflaps) was statistically significant. The methodology followed by SAE J1321 is based on f-test for equality of variances to choose the adequate F-test for difference in means. When the variances are equal the t-test for equality of variances shows whether the differences in fuel consumption between control and test vehicle are statistically significant. When variances are not equal, a t-test for inequality of variances indicates if the differences are significant. According to SAE (2012), 'the confidence interval value is determined from the variation (scatter) in the measured fuel consumption data, relative to the nominal value, and the number of data values obtained'. A confidence interval is a range (± value) around the nominal value that indicates the accuracy of the nominal value and its reliability (SAE, 2012). The outcome of such an analysis is shown in section 5.2 (Page 201).

In addition to verifying the FCR achievable by the low carbon technology tested, data was captured with dataloggers installed in both vehicles (Figure 80) with the aim of using this data to build driving cycles and using these for future simulations, avoiding the need to reproduce an on-road real world trial.

Figure 80. Connection of the datalogger used to the vehicle ECU.

4.4 BLOCK 2 - CARBON FOOTPRINTING WASTE-TO-FUEL PATHWAYS

Virtually, all UK HGV fleets run on diesel because the thermal efficiency of diesel engines is higher than petrol ones. Beyond these efficiency limits, further GHG emissions savings from powertrains can only be achieved by decarbonising fuels. As these vehicles can run on biodiesel as well, there is still scope for reducing carbon emissions in conventional HGVs. Low carbon fuel technologies (emanating from the literature review) are key to reduce the carbon footprint of logistics fleets, as electric powertrains seem to be a long way off.

The carbon footprinting methodology followed is based on a case study on quick service restaurants (QSRs) serviced by Martin Brower UK Ltd. The sponsor's fleet currently run on biodiesel produced from used cooking oil collected from its customer's kitchens. Discussions with the sponsor highlighted a knowledge gap in regards to the emission factors of the current waste-to-fuel pathway as well as about the amount of fuel that could be produced from different waste feedstocks. The GHG emission factor for the blend of biofuel used by the industrial sponsor's supply chain is one of the inputs used in the quantitative model, especially relevant when the objective function seeks to minimise carbon emissions. This is also fundamental to evaluate scenarios where the price of carbon is considered. Understanding the range of fuels that could be produced by waste and their carbon intensitites, offered the opportunity to the industrial sponsor of considering the environmental performance of other alternative fuel technologies (e.g. biomethane, bioDME) for future vehicle purchases; evaluating fuel savings and the impact on non-renewable fuel demand.

The methodology for measuring the carbon emission factors of waste-to-fuel pathways as well as the quantification of how much was available for its use on MB's fleet was based on a substantial database of waste collection movements from a major global fast food chain, comprising 34 months of separated waste collections from January 2012 to October 2014 from more than 1,000 British QSRs and their associated DCs. With the study of such flows, vehicle powertrain technologies and the research of EU waste-to-fuel infrastructure, realistic pathways were identified (Table 33).

The potential yields for each pathway as found in the literature (Table 33) along with the analysis of the waste collection data, were used to produce an annual waste profile for each restaurant. This waste profile was then extrapolated to the total number of British QSRs (39,762) providing an estimate of the waste-to-fuel potential across the whole sector.

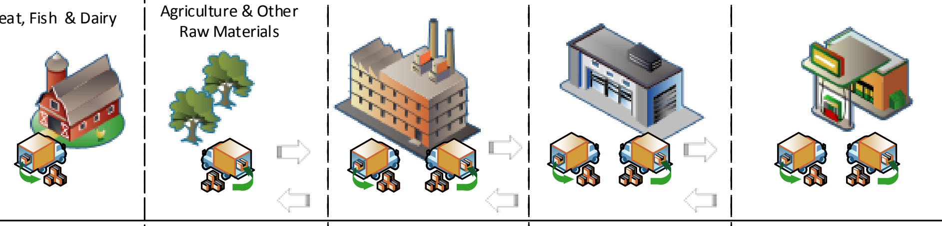
4.4.1 WASTE STREAMS EMANATING FROM QSRS

An analysis of the case study organisation showed the main waste types at different stages of their supply chain (Figure 81). The wastes that the FFSC can convert into usable fuels for transportation were classified into three main categories: organic waste, non-organic waste and water effluent. Organic waste includes animal losses and manure, damaged vegetables, by-products of processing and rendering such as tallow, oil seed cake, bone meal as well as out of date food from DCs and food wastage from restaurants. UCO and fat from cooked burgers and ligno-cellulosic wastes are also included in this category.

Table 33. Energy yields from different pathways. Assuming that ρ of methane is 726.3 kg/m^3 and conventional diesel ρ=839.6 kg/m^3.

Pathway Code	Waste Feedstock	Fuel	Conversion Factors	Conversion (weight / w)	Reference
WOFA3a	Used Cooking Oil	FAME (biodiesel 1st generation)	0.96 tonnes (output)/tonnes (input) refining 0.947 tonnes (output)/tonnes (input) transesterification	90.91 %	E4Tech and Concepto (2013) *
WOHY1a	Used Cooking Oil	HVO (biodiesel 2nd generation)	0.405 tonnes (output)/tonnes (input) refining 0.791 tonnes (output)/tonnes (input) hydrogenation	32.04 %	E4Tech and Concepto (2013 *
WOCG1	Used Vegetable Oil	Bio-Methane	0.6485 m^3/kg VS added	47.10 %	Labatut et al. (2011)*
	Waste Edible Oil		1.104 m^3/kg VS added	80.18 %	Braun et al. (2003)*
TOFA3	Burger fat (Tallow)	FAME (biodiesel 1st generation)	0.96 tonnes (output)/tonnes (input) refining 0.947 tonnes (output)/tonnes (input) transesterification	90.91 %	E4Tech and Concepto (2013) *
TOHY1a	Burger fat (Tallow)	HVO (biodiesel 2nd generation)	0.405 tonnes (output)/tonnes (input) refining 0.791 tonnes (output)/tonnes (input) hydrogenation	32.04 %	E4Tech and Concepto (2013) *
TACG1	Animal fat (Tallow)	Bio- Methane	1.0 m^3/kg VS added	72.63 %	Braun et al. (2003)*
FFCG1	Fast Food Waste	Bio- Methane	0.693 m^3/kg VS added	50.33 %	Braun et al. (2003)*
			0.473 m^3/kg VS added (pasteurised sample)	34.35 %	Banks and Zhang (2010)*
CACG1	Cardboard	Bio- Methane	0.267 m^3/kg VS added (pasteurised sample)	19.39 %	Banks and Zhang (2010)*
PACG1	Office Paper	Bio- Methane	0.137 m^3/kg VS added	9.95%	Banks and Zhang (2010)*
WWET1	Wooden Pallets	Bio-ethanol	0.98 tonnes (output)/tonnes (input) wood crushing 0.166 tonnes (output)/tonnes (input) production	16.27 %	E4Tech and Concepto (2013) *
PFSD	Plastic Film (LDPE)	Synthetic Diesel EN590	Between 750L/tonne (Cynar Plc.) and 950L/tonne (Klean Industries)	Average 73.32 %	Adapted from: 4R Sustainability Inc. (2011) *
PBSD	Plastic Bottles(HDPE)				

The latter includes non-edible parts of plants; card and paper used in packaging and food containers; and wooden pallets used in transportation. Non-organic waste involves mainly packaging film, plastic cases for transportation of goods and plastic bottles for drinks. A category for waste effluent was also included as this typically goes into the foul drain and ends in water treatment plants where organic effluents are treated producing biogas as a by-product.



TYPE WASTE	PRODUCTION		PROCESSING	DISTRIBUTION	QUICK SERVICE RESTAURANTS
	Meat, Fish & Dairy	Agriculture & Other Raw Materials			
Organic Losses & Waste	Dead Animals Manure Paper & Cardboard Pallets	Mechanically Damaged parts & Seed Losses Hard parts of Plants	Non-commercial Parts By-products: Tallow, Oil cake, Fish Meal Paper & Cardboard Wooden Pallets	Out of Date Food & Expired Promotions Paper & Cardboard Wooden Pallets	Used Cooking Oil, Fat, Coffee Grounds & Food Leftovers Paper & Cardboard Packaging & Cups
Other Organic Waste (Effluents)	Sludges	Cleaning Water (Vegetables)	Blanching, CIP Cleaning & Water Effluent	Cleaning Water Interceptors	Drinks, Ice Creams & Cleaning Water
Non Organic Losses & Waste	Plastic & Film Packaging	Plastic & Film Packaging	Plastic & Film Packaging	Plastic & Film Packaging	Plastic & Film Packaging, Plastic Cutlery & Bottles

Figure 81. Main waste streams along the fast food supply chain with waste-to-fuel potential.

Due to the limitations of this study, the boundaries were setup between distribution and QSRs. Waste streams from production and processing were excluded as reliable data could not be obtained. The segregated waste fractions considered in this study for their potential for producing fuels for transportation included UCO, burger fat, cardboard, plastic films and bottles, and food waste produced in the restaurants' kitchens and separate collections of food waste, wooden pallets, plastic film, cardboard and paper generated in the DCs.The quantitative analysis of over 1000 QSRs (around 2.5% of the British market) has to be understood in the context of the segment where the industrial sponsor operates and it may not represent the waste profile of chains specialised in other types of foods. This study excludes fish and chip shops as they are not classified as 'fast food restaurants and takeaways' by the Ordnance Survey geographical information dataset used in this research. Furthermore, access to segregated data for waste collections from such shops were not available. This highlights some limitations in the methodological approach, as the outcome of the analysis is extrapolated to the whole UK FFSC.

To identify the location and quantify the number of relevant restaurants Ordnance Survey 'Points of interest' dataset was processed with a geographic information software package (ArcGIS). 'Points of Interest' is a location based directory of British businesses (Ordnance Survey, 2014). The dataset contains a three levels classification scheme that in this particular case corresponds to the code ‘01020018’. The code represents the following classification: Level 1 – code ‘01’ represents ‘accommodation, eating and drinking’; Level 2 – code ‘02’ represents ‘commercial services’; Level 3 – Code ‘0018’ represents ‘fast food and takeaway outlets’. The dataset contains among other fields an identifier, name, address and geographical coordinates of each restaurant.

Accurate monthly waste tonnage data from QSRs and DCs were supplied by the industrial sponsor for the period between January 2012 and October 2014. Additional data regarding food waste collected in the restaurant bins were provided by a third party waste management organisation managing these. The total tonnage generated was divided by the number of restaurants in the chain to provide a mean waste profile per restaurant and year. This profile was extrapolated to the total number of QSRs in Great Britain. According to Ordnance Survey (2014), in 2013 there were 39,762 fast food and takeaway outlets in the UK. Data from waste collections was available through the ERP system and it was aggregated each month for each distribution centre (DC). By adding all DCs, the total of each fraction of separated waste was calculated using Excel. A two month trial of mixed waste collections from QSRs was conducted by a third party (Veolia). This company supplied an estimation of the food waste produced in the area of trial (Scotland) and this amount was extrapolated to the whole UK network of the sponsor.

The lower heating values of organic waste and fuels represent the amount of heat released during their combustion. In this study this energy value was taken from the literature and no independent measurements were undertaken to calculate specific calorific values. The characterisation of waste, the chemical analysis of feedstocks and the efficiency values of waste-to-fuel conversion processes were outside the scope of this research.

Unstructured interviews with the directors of two 3PL companies working in the fast food sector provided an insight into the challenges of waste management from an operational and legal perspective. Additional interviews were also conducted with several European truck manufacturers to ascertain the technology roadmaps of different fuel technologies and the impact of Euro 6 emissions standards on UK HGV fleets in regards to first and second generation biofuels. Interviews with logistics operators and vehicle manufacturers, combined with a literature research, allowed the identification of a range of realistic and feasible pathways for the conversion of QSR wastes into transportation fuels.

4.4.2 UNDERSTANDING ENERGY YIELDS FROM ALTERNATIVE FUEL SOURCES

Data on the energy yields from waste feedstocks for each pathway were obtained from multiple sources (Table 33). In this study, UCO was considered to be the same as used vegetable oil and wasted edible oil; and burger fat was similar to tallow or animal fat. Grease trap waste (GTW) was not included in this study as there were no detailed data related to interceptor's collections tonnage. The calculations made took into consideration the conversion factors appearing with an asterisk (*) in Table 33.

FAME represents pathways where certain feedstocks have been converted into biodiesel through a transesterification process; also known as first generation biofuel. HVO biodiesel can be produced from the same feedstock via a hydrogenation process and it is also known as second generation biodiesel. Bio methane is typically generated from organic waste via AD. The biomethane production potential from feedstock was calculated either as a main substrate or as a co-substrate . Woodchips were considered as a suitable feedstock for producing bio-ethanol or biodiesel via enzyme hydrolysis fermentation or BioDME (bio dimethyl ether) or biomethanol via gasification. So far, second generation biofuels are more expensive than conventional fossil fuels. Examples of BioDME plants are only found in European Nordic countries (Sekab, 2013, BioDME, 2012). Pyrolysis is also the main process to produce synthetic diesel from plastics. The conversion efficiency factor used in this study for plastic-to-fuel corresponds to the average of the values reported by a number of companies working in the sector as reflected in the 4R Sustainability Inc. (2011) survey.

To convert litres of UCO and tallow into kg, the yearly production was converted to kg assuming that both have a density of 0.92 kg/ L and a density for FAME biodiesel of 0.89 kg/ L and 0.78 kg/L for HVO biodiesel. Also, based on the values reported by Edwards et al. (2014), the densities of bioethanol and synthetic diesel considered were 0.794 kg/L and 0.78 kg/L respectively.

4.4.3 WELL-TO-TANK CARBON ACCOUNTING OF WASTE-TO-FUEL PATHWAYS

Typically, for carbon accounting purposes, UK organisations use the national official carbon emission factors suggested by DECC (2014b); however, due to the particularities of the supply chain of the industrial sponsor, it was considered that a carbon audit of their waste-to-fuel resources would give a more accurate estimation of the WTW GHG emissions of their road haulage operations. This also provided insights into MB's future energy security and its negotiating power regarding fuel prices purchases.

The GHG emissions of growing, harvesting, producing and distributing products (e.g. packaging, cooking oil, etc.) are attributed to the QSR chains that procured them in the first instance. For this reason, the embedded carbon intensity of waste as a feedstock is almost negligible at the point of generation. Well-to-Wheel (WTW) GHG emissions are the sum of Well-to-Tank (WTT) and Tank-to-Wheel (TTW) emissions. TTW emissions are those emitted when fuels are burned. In this study TTW GHG emissions are the ones reported by Edwards et al. (2014) in the CONCAWE report (Table 23, page 90). In this case, Well-to-tank (WTT) GHG emissions are emitted as a result of all the processes that convert waste feedstock into fuel. These include the collection, transportation, storage, manipulation, handling, and conversion of feedstock (waste) into fuel, and its subsequent transportation, storage, manipulation, handling and dispensing. The WTT carbon intensities of waste-to-fuel pathways were calculated with the assistance of the UK Carbon Calculator (E4Tech and Concepto, 2013); using the energy yields marked with an asterisk (*) in Table 33. Logistic companies operating in the USA could produce their own waste-to-fuel GHG emission factors calculations by using the GREET Model instead (Argonne National Laboratory, 2012).

Transportation represents a significant contribution to overall WTT GHG emissions. When moving liquid or solid feedstocks, appropriate liquid/bulk freight vehicles and vessels were assumed and their carbon intensity were the result of default options found in the UK Carbon Calculator (E4Tech and Concepto, 2013) for each particular vehicle type/category, unless specified otherwise. Details of inputs and processes' assumptions appear in Appendix 11 (Page 357). To calculate the carbon intensity of each pathway, it was necessary to specify transport modes, trip distances for transported feedstocks and fuels, fuel consumption of freight vehicles and shipping vessels, and the efficiency of each conversion process (among other factors). Typically, waste from restaurants was collected through reverse logistics and sent to a consolidation centre (in this case this happened to be the distribution centre). From there, the stored waste was sent for processing. Waste was sent by road if the production facility was in the UK or by ship when abroad. Once the fuel was produced, it made its way back to the distribution centre where it was stored and dispatched. Figure 82 schematises a typical flow; however, alternatives exist where fuel gases can be injected into the national gas grid. Methodologically, the energy consumption at each stage of the waste-to-fuel process was accounted for and it includd transportation, storage, handling, processing and conversion of waste into fuels and the reverse flow to supply the fuels to the refuelling station of the fleet. The WTT emissions obtained were aggregated to the TTW emission factors provided by Edwards et al.

(2014) to produce the final WTW carbon emission factors of each waste-to-fuel pathway that is used in the heuristics model to calculate the GHG emissions of the low carbon HGV during its lifetime.

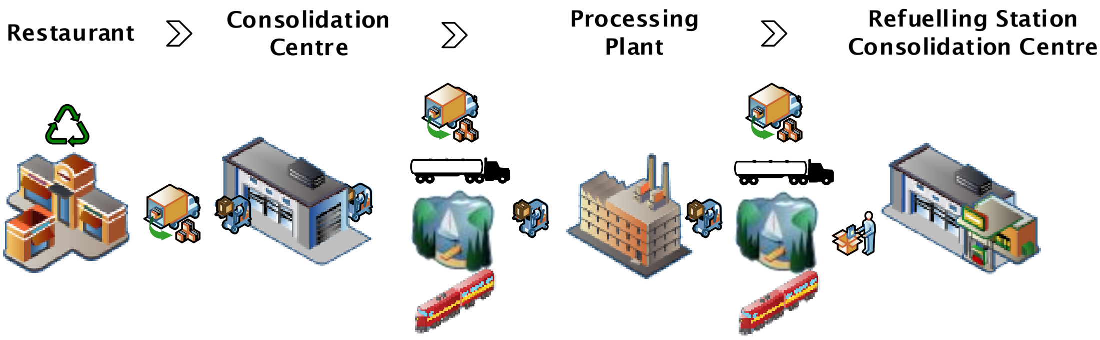


Figure 82. Typical waste-to-fuel downstream supply chain.

GHG reporting depends on carbon accounting practices, the emissions factors of each energy pathway and year, and the total fuel consumed. When organisations do not have information regarding their fuel purchases, the UK carbon reporting methodology followed by DECC (2014b) makes assumptions regarding driving cycles and loading factors. In this study, as the exact quantity of fuel consumed by the QSR fleet was known, it was possible to calculate the WTW GHG emissions directly without needing to evaluate driving cycles, vehicle types or loading factors. It was also assumed that during back-haul trips, vehicles did not carry any freight and as a result, carbon emissions of waste collections made by the 3PL fleet were almost negligible, contributing just marginally to fuel consumption due to the increase in vehicle mass compared to an otherwise empty back-haul trip.

4.4.4 GEOGRAPHIC DATA USED IN THE MODELLING PROCESS

The 'UK and Ireland Carbon Calculator' is a modelling software tool that allows the calculation of the carbon intensity of fuel supply chains in line with the last Renewable Transport Fuel Obligation guidance (E4Tech, 2015). The package considers the carbon miles of different transportation modes; these depend on the type of ships and road vehicles and freight distances. Carbon emission contributions also included the energy requirements associated with intermediate waste-to-energy processes (e.g. transportation, handling, processing, storage and refuelling), including the emission factors assigned to conversion processes assuming the UK energy mix in some cases. The distances between QSRs and DCs were taken as the averages observed for the case study supply chain as shown by the routing and scheduling software (this uses shortest-path algorithms to optimise routes). As a typical trip was around 280 km, this meant that the return

trip was half of this and as around 4 deliveries were typically undertaken, it was considered that 35 km could be attributed to each restaurant collection. Distances between the DCs and fuel processing plants were calculated using Google Maps (2013) for all road haulage trips. When waste was shipped abroad for processing, the port of origin was taken to be Felixstowe and the port of destination was the one clossest to the location of the waste processing plant. The shipping distances were obtained using Searates.com (2013). The location of British QSRs were obtained from Ordnance Survey (2014). The location of all UK QSRs is illustrated in Figure 83.

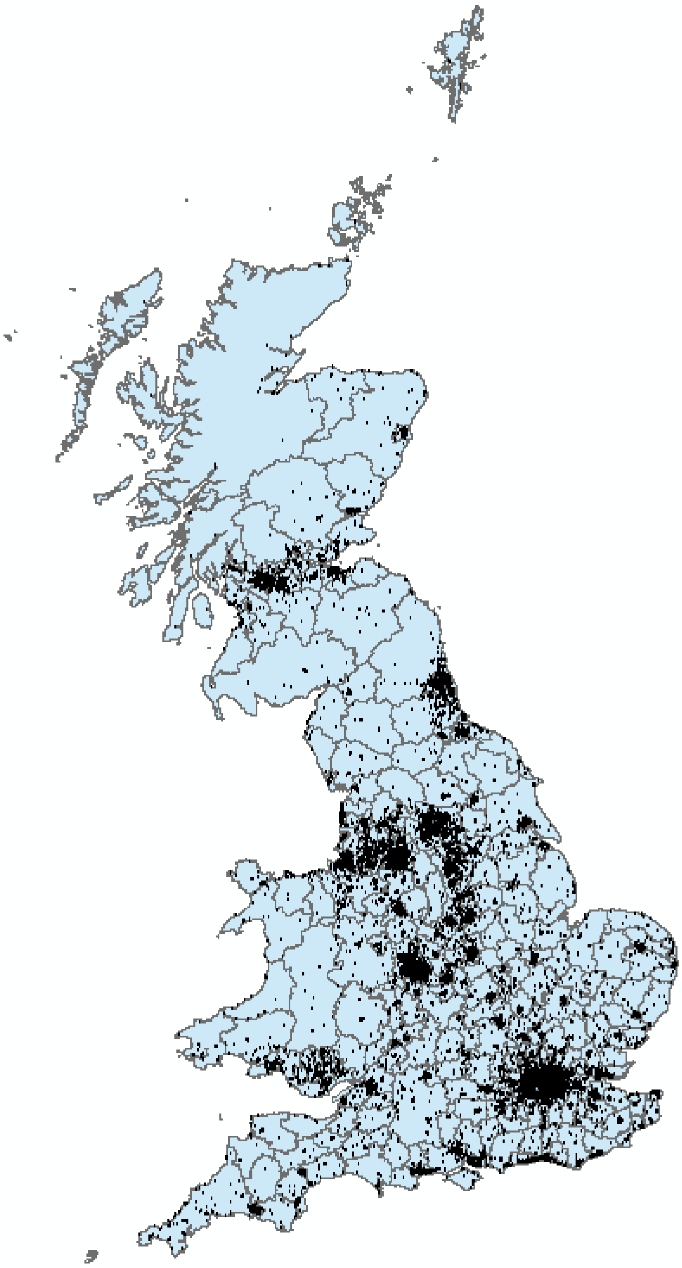


Figure 83. Distribution of fast food and takeaway restaurants in Great Britain (2013).

The energy consumed by HGVs in each British district was obtained from the sub-national road transport fuel consumption dataset produced by DECC (2013b). Both datasets were combined in ArcGIS to illustrate the percentage of diesel equivalent consumed by commercial HGVs that could be supplied by fuels produced from QSRs' waste according to three different scenarios, as it will be shown in Section 5.3.3 (Page 217). In all three scenarios it was assumed that paper and cardboard were used to produce biomethane, wasted wood to produce bioethanol, and plastics to produce synthetic diesel. However while in scenario 1 UCO and fats wereused to produce first generation biodiesel; in scenario 2 these were used to produce second generation biodiesel; and in scenario 3 these were co-digested in biomethane production. As waste-to-fuel processing facilities were located at different places, geographical information was critical to calculate the percentage that transportation movements represented on the total carbon intensity of each scenario.

4.4.5 CARBON EMISSION COSTS

The heuristics model is based on the industrial sponsor case study where the vehicles use first generation biodiesel B65; however the model can use any biofuel blend. Different technologies can reduce the amount of fuel consumed and also gas leakages; both having an impact on carbon emissions. In the future, logistics fleets may be economically liable for their GHG emissions; however, nowadays they do not have to pay for these. As a result, in the quantitative model, GHG emissions costs were disregarded and set-up to zero. This does not mean that carbon emissions are trivial, this means that the economic benefits of lower carbon emissions are dependent on lower fuel usage and the level of emissions depends on the objective function selected. These emissions are also taken in consideration in the multicriteria decision approach by means of pair-wise comparisons between different vehicle specifications, according to the relative importance of carbon emissions versus total costs and risks as stated by the industrial sponsor preferences.

In the section 5.4.4 (page 260), a sensitivity analysis was conducted to assess how carbon prices would affect the final solution. This was considered relevant as Governmental policy could change in the future in regards to carbon pricing. It is considered that a carbon price of €20/t CO_2 would trigger price increases of 0.1-5% along the value chain for most energy and carbon intensive industries in order to maintain profitability and it represents "the cost of the carbon constraint imposed to the European economy by the Kyoto Protocol" (Bergmann et al., 2007). This is also the price expected for the carbon price of auctioned emissions allowances in 2020 according to a survey from the International Emissions Trading Association.

This is considerably lower than a cost of carbon of €50/t CO_2 considered necessary to achieve a European target of 80% GHG emission savings by 2050 (House of Commons, 2012). However, these medium and high forecasts could be reviewed as the value of carbon emissions certificates have plummeted. Currently, carbon prices have been at their highest level for the last 24 months at a price of £6.77/t CO_2 [13]from a low of £2.70/t CO_2 on the 16/04/2013 based on market prices reported by the European Energy Exchange AG (2014).

4.5 BLOCK 3 - LOW CARBON TECHNOLOGIES SELECTION USING COMBINATORIAL OPTIMISATION

The aim of the quantitative model is finding the combination of technologies that minimises either the total net present cost (NPC) of a HGV over its life span, its carbon emissions or its NPC under a specific risk profile. There is a large number of low carbon technologies that can be fitted on HGVs and when combined in packages, the combinations grow into the millions, making very difficult to assess the net present costs and carbon savings that can be achieved. To facilitate this task two approaches were developed. The first one assessed all the potential feasible combinations. The second one took a heuristic approach based on evolutionary algorithms. As it will be seen in the next section, the combinations of low carbon technologies do not yield linear results (e.g. costs, GHG emissions) from the addition of performance inputs. For example, two technologies saving 20% of fuel each, would reduce fuel consumption by 36% instead of 40%. A vehicle that would initially decrease its fuel consumption by 20% would consumes 80% of the total fuel. An additional technology reducing consumption a further 20% would in fact reduce fuel consumption by 16%; the result of reducing 20% over 80%.

In essence, the financial analysis performed in this framework is based on combinatorial optimisation and it is a complex, non-smooth problem that presents two main challenges. The first one is that as mentioned by Misevičius et al. (2015), combinatorial optimisation problems tend to be NP-hard and cannot be solved optimally in reasonable time. This situation precludes that the optimal way of solving these problems is through heuristics. There are many heuristics optimisation techniques; however, as the problem is not linear (non-smooth), techniques such as linear programming and mixed integer linear programming optimisation techniques are of no use to solve this combinatorial problem.

[13] The prices were between 3.14€/t CO_2 and €7.87/t CO_2 and the exchange rate applied €0.86134/£.

In the mindmap attached to this thesis, almost 200 technologies that can have a positive impact on the reduction of carbon emissions were identified. From those, 25 were chosen based on the availability of reliable and relevant data (Table 28, page 132). A vehicle could fit any combination of these and it is necessary to find the optimal one according to the objective function sought. The current problem evaluates 2^{25} combinations of technologies (this is over 33.5million); however, due to the built-in constraints, the total number is reduced to 660,481. The model can include many more LCTs and for each unconstrained one, the number of combinations doubles. This means that when the number of technologies exceeds 25-30, solving the problem by evaluating each single possible solution is too time consuming. It is obvious that choosing the optimal combination of technologies without the assistance of computers is not realistic and so far there is not any tool at present that can help industry to solve this effectively. Addressing this problem is one of the main contributions of this research.

Two approaches to deal with this challenge were undertaken. One used a program in Visual Basic to check all possible solutions. The second one was based on heuristic techniques. While solving the problem with VBA in Excel takes almost 3 hrs., with a commercial algorithm (OPTQuest) it takes less than a minute. A copy of the VBA code for generating the matrix of all feasible technology combinations appears in Appendix 12.

Typically, for a fleet of homogeneous HGVs, the importance of getting the solution right is very important and leaving a computer calculating the optimal solution for a few hours is not an issue, as most likely, this will be done once or twice per year (only when the scenarios change significantly). When the number of technologies increases, the time needed to solve the problem grows exponentially. This means that for each new unconstrained technology, the time required to build the matrix of possible technological combinations doubles, as it does the time needed to find the best solution. Assuming this, a problem with 30 technologies (5 additional ones to the current 25) would increase the calculation time in VBA by 32, increasing to 89:55:12 hrs. (almost 4 days).

This highlights the correctness of using heuristics when the number of potential technologies increases. The issue with heuristics is that it is not 100% guaranteed that the solution found is a global optima (instead of a local optima); however for some problems this is the only approach possible otherwise the time needed to solve the problem could be longer than the age of the universe. In this particular case, it is possible to test all options and both approaches have been compared (Table 34). The brute force approach of testing all solutions took almost 3 hrs. in finding the optimal one. The heuristic approach took 20 seconds. Both found the optimal solution and this suggest that the heuristics algorithm explores the solution space very efficiently and it was used to found the solutions in all the scenarios and cases explore.

A stochastic analysis of the NPC could be added to the quantitative model; however, bearing in mind the amount of uncertainties that exists in the inputs (e.g. evolution of energy prices, GDP, mileage run, other operating costs, etc.), it did not seem that this would provide a result that could be easily interpreted. A stochastic approach to risk calculation was also considered and later disregarded due to the lack of historical data of reliability issues (e.g. down time due to technical failures) for each technology and not having this data did not make possible to find the best fit for the probability distribution functions that would represent vehicles' break downs.

Robust optimisation is about goal programing and penalty functions. As all the variables related to the selection of LCT are binary (0, 1) no penalties could be applied over these, whether a technology was chosen or not. There was scope for applying penalties over the risks levels and penalising the riskier solutions. However, there was no point in doing this, as unacceptable risk where built as an additional constraint; technologies exceeding certain risk levels were excluded from the solutions.

Table 34. Performance comparison of heuristics and non-heuristic solving approaches for the minimisation of total net present costs.

Computer: Intel i7-2600 32GB @3.40 GHz RAM Software: MS Excel 15 64-Bit		
Description problem: Find the combination of technologies that minimises the total net present cost of a HGV over its life span.		
Initial NPC was £512,559 Optimal Value found: £360,886		
Number of unconstrained combinations : 33.5 m Number of constrained combinations : 660,481 Combination number of the optimal solution: 659,175		
Comparison	**Check All combinations**	**Metaheuristics Approach**
Time	2 Hrs 48 Min 36 Seconds	20 seconds
Achieved Optimal Result?	Yes	Yes (Near Optimal approach)
Solving method	Brute force Visual Basic Applications	Recipe OPTQuest

4.5.1 METAHEURISTICS MODEL

The quantitative model developed in this research is in essence a combinatorial binary optimisation problem that yields complex, non-smooth and non-linear solutions that use a metaheuristics. A bespoke mathematical model based on evolutionary algorithms was developed to optimise the selection of low carbon technologies for different types of HGVs based on four objectives functions (minimising total costs, GHG emissions or total costs given a technology maturity or technology safety and limitations profile). The generic formulation of this type of problem is defined in Table 35 and it can be described as follows. Let (1) be a set of solutions within the solution space of the combinatorial optimisation problem. Each solution is based on permutations of binary integers (where 0=no technology selected; and 1=technology selected), where n represents the number of technologies (2). The solution is a permutation of 'n' technology combinations (3) where some of these permutations are subject to constraints as some technologies cannot work together[14]. Let (4) be a function that seeks a global minimum of the objective function (6) where the function represents the total net cost (7). A neighbour function [15](8) adds a set of neighbouring solutions of 's' (9) for each possible solution of the solution space (5). Each new solution (10) can be reached from 's' by using one or a combination of neighbourhood functions after each trial. The neighbourhood solution of order $\lambda (1 \leq \lambda \leq n)$ is (11), where $s \in S$ and $\rho(s, s')$ is the Hamming distance (a measure of difference among two solutions) between the current solution 's' and the new one (12). If λ=2 a two exchange neighbourhood function is obtained, used typically in combinatorial problems (Misevičius et al., 2015).

Table 35. Generic mathematical formulation of the problem. Adapted from Misevičius et al. (2015)

$S = \{s_1, s_2, \dots, s_i\}$ (1)
$\forall s_i \in S, Si = (s_i(1), s_i(2), \dots, s_i(n)) \in \{1, 2, \dots, n\}$ (2)
$S = !n$ (3)
$f: S \rightarrow R^1$ (4)
$s^* \in S$ (5)
$s^* = \arg\min f(s)$ (6)
$f(s) = Net\ Present\ Cost\ (s)\ [or\ GHG\ Emissions\ (s)]$ (7)
$N: S \rightarrow 2^S$ (8)
$N(s) \subseteq S$ (9)
$s' \in N(s)$ (10)
$N_\lambda(s) = s' \mid s' \in S, \rho(s, s') \leq \lambda$ (11)
$s': \rho(s, s') = \sum_{i=1}^{n} sgn \mid s(i) - s'(i) \mid$ (12)

[14] Details of these constraints are described in section **Error! Reference source not found.**, pages 174-176.

[15] Neighbouring solutions are those that share some (but not all) characteristics with each other.

The model includes parameters found in the data collection process (Block 1) and data production stages (Block 2), including performance values and financial, operational and environmental factors. The metaheuristic model uses an implementation of a commercial solver (Palisade Evolver OPTQuest) that runs as an add-on in Microsoft Excel. This solver is a ‘black-box’ optimiser that does not use context information and does not take advantage of the problem’s specific structure (Laguna, 2011). This means that the solver acts as a general purpose procedure that does not exploit the structure of the problem, in contrast, for example, to linear programming solvers (Gortázar et al., 2010). Despite the fact that a bespoke context-dependent program could yield better solutions when applying the same computational effort (Laguna, 2011), time is not a critical factor in the problem being evaluated here (as it take just under a minute to find a solution) and for this reason, instead of creating an off-the-self heuristic algorithm, a commercial “black box” optimizer was used. As the ‘black-box’ has not context information it combines a range of approaches to solve the problem such as design of experiments, cross entropy, genetic algorithms, particle swarm optimisation, simultaneous perturbation stochastic approximation, linear and mixed integer programing and complete enumeration technologies (Laguna, 2011). Methodological details of how this ‘black-box’ optimisation framework works are explained in Laguna (2011), Laguna et al. (2013). Due to the nature of this problem (this is a combinatorial binary optimisation problem), it could be assumed that Palisade Evolver OPTQuest focuses on scatter and tabu searches; however as it is a ‘black-box’ this cannot be confirmed. Gortázar et al. (2010) compared the relative percent deviation (RPD) between of the best solution value and the solution given by three popular commercial solvers that can deal with scatter search for general classes of binary optimisation problems and they found that Palisade OPTQuest RPD underperformed the other tools when solving problems that take more than one minute. As a result, as the quality of the solution was unknown, a non-heuristic algorithm was developed in VBA which yield the same solution (in much longer time-period though). This proved that the approach used in the Palisade ‘black-box’ was good enough in regards to the accuracy of the solution and the time used to calculate it. After validating the results, Palisade Evolver became the preferred approach as it allowed the calculation of tens of scenarios in reasonable time.

With the metaheuristics quantitative model here presented, logistics operators do not need to develop programming skills to produce results and they can assess the outcome of different truck configurations without having to conduct expensive and time consuming physical trials. Third party consultants can charge around $33,000 in the USA for evaluating a trial experiment with up to three low carbon technologies (National Research Council, 2010). In the UK, Millbrook Proving Ground charges £600/hr. for self-managed technology trials with no support (just renting the test track), as reported in personal communications by Millbrook Proving Ground (2015). On top of this, the customer has to add the costs of experienced drivers, engineers and statisticians to analyse results, either by using their own engineers or hiring the ones that Millbrook Proving Ground can supply.

The metaheuristics quantitative model considers seven main types of inputs (Figure 71, page 125) to yield the vehicle specification with the cheapest cost or lowest carbon emission combination of technologies depending on the objective function; however, there are hundreds of other less critical parameters. In addition of the do-nothing scenarios with energy prices based on the central forecast of DECC (2014e) and higher/lower energy costs (±20%), three scenarios were created for each objective function. This means that there were 15 scenarios for urban, 15 for regional and 15 for long haul vehicles. Futhermore, other scenarios were created to evaluate sensitivity analysis of energy prices, carbon costs, mileage run and working hours (the later for TRUs). The final solution for each duty cycle and objective function, yielded a risk profile and an estimation of GHG emissions (the later based on fuel consumption, emission factors and leaked refrigerant gases). The projections of technology costs took the year 2015 as a baseline and were updated according to the DECC (2014e) UK GDP forecast into the future.

Two of the most critical parameters in the model were the fuel savings from each individual technology and its cost. The fuel consumption reduction (FCR) achievable by a combination of low carbon technologies is defined in Equation 13. The potential FCR represents the fuel savings of each individual technology for a particular duty cycle and vehicle (up to a maximum of 100% savings). This formula is used to calculate total fuel savings but does not take into account the different levels of technology maturity, safety and limitations (e.g. lack of refuelling infrastructure or biodiesel availability). The model deals with these risks by assigning a risk profile to the solution that represents the riskier technology selected within the whole package.

$$\text{Combined FCR (\%)} = 100 \times \left(1 - \left(1 - \frac{\%\,FCR_1}{100}\right) \times \left(1 - \frac{\%\,FCR_2}{100}\right) \times \ldots \times \left(1 - \frac{\%\,FCR_n}{100}\right)\right)$$

Equation 13. Source:Cooper et al. (2009), National Research Council (2010)

Where:

FCR_1 represents the FCR of technology 1, FCR_2 the FCR of technology 2, and FCR_n represents the FCR of technology n.

The FCR of a solution has to consider constraints regarding the compatibilities among different LCTs. Some technologies are incompatible due to packaging and technical issues (e.g. hydraulic and electric hybridisation are redundant and therefore cannot work together). An example of a technical issue occurs when waste heat recovery systems need a good quality source of heat; this technology interacts with the selective catalytic reduction system. Other technologies may benefit from working together (e.g. heat recovery and turbo compounding). Caution must be applied to avoid double counting effects. Only the synergies between conventional powertrain and 3 phase alternator auxiliary refrigeration systems and between vacuum insulated panelsand TRUs were modelled. Other synergies are much more complex to model (e.g. aerodynamic interactions between spray suppression mudflaps, undertray trailers and side skirts) and for this reason in the aerodynamic trailers were considered as a package of technologies (e.g. front fairings, turning vanes and side skirst), instead of individual components.

Low carbon technologies have been divided into four categories: vehicle, powertrain, TRUs and fuel technologies. The location of some of these appear in Figure 84. The costs of the technologies appeared in Table 28 (page 132) and their FCRs is based on the results reported by Hill et al. (2011) which were updated with commercial information, and the results of simulations and trials (Table 36). The reason for relying on a single source, as previously explained was due to testing consistency (e.g. using the same driving cycleas each time) but also because simulating all technologies would have required exhaustive engineering skills in many different areas and a time frame beyond the limitations of this research.

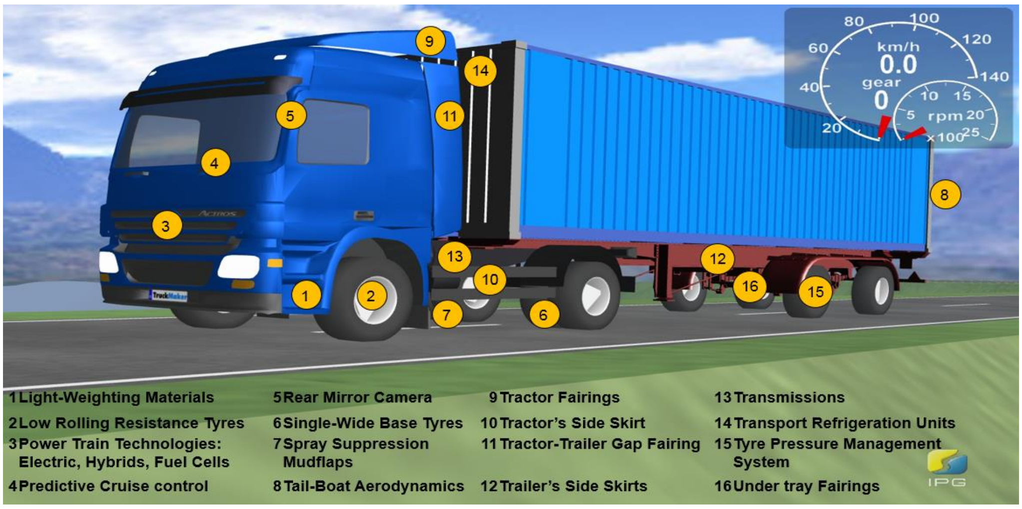


Figure 84. Location of some of the technologies considered in the heuristics model.

After conducting a thorough literature review, a review of evidence and analysis, it was decided that battery electric powertrains and alternative fuel technologies would be excluded for two main reasons: 1) the operating characteristics of refrigerated freight operations are energy intensive and there are no e-trucks capable of satisfying the requirements of the live case study; 2) there was not enough data regarding the improvement that could be achieved by using green hydrogen and biomethane powertrain technologies (improvements in regards to heat recovery, energy efficiency, etc.). As a result, the model focused on diesel and biodiesel trucks.

Table 36. Fuel consumption reduction percentages for each technology, according to different duty cycles.

Low Carbon Technology		Areas for improvement	Urban (%)	Regional (%)	Long Haul (%)
Vehicle Technologies	Reduced Aerodynamic Resistance	Aerodynamic Trailers	1.0	11.0	11.0
		Aerodynamic Irregular body shape	1.0	1.0	0.4
		Aerodynamic Fairings	0.0	6.5	5
		Spray Reduction Mud Flaps	0.5	1.0	1.5
	Reduced Rolling Resistance	Low rolling resistance tyres	1.0	2.5	5.0
		New generation wide-base single tyres	4.0	6.0	5.0
		Automatic tyre pressure adjustment	1.0	2.0	3.0
	Vehicle Mass	Lightweighting Materials (500kg)	2.2	2.2	2.2
	Intelligent VT	Predictive Cruise Control	0.0	5.0	5.0
	Auxiliary Systems	Controllable air compressor	0.0	1.0	1.5
Powertrain Technologies	Exhaust Heat Recovery	Heat Recovery (in general)	1.5	2.5	5.0
		Electrical Drive Turbocompound	1.0	2.5	3.0
	Transmissions	Automated Manual Transmission	5.0	1.5	1.5
	Mild Hybrid	Flywheels Hybrid	15.0	7.5	5.0
		Stop-Start: Electric Hybrid	6.0	3.0	1.0
		Pneumatic Booster - Air Hybrid	4.3	3.1	1.9
	Alternative PT	Full Hybrid: Series / Parallel Electric	10.0	0.0	0.0
		Series / Parallel hydraulic	10.0	0.0	0.0
Transport Refrigeration	Mechanical Refrigeration	Frigoblock 3 phase alternator Unit (HK)	100.0	100.0	100.0
		Hybrid Carrier MT-1850	10.0	10.0	10.0
		Lower GWP Gas (CO_2) TRU	0.0	0.0	0.0
	Non Mechanical Refrigeration	Cryogenic LIN	100.0	100.0	100.0
		Cryogenic CO_2	100.0	100.0	100.0
		Cryogenic Air (LAIR)	100.0	100.0	100.0
	Other	Vacuum Isolated Panels	1.0	5.0	5.0

4.5.1.1 OBJECTIVE FUNCTION: MINIMISING COSTS AND GHG EMISSIONS.

There were four objective functions. One consisted in minimising GHG emissions at any cost. The other three sought to minimise the net present cost (NPC) of a refrigerated HGV according to different levels of risk. These functions considered capital (leasing) and operating expenditure of the vehicle and added-on technologies during the 5 year lifetime of the investment. All the literature focusses on the payback period an investment decision technique for low carbon technologies selection guidance. However, as discussed by Burns and Walker (1997), this method suffers from several flaws as it does not i) consider the time value of money; ii) provide a monetary value that allows a clear comparison of what alternatives are preferable; and iii) consider returns beyond the payback period. The model described in this thesis considers the net present value (NPV) as a more suitable technique for financial decision making, as it overcomes the payback flaws by allowing the evaluation of specific rates of return, economic cash flows at different points in time, and a more realistic scenario analysis. As cash inflows were excluded, the objective function minimised just the net present cost (NPC) of a straight purchase as the result of cash outflows during the life of the investment (Equation 14). In a leasing, there is no initial capital investment (C^0), and the cost of the vehicle is distributed over its life.

Equation 14 Net Present Cost formula for a straight purchase.

$$NPC = C^0 + \sum_{t=1}^{5} \frac{C_t}{(1+r)^t}$$

Where

C^0 = Initial investment (cash flow of capital expenditure at year 0).

C_t= Cash flow in year t (capital and operating expenditure).

r= required rate of return.

t= project life expectancy (in years) as indicated by the industrial sponsor.

In the model developed here, the initial capital investment is zero and the annual leasing payments were the result of the capital recovery factor applied by a lessor (Equation 15) for the cost of the HGV and all the LCT fitted. As capital investment is deferred over time, the NPC of a leasing tends to be lower than a straight purchase (an example of this is illustrated in Table 37). The model is based on this case (contract hire), as it reflects the reality of the logistics sector. As a result, the model does not include the recovery costs of the sale of the vehicle at the end of its life but it includes maintenance costs.

Equation 15 Capital recovery factor.

$$A = C \times \frac{[(1+i)^n \times i]}{[(1+i)^n - 1]}$$

Where

A= Annual payment.

C= Capital investment.

i= Interest rate.

n= project life expectancy (in years).

The model assumes that the HGV is contract hired and it uses the NPC as a financial appraisal technique. This technique considers the initial investment cost, the life expectancy of the investment, the rate of return expected by the buyer (opportunity cost), different cash outflows during the life of the asset and a it excludes a potential recovery of the residual value of the vehicle at the end of the period (vehicle's life) by the lessee.

Information regarding purchasing costs of tractor, trailer and refrigeration units were provided by the industrial sponsor as these reflected their reality. They also specified the life expectancy of the vehicles and their expected rate of return (e.g. opportunity cost). Other users could change these values with estimated standing, running and vehicle cost details and operating assumptions according to their personal circumstances or use the ones reported by FTA (2014a) that reflect the costs for UK logistic operators, based on the type of vehicle and mileage.

The net present cost technique used in the financial model can be used for the procurement or leasing of HGVs. The differences are in the initial outlay of capital and the possibility of selling or buying the vehicle at the end of its life or contract, and who bares the risks of vehicle ownership. Some of the differences between procurement financial options for the acquisition of HGVs and how to adapt the financial model to allow these, appear in Table 38. Initially, the model dealt with straight purchases (self-purchases); however, after comparing these with leasing, it was seen that the latter represented a lower NPC. In the example from Table 37, this can be seen clearly.

In a straight purchase, the logistics firm pays the vehicle cost upfront (year 0) and it recovers a residual value at the end of its life by selling it. The company requires a rate of return for their investments (e.g. 10%) that represents the opportunity costs of investing in something else (this is a proxy for the financial risk that the company is willing to take). In a leasing, the initial investment is paid by the lessor who charges regular payments to the lessee at a given interest rate. A leasing company typically has a higher purchasing power and procurement

Table 37. Comparison of the financial advantages of a leasing versus a straight purchase.

Purchase Agreement	RR	Years	Cash flows (£) Year						Buyer Pays	
			Initial Capital Investment	1	2	3	4	5 (RV)	Over 5 years	Net Present Cost (£)
Self-Purchase	10.00%	5	100,000	0	0	0	0	5,000	95,000	96,895

Leasing Agreement	Interest Rate	Years	Cost Lessor	Cash flows (£) Year [Capital Recovery Factor]						Lessee Pays	
				0	1	2	3	4	5 (RV = 0)	Over 5 years	Net Present Cost (£)
Hire Contract	3.00%	5	100,000	0	21,835	21,835	21,835	21,835	21,835	109,177	82,774

Table 38. Some financial options for the procurement of vehicles and how this influences the financial model.

Funding Options	Characteristics	Changes needed in the Financial Model
Self-Purchase	The ownership of the HGV belongs to the logistics firm. Big initial capital expense outlay with recovery of residual value at the end of the life of the vehicle (through sale). Owner bares the risks of maintenance and residual value fluctuations) All operating expenses (e.g. service and maintenance) are responsibility of the buyer. It appears on the balance sheet.	Add capital costs (vehicles + technologies) to the outcome of the NPC (year 0) and eliminate leasing quotas from the operating expenses. The rate of return considered in this option is 9.7%; other sources suggest that 12% is appropriate for road haulage firms.
Contract Hire	Fixed monthly rental payments; result of an initial agreed number of advanced rentals minus the expected residual. No residual value for the lessee. Rental payments offset against taxable profit and 100% of VAT can be claimed (including maintenance VAT). It does not appear on lessee's balance sheet. Tax managed by seller. Return vehicle at the end. Lessor bares the ownership risk. Service and maintenance fees may be (or not) included in the contract.	The model is designed primarily for this option. No changes are needed. Leasing interest rate is 3%. Maintenance costs are not included in the contract (e.g. tyre wear costs, etc.) and must be paid by the lessee. Using capital recovery factor, the capital costs become operating costs and are spread over the life of the vehicle (5 years).
Hire Purchase	Same as contract hire but with the option to buy the HGV at the end of the contract for a fee negotiated at the beginning (e.g. lump sum or fee). Full VAT is paid with initial deposit payment (reclaimable by the lessee). It appears on lessee's balance sheet. It is a conditional sale.	Same as contract hire but a purchasing nominal fee and a balloon payment must be added in year 5.
Contract Purchase	Similar to hire purchase. At the end of the agreement the vehicle can be purchased for a lump sum plus activation fee, returned to the seller and part-exchanged for a new vehicle (as the future value of the vehicle is included in the original agreement).	If the vehicle ends being purchased or part-exchange, then it is the same as hire purchase. If the vehicle is not, it is similar to contract hire.

expertise than an individual logistics firm. This means that the lessor can buy HGVs at a cheaper rate than the lessee, as well as expecting a lower rate of return (e.g. 1%) as their expertise leads to lower risks.

The purchase of a £100k HGVs with a 5% resale value at the end of its life, represents a total cash outflow of 95,000 over 5 years which equates to a net present cost of £96,895 for the logistics firm. If a leasing company buys the same vehicle at the same cost, the lessor could offer the same vehicle to the lessee more cheaply. The reason for this, is that despite the fact that the lessee would end paying almost £15k more over the following 5 years, as there would not be an initial capital investment (the expenditure would be spread over time), the total net present cost would decrease from around £96.9k to £82.7k, representing net present savings of £14k. This justifies that the model focuses on contract hire agreements (a type of leasing).

4.5.1.2 DECISION VARIABLES

In the financial model, decision variables are binary (0=not chosen, 1=chosen) and they represent the LCTS that are selected (or not) to form part of the vehicle specification. Each technology has a FCR, cost and associated risk level (Table 39). The FCRs of each technology selected are added to yield the vehicle total FCR (according to Equation 13, Page165) and this is subtracted from the fuel consumption of the baseline vehicle. The capital costs of a baseline vehicle are also updated with the on-top costs of the additional technologies selected. The decision variables determine capital costs, operating costs, GHG emissions and the risk profile.

4.5.1.3 CONSTRAINTS

The financial model has several technology constraints and a financial one. The financial constraint limits the net present budget available. This is more relevant to straight purchases than for leasing, as the capital expenditure is spread over the life of the investment. A qualitative engineering analysis of LCT has also been conducted to identify technologies that cannot work together because of different types of incompatibilities.

Table 39. Extract of the main decision variables and parameters in the quantitative metaheuristics model.

Year 2015		Areas for improvement	Select (Y=1, N=0)	FC R (%)	Risk Maturity (RITM)	Risk Limit (RISL)	On Top Cost (£)
Vehicle Technologies	Rolling Resistance	Low rolling resistance tyres	1	5.0	9	7	325
		New generation wide-base single tyres	0	5.0	9	5	1,207
		Automatic tyre pressure adjustment	1	3.0	8	8	1,225
Powertrain Technologies	Exhaust	Heat Recovery (in general)	0	5.0	5	4	10,742
		Electrical Drive Turbo compound	0	3.0	8	4	6,499
	Mild Hybrid	Flywheels Hybrid	1	5	6	4	6,891
		Stop-Start: Electric Hybrid	0	1.0	8	5	873
		Pneumatic Booster - Air Hybrid	1	1.9	4	4	743
	Alternative	Full Hybrid: Series / Parallel Electric	0	7.0	7	3	20,672
		Series / Parallel hydraulic	0	0.0	5	2	12,256

4.5.1.3.1 VEHICLE TECHNOLOGIES CONSTRAINTS

Vehicle technologies were reviewed in section 3.5.1 (page 43) and some constraints were considered to restrict the technologies that are redundant among theirselves. It was assumed that vehicles with irregular bodies (e.g. teardrop shape) already have aerodynamic trailers. Also, aerodynamic trailers have aerodynamic fairings. This means that when evaluating the decision variables: 0≤ aerodynamic trailers + irregular bodies = 1 and 0≤ aerodynamic trailers + aerodynamic fairings ≤ 1.

It was also presumed that when a vehicle is fitted with new generation single wide-base tyres (SWBT), it cannot have low rolling resistance tyres simultaneously. The constraint was: 0 ≤ low rolling resistance + SWBT ≤ 1.

4.5.1.3.2 POWERTRAIN TECHNOLOGIES CONSTRAINTS

The compatibility among the powertrain technologies reviewed in section 3.5.2 (Page 61) were assessed and restrictions were built into the quantitative model. It considers exhaust heat recovery technologies, more efficient transmissions, and hybrid powertrains. After the evaluation of the literature it was considered that just one hybrid technology (plus pneumatic boosters) could be chosen as it would make no sense to have two or three powertrain systems duplicating the same function. For example, flywheels and electric and hydraulic hybrids have similar functions and also they all have some sort of stop-start technology embedded into them with some kinetic energy recovery system that power their energy storage system (e.g. batteries, hydraulic compressor or flywheel). The constraint specified that 0 ≤ flywheels + stop-start + electric hybrid + hydraulic hybrid ≤1.

A pneumatic booster is not compatible with electric engines; as it is a technology that works with internal combustion engines only. However, it is compatible with hybrid powertrains as these also have an ICE engine (typically downsized). This technology provides energy savings in conventional powertrains and despite the fact that it has been allowed in the current model, the FCR may be overestimated as the synergies with downsized engines have not been modelled. The same occurs with exhaust heat recovery; the FCR reported in the literature refers to diesel conventional powertrains; however, the synergies with downsized ICE have not been properly studied in the literature yet.

4.5.1.3.3 REFRIGERATION TECHNOLOGIES CONSTRAINTS

The constraints regarding the transport refrigeration technologies relate to the redundancy between different types and also the impact that one of them (3 phase auxiliary alternator unit) can have in the vehicle's engine fuel consumption. A trailer cannot have more than one TRU, as it would not make sense to duplicate the same function. The sum of the binary decision variables was constrained to up to 1 technology in total: 0 ≤ 3 phase alternator unit + hybrid unit + cryogenic TRUs ≤1.

When using start-stop technology, 3 phase alternator units cannot be selected as these draw power from the engine. If a vehicle stops in congestion, the engine would switch off and despite that an inverter could be installed to obtain power from the battery, the energy required (~ 10 kW) is too much for the capacity of a conventional battery. For this reason, a constraint was added where: 0 ≤ stop-start + 3 phase alternator ≤1. When 3 phase alternator TRUs are selected, a penalty of 8.93% on the fuel consumption of the tractor unit is applied. The way of calculating this using long-haul HGVs as example was as follows. Assuming that the TRUs of the industrial sponsor work 3,550 hrs. per year and that a 3 phase alternator unit consumes half of the energy of a conventional TRU (Frigoblock UK Ltd, 2007), the 1.45L/hr. were multiplied by 3,5550 hr./year. The resulting 5,174.75L/year were then divided by the total mileage (170,406 km/year). This equated to 2.99L/100km, a penalty of almost 9% on the tractor fuel consumption.

The sizes of the TRU boxes were assumed to be 61.15 m^3 for rigid lorries of 10.4 m and 78.79 m^3 for 13.4m semi-trailers (Tassou et al., 2009a). The predefined

TRU models were 'Carrier Supra 950' in smaller trailers (used for urban deliveries) and' Carrier Transicold Vector 1950' in the bigger ones (used in regional and long haul deliveries).

Lower GWP gas refered to TRUs using recycled CO_2 as refrigerant gas. This had no impact on FCR; however, it reduced GHG emissions due to the GWP of CO_2 is 1 and conventional refrigerants are 3 orders of magnitude larger. Another constraint was added to reflect that cryogenic TRU do not have any refrigerant gas (this also excluded using gases with lower GWP). The constraint was: $0 \leq$ Lower GWP gas + cryogenic TRUs ≤ 1.

As the mass difference between mechanical and non-mechanical TRUs was unknown, it was not possible to account for the vehicle fuel savings/penalties derived from the different weights of systems with cryogenic containers; however, according to TRU manufacturers, the weights were similar to conventional TRUs as the excess of weight from the cryogenic tanks was equivalent to the weight reduced by eliminating the ICE of the TRU.

Regarding refrigerant gases, conventional and hybrid TRUs were constrained to R404A, 3 phase alternator refrigeration machines to R410A, lower global warming potential gas units and cryogenic CO_2 to R744 gas, and cryogenic LIN and air to liquid nitrogen and liquid air respectively, as per manufacturers' technical specifications.

4.5.1.3.4 FUEL TECHNOLOGIES CONSTRAINTS

From the range of technologies reviewed in Section 3.5.3 (page 74), the model focuses on diesel HGVs and allows biodiesel blend from 0 to 100%. Despite the fact that, initially, the model could also optimise the fuel mix (from mineral diesel to 100% biodiesel), it was appreciated that this was unnecessary for two main reasons. Firstly, companies do not pay for their GHG emissions and the model always chose the cheaper blend (in the case study biodiesel). Secondly, because the content of biodiesel in average fuel blends is limited in low temperature environments due to the waxing effect, as commented on the literature review. As a result, in the current model, the biofuel content was specified by the user. The results were based on the average biofuel blend used by the industrial sponsor (B65) in the tractor unit and red diesel (mineral diesel) when the model selected a conventional TRU. The B65 biofuel blend corresponded to the WOFA3a pathway (first generation biofuel produced from used cooking oil) that appeared in Table 23 and Table 33 (Pages 90 and 152, respectively).

4.5.1.4 PARAMETERS

The main parameters included in the metaheuristics model considered the financial, operational, engineering and environmental aspects necessary to take the right procurement decision.

4.5.1.4.1 ENGINEERING PARAMETERS

The main engineering parameter were related to the FCR of each technology, a key parameter in the quantitative model which was obtained from the literature, and triangulated with simulations and trials (the outcome of which appears in Table 36, page 167). The model included vehicle technologies, powertrains and refrigeration technologies engineering considerations.

Regarding vehicle technologies the model assumed that conventional steering, driven and trailer tyres life span was 120,000 km, while low rolling resistance tyres life was 100,000 km, as reported by Baker et al. (2009b). Regarding powertrains, it was assumed that the efficiency of the engine decreased 1%, 1.5%, 2%, 2.5% on years 2, 3, 4 and 5 respectively, as reported by the industrial sponsor. The same penalty was applied to all TRUs except the cryogenic ones as they do not have engines. Diesel exhaust fluid costs, popularly known as 'AdBlue', were also included in the model. A 5% consumption of DEF by volume of diesel consumption was assumed, as reported by the industrial sponsor.

Following the UK '2013 Government GHG Conversion Factors for Company Reporting' (Defra/DECC, 2012), 15% of gas leakages for conventional and hybrid TRUS were assumed, which equated to 1.2l/year considering the size of the tank. Units running with R410A leakage was 7.5% and the one of cryogenic units was 100% as the gas is vented in to the atmosphere; as per manufacturers' technical specifications. As a result, the specific maintenance costs for refilling the refrigerant gas tank each single year, the cost of the gas itself and its impact on GHG emissions were also included in the model. Further considerations were modelled such as the energy consumption for the production of cryogenic gases and the electricity to power hybrid TRUs (it was assumed that these units were connected to the grid just 10% of the time, as reported by the industrial sponsor).

4.5.1.4.2 FINANCIAL PARAMETERS

The financial parameters included in the quantitative model included rates of return, leasing interest charges, updates according to the UK's GDP forecast, budgets constraints and the life expected for the investment as well as the costs of capital investments for infrastructure (e.g. cryogenic facilities, electrick sockets for hybrid units, etc). Other (operating) financial parameters included the costs of fuels, gases, DEF, maintenance, insurance and taxation.

To calculate the net present costs, the rate of return required by the industrial sponsor was 9.7% and a vehicles' life was 5 years, as specified by the finance director. This rate of return seems slightly lower than the 12% reported by European Commission (2013c) for the road haulage sector but it appears to be in the upper band compared to the estimations by Meszler et al. (2015), where the highest rate or return was 10%. The interest rate of the leasing company was 3%.

The model took the central baseline scenario assumptions for energy prices and GDP forecast from DECC (2014e) to update future technology costs and labour costs for tasks such as refrigerant gas refilling and maintenance of TRUs. Retail DERV price was based on the reference scenario developed by DECC (2014e). The price of red diesel was assumed to be half of the price of DERV, as the result of a statistical analysis of historic prices for the last 5 years. Biodiesel prices for 2015 were based on MB costs; however, future prices up to 2024 correspond to the forecast developed by OECD/FAO (2015). After this date, the biodiesel cost is 37.55% lower than DERV, as derived by calculating the estimated differentials between the DECC and the OECD predictions for the years 2015-2024. The fuel price assumptions based on DECC (2014e) and OECD/FAO (2015) projections appear in Table 40. In the results section, 3 different energy prices scenarios have been produced for each strategy, where the values from Table 40 represent the a low energy price projection with prices 20% lower than the medium forecast, a medium forecast that represent current and expected prices and a high energy price forecast that represents prices 20% more expensive than the central forecast.

Table 40. Estimation of fuel prices (pence/ L) adapted from DECC (2014e) for DERV and Red Diesel. B100 prices have been extrapolated from the industrial sponsor current prices and the fuel prices growth from DECC (2014e).

Fuel	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
DERV	133.5	134	133	133	135	137	139	142	144	146
B100	96.4	76.1	89.7	85.1	86.7	86.1	88.9	87.0	86.4	88.7
Red Diesel	72.0	67	66	66	67	68	70	71	72	73
B65	109.0	96	105	102	103	104	107	106	107	109

The financial model was designed to accept three carbon prices scenarios; however the cost of carbon was set-up to 0 £/ton as carbon emissions prices are only binding for energy suppliers participating in the EU Emission Trading Scheme.

In addition to the purchasing costs of low carbon technologies reported by commercial sources, the model used the costs published by Hill et al. (2011) and

projected these into the 2015-2020 timeframe according to DECC (2014e) GDP projections. This may be an arguable approach as some technologies may decrease their cost over time; however, there was not enough evidence to find out how the prices of each technology will evolve during the period. Maintenance costs for each type of tractor unit were taken from FTA (2014a).

4.5.1.4.3 OPERATIONAL PARAMETERS

The operating parameters were estimations for each specific year within the 2015-2020 timeframe. Further operational details were presented in Chapter 1.Fuel costs depend on the mileage, the baseline fuel consumption of the vehicle, the efficiency losses of the powertrain and the energy density of the fuel mix. Data regarding driving distances and trips per day were obtained from the statistical analysis of the telematics records of the fleet (Table 2, page 16). In the model, the vehicles that follow urban, regional and long-haul duty cycles are assumed to run in 2015 an average of 112k, 151k and 170k km/year, with a yearly increment of 0.5% to reflect the targets expected from efficiencies delivered by the routing and scheduling team. The fuel consumption of urban, regional and long-haul vehicles are the ones calculated from the statistical analysis of the total mileage and fuel consumed for the years 2013 and 2014 and are 25.82, 30.78 and 29.68 l/100km respectively. When the biodiesel blend varies, the fuel consumption takes into accounts the different energy intensity of the mix and adjusts the fuel consumption accordingly. The energy consumption of vehicles using biodiesel B100 is 13.31% higher than DERV due to their different energy densities (37.2 MJ/L for B100 and 42.91 MJ/L for DERV). These values were the ones reported by DECC (2014c). However, the values considered by Edwards et al. (2014) for the EU were 43.1 MJ/L for DERV and 33.11 MJ/L for FAME Biodiesel (B100). For example, for B65, the fuel consumptions assumed were 28.05, 33.4 and 32.25 l/100 km for each duty cycle (urban, regional and long-haul respectively).

The fuel costs of the TRUs were also included and they were the result of the annual working hours (predicted) and the fuel consumption of each refrigeration system. The red diesel consumption of urban TRUs was 1.8L/hr., and 2.9 L/hr. for regional and long-haul deliveries. These were assumed to work a total of 1,650 hrs. each year under urban; 2,130 hrs under regional and 3,550 hrs. under long-haul duties. Other operating costs included the cost of tyres per km and the percentage of DEF per litre of fuel.

4.5.1.4.4 ENVIRONMENTAL PARAMETERS

The solution of the quantitative model calculated the carbon footprint for the operating lifetime of the vehicle (excluding manufacturing and end of life emissions). It included the emissions of the tractor, TRUs and gas leakages. The model provided calculations of the total tonnes of GHG emissions by scope, but also indicators that included kg CO_2/case-km, kg CO_2/cage-km and kg CO_2/tkm (the latter to facilitate comparisons with other logistics operators). The carbon footprints considered by the model used the TTW emissions factors from Edwards et al. (2014) and the WTT factors calculated in this research from the waste-to-fuel opportunities identified in the supply chain of the industrial sponsor. A summary of these GHG emission factors appear in Table 41 (Page 179). Users not aware of the characteristics of their biofuels could use the generic values provided by DECC (2014c).

Table 41. Fuels' GHG emission factors used in the metaheuristics model.

Fuel Used	SCOPE 1 (TTW)	SCOPE 3 (WTT)	SCOPE 1 & 3 (WTW)
Red Diesel (100% Mineral) (Kg CO_2 / L fuel)	2.6769	0.5644	3.2413
DERV (B5) (Kg CO_2 / L fuel)	2.4557	0.577	3.0327
Diesel B100 (WOFA3a) (+2.49 Outside All Scopes) (Kg CO_2 / L fuel)	0.01976	0.4990	0.5188
Diesel B65 (+1.65 Outside All Scopes) (Kg CO_2 / L fuel)	0.9172	0.5277	1.4449

The emissions from refrigerant gases were calculated depending on the type of TRU and refrigerant gas used by the particular unit. For example, a conventional TRU has an 8.3 L refrigerant tank which leaks around 15% each year. The 1.2 l leaked each year produces the equivalent of 3,912 kg of CO_2; assuming the GHG emission factors that appear in Error! Not a valid bookmark self-reference. and a density for R404A of 1.0673 kg/L (at 20°C).

Table 42. Carbon emission factors of refrigerants gases (Scope 1). Adapted from DECC (2014c).

Type of Transport Refrigeration Unit	Refrigerant Gas Used	Emission Factor ($KgCO_2eq$/kg gas)
Conventional and hybrid	Refrigerant R404A	3,260
Three-phase auxiliary alternator	Refrigerant R410A	1725
Lower global warming unit	Refrigerant R744A (CO_2)	1

4.6 BLOCK 4 – USING AN ANALYTIC HIERARCHY PROCESS FOR ASSESSING MULTIPLE GOALS

Internal discussions whithin MB took place for evaluating the trade-offs between net present costs, risks' aversion and the relevance of GHG emissions. This was assessed following an analytic hierarchy process methodology (Figure 85); a multicriteria decision analysis technique that allows the evaluation of quantitative and qualitative objectives. Once the qualitative importance of the priorities was clear, the outcome of the metaheuristics model (Block 3) was assessed, producing a ranking of solutions. The solution with the highest score represented the vehicle specification that better met the preferences of the industrial sponsor.

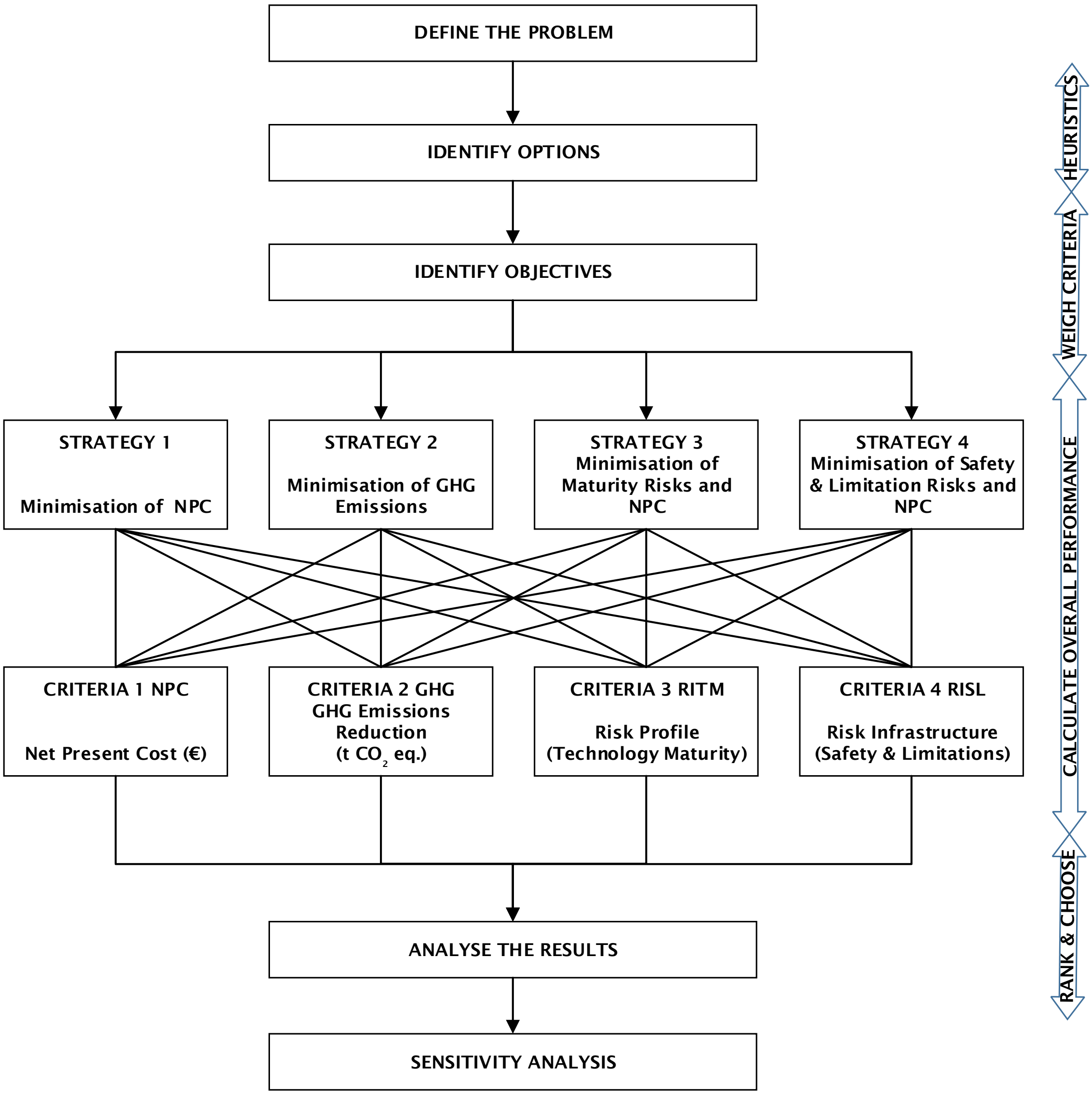


Figure 85. Hierarchy of energy efficient technology decision

While the quantitative model provided the combination of technologies that yielded the lowest total NPC of ownership when the objective function was cost minimisation, in some cases, a marginal additional cost could deliver considerably higher GHG savings. A solution could be considered riskier than another one, and the user could prefer a lower risk investment over a higher one. For this reason, the metaheuristics model was adapted to provide other solutions where other non-economic objectives were favoured. This was done by changing the objective function (minimising GHG instead of NPC) or by constraining the risk profile level of the objective function.

The AHP methodology followed 6 steps to determine the realistic alternatives that met the industrial sponsor's preferences. This was done by conducting pair-wise comparisons of the objectives (trade-offs) and of the performance of each solution in regards to each criteria. The stages of AHP are explained below:

1. DEFINE THE PROBLEM

Procure a more fuel efficient HGV (or a fleet of heterogeneous HGVs) by reducing GHG emissions cost-efficiently and with a specific risk profile acceptable by the industrial sponsor.

2. IDENTIFY OPTIONS

For each duty cycle, three scenarios were built based on low, medium and high fuel prices. For the reference scenario (central forecast), four strategies were defined. Strategy one represented a HGV with the lowest net present costs of ownership (the result of the metaheuristics financial mode with the objective function seeking to minimise costs); regardless of GHG savings, technological maturity or safety and infrastructure risks. The second strategy included all the feasible technologies that could be specified with the goal of maximising GHG emissions savings; regardless of their costs and risk levels. The third strategy minimised the total NPC accepting technologies with an RITM level of 6 (solutions with at least one technology that is being trialled) or over (more mature).In the fourth strategy, the lowest NPC configuration accepted only technologies with an RISL risk level of 6 ('No additional safety concerns or limitations with using this technology') or higher (less limited).

3. IDENTIFY OBJECTIVES

Following internal discussions among MB's directors, the industrial sponsor gave the four most relevant criteria when selecting the technologies for brand new

HGVs. The objectives were total net present cost of ownership (NPC), GHG emission savings (GHG), technology maturity (RITM) and safety and infrastructure limitation concerns (RISL). These objectives were compared to each other to produce a weight that reflected how important each objective (n) was against each other (trade-offs). The way in which this pair-wise process worked followed several steps:

- **i) Firstly, a pair-wise comparison was conducted to determine the importance of net present costs (NPC) and each one of the other three criteria.**
- **ii) Then, the same was done for the remaining criteria (GHG, RITM and RISL). The results of the comparison were input in a n x n matrix 'A' (known as the pairwise comparison matrix) similar to Table 43. The matrix is built with numbers from 1-9 (or their inverse). The entry in row i and column j of A (called a_{ij}) describes how much more important I is than objective j. The meaning of these indices is explained in Table 44. For all i, a_{ii} must be equal to '1'. In Table 43, this is shown in the values a_{11}, a_{22}, a_{33} and a_{44}.**

In the example portrayed in Table 43, GHG emissions are strongly more important (index 5) than NPC, and moderately more important (index 3) than risks. In the example, the risks of technology maturity are very strongly more important (index 7) than costs and strongly more important (index 5) than RISL. This means that for a decision maker, the final solution would be biased towards low GHG emissions and low technology maturity risk.

Table 43. Scoring Objectives (Matrix A)

Objectives (Criteria)	NPC	GHG	RITM	RISL
NPC (Net Present Costs)	1	1/5	1/7	1/3
GHG (Carbon Emissions)	5	1	3	3
RITM (Risk Technology Maturity)	7	1/3	1	3
RISL (Risk Safety & Limitations)	3	1/3	1/3	1
Total	16.0	1.9	4.5	7.3

Table 44. AHP pair-wise comparison scale. Adapted from Saaty (1990) and H.M. Treasury (2013).

1-Both criteria are equally important.
3-Criteria on the left is moderately more important than the criteria on the top.
5- Criteria on the left is strongly more important that the one on the top, according to your experience or judgement.
7- Criteria on the left is very strongly or demonstrably more important than criteria on the top.
9- Criteria on the left is extremely more important than objective on the top. The evidence favouring one objective over another is of the highest possible order of preference.
2,4,6,8 – Are intermediate values that represent preferences between two indexes when compromise is needed.

The pair wise comparisons (Table 43) need to be normalised. This is done by dividing each value in column i of matrix 'A' by the sum of the entries in column i. For example, the normalised result of the first cell in Table 45 is the result of dividing 1 by 16; sixteen being the sum of 1+5+7+3 (scores from the first column in Table 43). This yields a new normalised matrix (A_{Norm}) that in this example is represented by Table 45. The sum of each column in A_{Norm} adds up to 1. To find the weight of each criteria (w_1,w_2,w_3,w_4), the weights of each row are averaged. For example, the weight of NPC (w_1) is (0.063+0.107+0.032+0.045)/4 (Table 46). The sum of all the normalised weights is equal to 1.

Table 45. Normalised scores pair-wise comparisons (Matrix A_{Norm}).

OBJECTIVES	NPC	GHG	RITM	RISL
NPC (Cheap Net Present Costs)	0.063	0.107	0.032	0.045
GHG (Low GHG Emissions)	0.313	0.536	0.670	0.409
RITM (Low Technology maturity risks)	0.438	0.179	0.223	0.409
RISL (Low Safety & infrastructure risks)	0.188	0.179	0.074	0.136

Table 46. Weight attributed to each objective (w^T).

OBJECTIVES	NORMALISED AVERAGE WEIGHT
NPC (Cheap Net Present Costs) (w_1)	0.062
GHG (Low GHG Emissions) (w_2)	0.482
RITM (Low Technology maturity risks) (w_3)	0.312
RISL (Low Safety & infrastructure risks) (w_4)	0.144

The weights of each criteria are valid when the pair-wise comparisons have been consistent. This is checked with a consistency index (CI) that measures the deviation from the consistent approximation. For example, if a person likes A more than B (A>B), and B more than C (B>C), this means that he person likes A more than C (A>C); if the decision maker states that s/he likes C more than A (A<C) then his/her judgement is inconsistent. This is checked following several steps. Firstly Aw^T is computed by multiplying the initial matrix 'A' (Table 43) by the weights of each criteria (Table 46). In the example above, Aw^T={0.25,2.16,1.34,0.59}. In the next step, each entry in Aw^T is divided by the weight of each entry (w^T) for each criteria (the latter is the weights (w^T) that appear in Table 46) and then averaged. The result in this case is 4.32. In the third stage, the consistency index is calculated. This is the result of the previous step (4.23) minus the number of criteria (n) and then divided by n-1. The result is 4.23-4 / 4-1= 0.079. In the last step, the CI is compared with the RI for the appropriate value of n. Saaty (1990), justifies that this ratio must be inferior to 0.1. The RI is a fix value according to the number of objectives (n). As in this case there are four, the random index is 0.9. The ratio CI/RI (0.079/0.90) is 0.088 and therefore it

means that the pair-wise comparisons have been consistent enough (as 0.088<0.1). Othewise, if the matrix is not consistent, AHP cannot provide valid results. The same approach applies for the pair-wise comparisons of the performance of each of the strategies in regards to each individual criteria.

4. CALCULATE OVERALL PERFORMANCE

After obtaining the average weight score for each objective, the performance of each strategy over each target has to be calculated, based on the combinations of technologies identified in the metaheuristics quantitative model. Assuming the trade-offs stated in Table 43, each strategy was compared to the others following the same pair-wise process as explained in step 3 in regards to their performance for each single criteria (Table 47); this means that this sort of table is reproduced for each objective (in MB's case four similar tables). Taking as example the NPC objective and the values that appear in Table 48, strategy 1 is the cheapest one and strongly cheaper than strategy 2 (which is almost £26k more expensive) or strategy 4 (which is £17k more expensive). Strategy 1 is slightly cheaper than strategy 2 (only £3k of difference) and for this reason it gets a score of two.

Table 47. Scoring performance assigned by the decision maker by comparing alternative strategies (solutions) in regards to their net present cost objective.

OBJECTIVE 1: Net Present Cost	STRATEGY 1	STRATEGY 2	STRATEGY 3	STRATEGY 4
MIN NPC (STRATEGY 1)	1	5	2	4
MIN GHG (STRATEGY 2)	1/5	1	1/5	1/2
MIN NPC & RITM (STRATEGY 3)	1/2	5	1	4
MIN NPC & RISL (STRATEGY 4)	1/4	2	1/4	1

Table 48. A potential outcome of the financial model.

STRATEGY	OBJECTIVES			
	NPC (£)	GHG (t CO_2 eq.)	RITM (Risk Level)	RISL (Risk Level)
MIN NPC (STRATEGY 1)	226,318	187	4	4
MIN GHG (STRATEGY 2)	252,666	171	4	3
MIN NPC & RITM (STRATEGY 3)	229,675	195	6	4
MIN NPC & RISL (STRATEGY 4)	243,408	295	7	6

To assign values to the quantitative criteria (e.g. NPC and GHG) is much more intuitive than assigning scores to qualitative data (risk). For example, a NPC of £226k is better than another of £252k, but determining how much better by applying the scale shown in Table 44 is rather subjective. To become more consistent between different projects, Figure 86 can be helpful when there is a linear relation in the performance of one target such as the one that represents

money or GHG emissions. AHP also checks the consistency of indices, to verify that the pair-wise comparisons make logical sense.

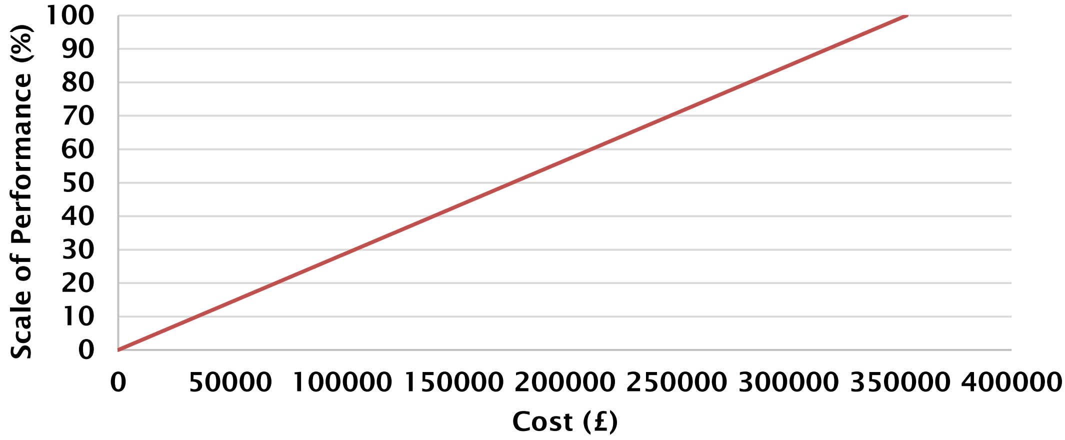


Figure 86. Possible approach to score quantitative objectives (e.g. cost).

Other objectives, especially qualitative ones, can be trickier to compare. The RITM (Table 26, page129) and RISL (Table 27, page 130) risk levels were explained in the methodology. The pair-wise comparison of qualitative criteria for each strategy (solution) was subjective and depended on the decision maker's perception (in this case perception of risks). For example, considering the RITM, a solution including a technology just released into the market (RITM level 7) is assumed to be more reliable than another one including another technology that would have been trialled (RITM level 6) but that would have not reached commercialisation. Despite the fact that some sort of linear relation between risk levels could be interpolated, in the application of the methodology, the risk aversion manifested by the industrial sponsor indicated that a logarithm approach was more suitable7. For example, solutions that only include very mature technologies (RITM level 10) were considered as demonstrably more important (AHP index of 7) than solutions that included new commercially available technologies (RITM level 7) and overwhelmingly more important (AHP index of 9) than strategies that included technologies that were being trialled at the moment of evaluation but not commercially available (RITM level 6). Figure 87 reflects this by illustrating a radical change on the scale of importance of the pair-wise comparisons for the qualitative objective. In this scoring approach, a solution with a LCT in a trial stage (RITM level 6) would be perceived almost as risky (AHP index of 1) as a technology that is being tested in a University lab (RITM level 1). In the illustration below, the decision maker would only consider that there is a considerable difference when all the technologies have a RIM of 8 or higher. This seems to be a fair assumption as reliability is critical in logistics operations, as fitting a technology that has not yet been in the market for many years could mean that the likelihood of a breakdown is higher. In a similar way, a technology without a good infrastructure support is riskier as it could lead to vehicles stranded on the roads.

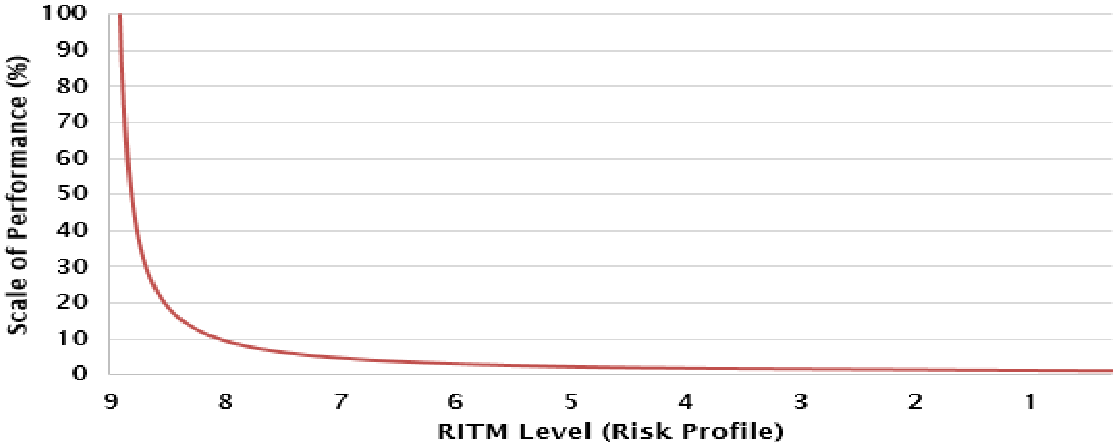


Figure 87. Possible (non-linear) approach to risk scoring.

5. ANALYSIS OF RESULTS

By applying the AHP formulation at the end a score was generated for each strategy (based on their performance on each target) and the strategy with the higher score was chosen. An example is illustrated in Table 49. Sometimes, several solutions may yield similar results and the user could decide to go for more than one alternative; however, in this particular case study, the strategies are exclusive as having vehicles with the same configuration presents advantages (e.g. less complexity to maintain the vehicles). The outcome of the AHP suggested the preferred solution for the industrial sponsor and therefore, the recommended solution that included the optimal combination of low carbon technologies according to the decision maker's preferences. The final solution represented the trade-offs between the objectives assessed.

Table 49. Final weighted score of each strategy based on the objectives selected.

Final Weighted Score	STRATEGY S1	STRATEGY S2	STRATEGY S3	STRATEGY S4
Net Present Cost (£)	0.029	0.004	0.021	0.007
GHG Emissions (t CO_2 eq.)	0.140	0.208	0.101	0.033
Risk Technology Maturity (RITM)	0.028	0.028	0.089	0.168
Risk Safety & Limitations (RISL)	0.022	0.009	0.022	0.091
Final Score	0.219	0.249	0.233	0.299

6. SENSITIVITY ANALYSIS

Conducting a sensitivity analysis of the results in regards to changes on scores or weights was very helpful to examine how different scoring and weighing changed the solution. If for example, a solution always presents the highest ranking, it makes the selection easier, as there is no room for discussion. If a couple of alternatives present similar scores, then AHP may help to resolve disagreements between stakeholders. A sensitivity analysis of the weights assigned to each criteria (Table 46, page 183) was conducted.

KEY FINDINGS OF THE METHODOLOGY

- **Data collection from secondary sources is likely to yield inconsistent FCR as the conditions under which the experiments are run and the characteristics of the vehicles used to produce the results are likely to differ considerably.**
- **Obtaining good quality data regarding the fuel consumption reductions of low carbon technologies is very difficult, even when following strict standards. Undertaking trials according to SAE J1321 Type II on public roads is prone to distortions beyond the control of the test manager. Even when conducting trials on test tracks, it is very difficult if not impossible to be consistent not only because of the human factor but also due to weather conditions.**
- **WTT Emission factors of waste-to-fuel pathways are specific to the supply chain and country, due to the emission factors of fuels, modes of transport, distances among different stages in the chain and the carbon intensity of the national energy mix used in the production and conversion processes.**
- **Simulations produce reliable data and a consistent and controlled environment to reproduce experiments.**
- **Heuristics methods allow the fast evaluation of millions of combinations; however, some algorithms provide a near optimal solution rather than a truly optimal solution. Testing all the solution space becomes quickly too time consuming when evaluating over 30 technologies.**
- **The quality of the heuristics model could be improved by considering futher synergies between technologies; however, this would require the test of those which would increase the number of experiments to unmanageable levels (technically and time-wise) considering the limitations of this research.**
- **The solutions of the quantitative model are as good as the quality of their inputs. Governmental projections have been used to reduce uncertainty to some extent; however, the results of the scenarios into the future must be taken with caution.**
- **The outcome of the multicriteria decision analysis is particular to each specific organisation, as these may define their objectives differently and their subjective perception of the differences on performance for each strategy.**
- **Sensitivity analysis of weight scores among different criteria can help to evaluate the robustness of the decision made following AHP.**

5. RESULTS

Chapter Aims:

To identify and quantify the potential of the fast food supply chain to generate fuels from waste streams.

To calculate the GHG emission factors of different fuel pathways

To reveal the fuel consumption reduction of several low carbon technologies following simulations and the results of a real world trial of spray suppression mudflaps.

To present the combination of technologies that minimises the vehicle's net present cost of ownership, GHG emissions and risks, under different scenarios and strategies.

To justify the multicriteria goals established to yield the optimal solution.

To provide a suggested vehicle specification that meets the multiple goals of the industrial sponsor.

The results have been organised in five sections, according to the chronological order in which they were conducted (Figure 88). In section 5.1, the fuel consumption reduction of several simulated technologies are presented. In the section 5.2 the fuel savings results of live trials are revealed. In section 5.3 the results of a waste-to-fuel audit are described in detail. The outcomes of these three sections and the literature review were used as inputs in the metaheuristics model. Section 5.4 presents the results of the quantitative model according to different scenarios. In section 5.5, after revealing the relative importance of different criteria for the industrial sponsor, the four solutions for each scenario are ranked to provide the vehicle specification that meets the multiple objectives of the sponsor organisation.

5.1 SIMULATING THE IMPACT OF LOW CARBON TECHNOLOGIES

The methodologies followed to produce the results here presented were explained in detail in the simulation section (Section 4.2.1, page 133). A series of experiments were conducted to ascertain the fuel savings achievable from several low carbon technologies and assessing the suitability of different approaches to get those results. The results were compared to the figures reported by Hill et al. (2011); the main source of fuel consumption reduction values used in the metaheuristics model. The techniques used to calculate the FCR of individual technologies include CFD, vehicles and trips simulations in a 3D environment. The outcome of these experiments were used to amend some of the inputs used in the quantitative model.

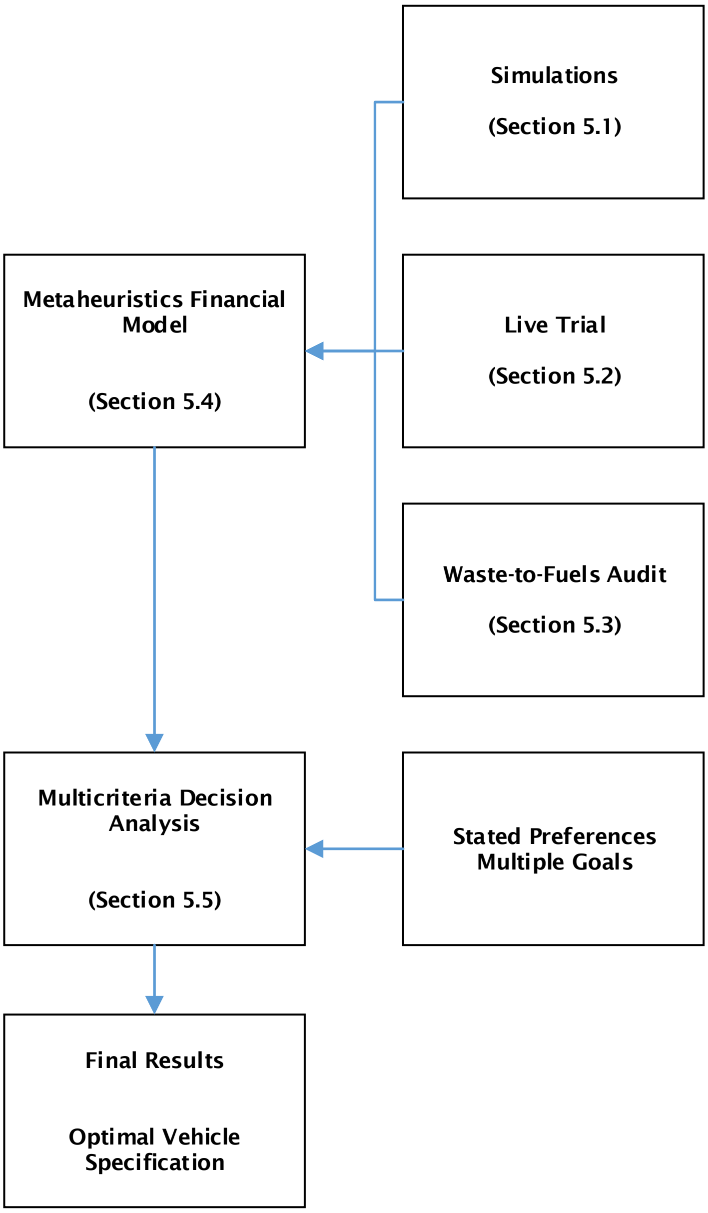


Figure 88. Structure of the results chapter.

5.1.1 AERODYNAMIC IMPROVEMENTS

CFD was used as a simulation technique for assessing aerodynamic improvements; according to the methodology stated in section 4.2.1.3 (Page 143). Based on data from the DAF Trucks (2015) repository, a DAF CF65 lorry and a DAF CF85 tractor unit were modelled. CFD simulations need to do complex and time consuming calculations. The simulations here presented were run on a virtual wind tunnel for 60 minutes; firstly on a simulated DAF CF65 rigid box lorry with no aerodynamic improvements. The results found that at 90km/h, the aerodynamic drag coefficient (C_D) was 0.60 and the resistance force was 2,347 N

(Figure 89). At the same speed, the same vehicle with roof and collar fairings installed, presented a much lower drag coefficient (Cd=0.46) which resulted in a force of 1,796 N (Figure 90). This translated to a power difference of 13.7 kW and an increase in fuel consumption of 1.42 l/100km. Assuming an average fuel consumption of 23.5 l/100 km for a 18t GVW HGV this represented fuel savings of 6%. However, this is not a realistic prospect as urban vehicles are unlikely to run at such a high speed.

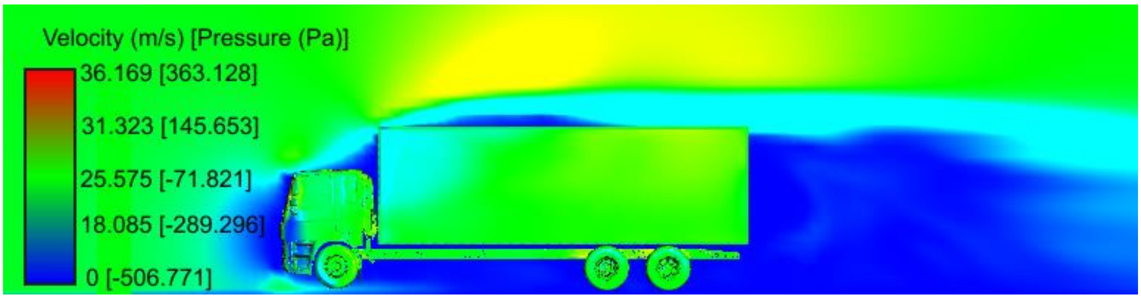


Figure 89. Aerodynamic drag at 90 km/h for a simulated rigid lorry is 2,346.7 N (Cd=0.60).

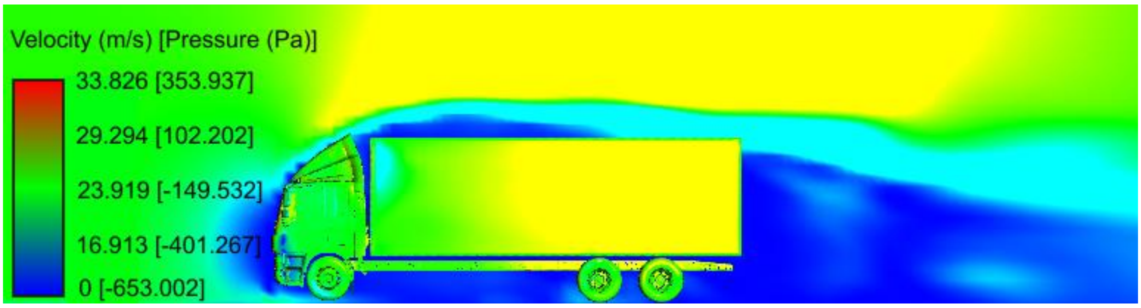


Figure 90. Aerodynamic drag at 90 km/h for a simulated rigid lorry is 1,796 N (Cd=0.46).

At lower speeds however, the benefits from aerodynamic improvements are much more modest, worsening the business case for their purchase. At a speed of 36 km/h (a normal speed in city logistics), the difference between a lorry without aerodynamic improvements (Figure 91) and another with them (Figure 92) results in a reduction of 1 kW. This translates to FCR of 1 l/100km or around 4.2%. From a frontal perspective, this is illustrated in Figure 93 (36 km/h) and Figure 94 (90km/h), where it can be seen that roof and collar fairings displaced wind flows reducing drag forces.

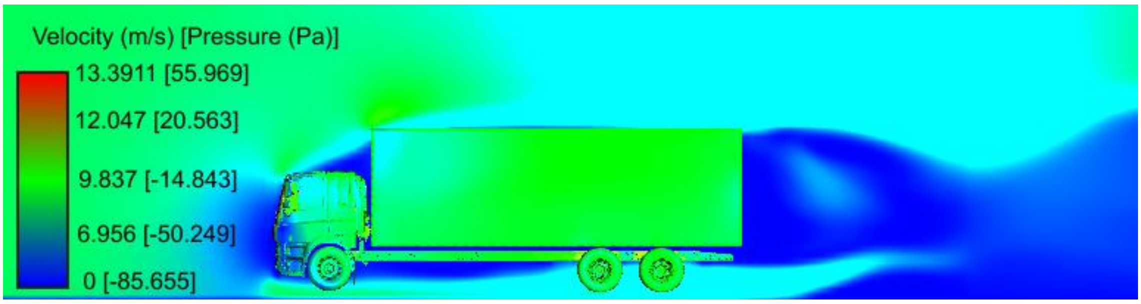


Figure 91. Aerodynamic drag at 36 km/h for a simulated rigid lorry is 368 N (Cd=0.60).

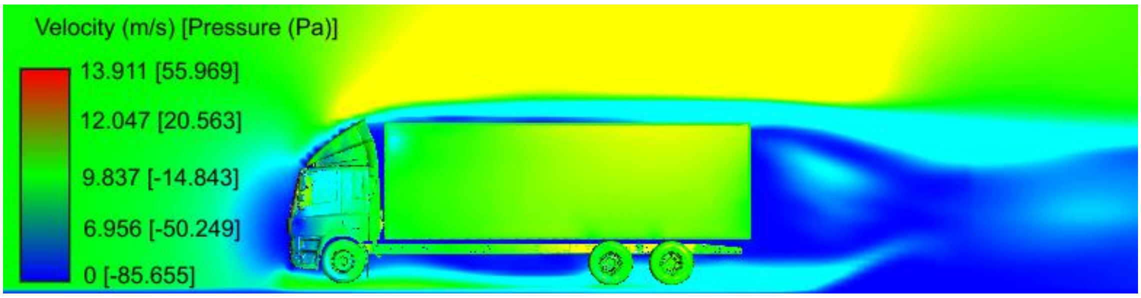


Figure 92. Aerodynamic drag at 36 km/h for a simulated rigid lorry is 261 N (Cd=0.46).

The drawings on the right of Figures 93 and 94 display lower pressure than the vehicles on the left. This indicated that aerodynamic improvements were efficient technologies for reducing drag forces, and therefore energy consumption. A similar study for a simulated DAF CF85 tractor units (with no trailers) has been included in Appendix 13.

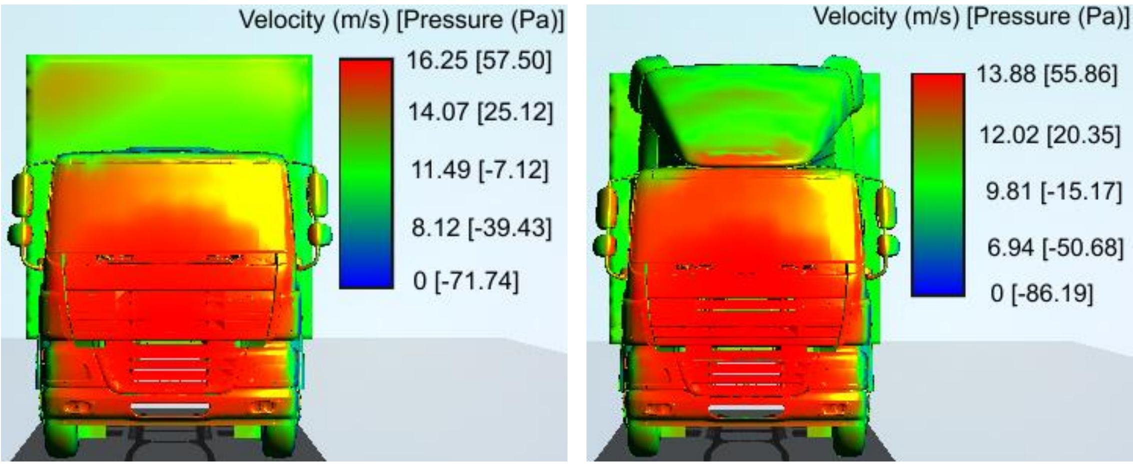


Figure 93. Frontal view of a simulated DAF CF65 at 36 km/h without roof and collar fairings (left) and with them (right).

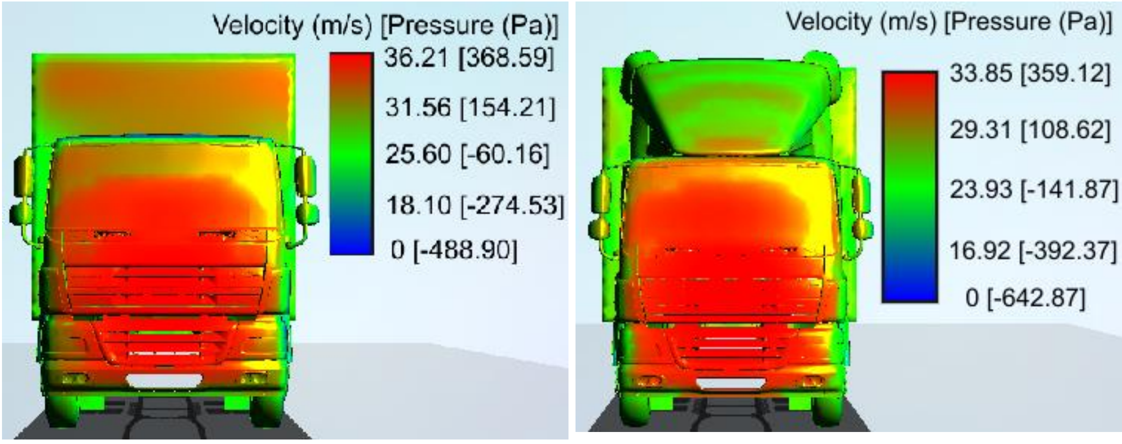


Figure 94. Frontal view of a simulated DAF CF65 at 90 km/h. without roof and collar fairings (left) and with them (right).

Two videos of the simulations undertaken have been included in the CD accompanying this thesis.

5.1.2 VEHICLES AND TRIPS SIMULATIONS

Simulations of light weighting materials and speed limiters fitted on a DAF CF85 over a virtual path were conducted to validate the results found in the literature. The engineering parameters of the virtual vehicle appear in Appendix 7. The FC of the virtual DAF CF85 was 30 L/100 km and the one in the real world is around 30.49 L/100 km (1.6% higher). This has been considered to be an acceptable difference that should not distort the findings of the simulations.

Simulations reproduced a 4x2 axle semi articulated trailer, with weights of 6.5 (tractor unit) and 4.8 tonnes (trailer unit) respectively plus a cargo load of 10 tonnes. The baseline conditions for the virtual vehicle considered that the fuel tank of the virtual vehicle was filled-up with 400 L of diesel and without speed limiters (maximum speed set at 90 km/h). The simulations reproduced the real driving cycle rendered by professional drivers driving from Basingstoke to Cornwall (route 'A') and from Basingstoke to Bristol (route 'B'), as read from the vehicles' telematics data used by the industrial sponsor. The main difference between both routes was that the percentage of motorway driving was higher in route 'B'. The driving cycles were statistically analysed with DRIVE and the time-speed points of the statistically representative driving cycle were imported as an external input for driving manoeuvres in IPG Truckmaker as described in section 4.2.1 (Page 133). Based on a series of data files with GPS coordinates for the period studied, the original cycles were filtered, corrected, aggregated and a representative compressed cycle was built. DRIVE also compared several statistical variables such as maximum speed and average speed with other standard cycles. Details of the statistical analysis of a driving cycle appears in Appendix 8. The result of an analysis made with DRIVE of the driving cycles is shown in Figure 95.

An animation of a simulated vehicle has been included in the CD accompanying this thesis.

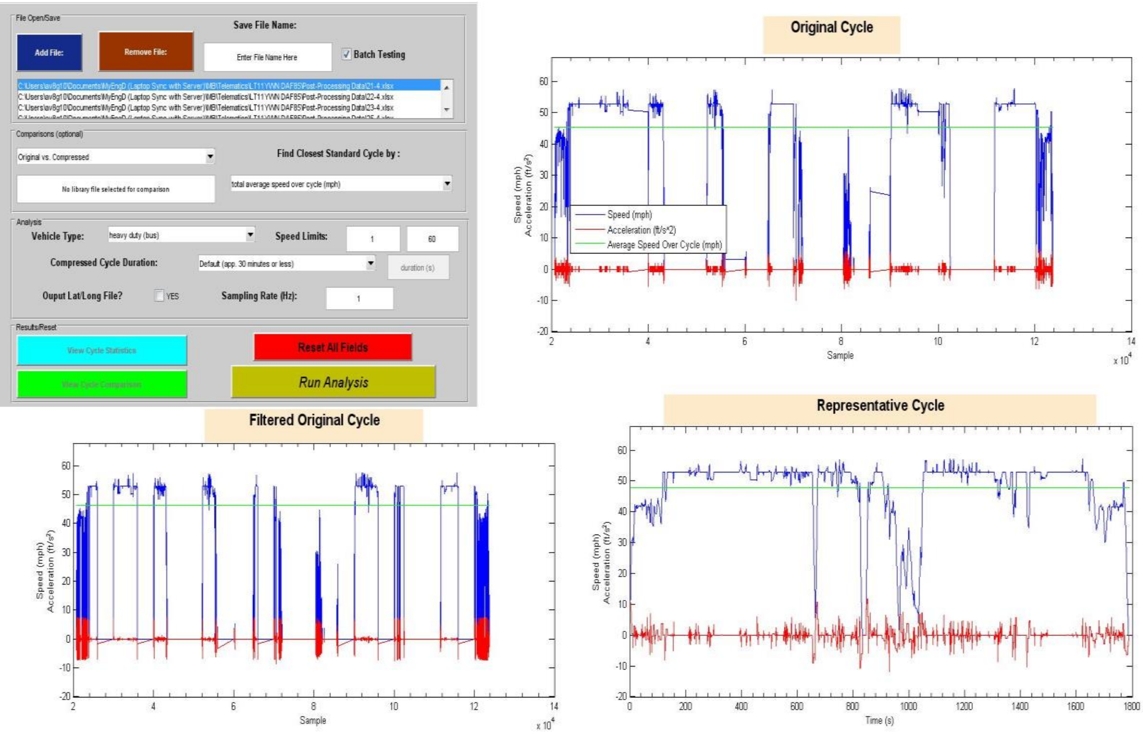


Figure 95. Statistical analysis of driving cycles using DRIVE TOOL for trips conducted from 21stApril to 1stMay 2013.

5.1.2.1 SIMULATING WEIGHT REDUCTION TO IMPROVE FUEL CONSUMPTION

It is reported in the literature that it is possible to reduce FC by up to 2.2% by reducing vehicle mass by 450kg in long haul duty cycles (Table 7, page49). This was tested by simulating a similar weight reduction in route 'A' (Table 50). The results suggested that reducing the vehicle mass by 500 kg could save 1.17% of fuel. Bearing in mind that mass has an impact on the power required to overcome gradient, the difference can be explained on the profile of the road used to conduct the test. As the results seem fairly consistent with the values reported in the literature (Hill et al., 2011), a FCR value of 2.2% was used in the financial model. A weight reduction of 500 kg could be achieved by using an aluminium and composite materials to manufacture trailer frames, fuel tanks or wheels rims (further alternatives were mentioned in section 3.5.1.2, page 49). During this research, the possibility of reducing the weight of roll cages was also explored. Each rolling cage weighs 34.5 kg including the base (dolly) and each trailer can carry up to 41 cages. By eliminating the metallic frame (walls) and wrapping the load with plastic film, it is likely that more than half a tonne of weight could be avoided. This sort of weight reduction should reduce fuel consumption by 1.17% approximately. After a visit to the facilities of the industrial sponsor in Manassas (USA, Washington) it was observed that this was the approach taken; however, the challenge of this approach was that bits of plastic film ended sometimes in the transport refrigeration evaporator units, with the potential of increasing maintenance costs of the mechanical refrigeration devices. An alternative that was pursued was using rolling cages with plastic walls; however, none was found that could offer a similar performance to the ones currently used by MB.

Table 50. Simulation of lightweight materials on route ‘A’ (500kg mass reduction).

N	Trip Time (s)	Speed Limiter (Km/h)	Vhcl.Distance (km)	PT.Engine. Consump_Abs (L)	Fuel Economy (Km/L)	Average Consumption (L/km)	Weight
1	27822	90	501.88	156.661	3.203	0.312	-500 kg
2	27823	90	501.87	158.520	3.166	0.316	Baseline

After conducting this experiment, it was decided to test whether a refuelling strategy consisting of filling the vehicles’ fuel tanks with smaller amounts of fuel could deliver any noticeable fuel savings by using the principle of mass reduction. The simulations in route ‘A’ (Table 51) showed that when the speed was 90 km/h, the fuel consumption decreased by almost 0.2% when the fuel tank was filled with 100 litres less of fuel (300 L instead of 400L). Similarly, when the fuel tank was filled with 200 L less, the reduction of 166 kg of fuel mass led to fuel savings of 0.39% and the vehicle could end the trip with enough fuel (42 L) to return to the DC. This was the result of subtracting the total fuel carried (200L) to the 158 Lconsumed during the trip. This meant that it was possible to save fuel by reducing the amount of fuel carried in the vehicle’s tank.

A similar study was conducted for route ‘B’ (Table 52) where reducing fuel from 400L (simulation 36) to 96L (simulation 31) yielded savings of 0.51%. In this case, the vehicle could save around 4 L of fuel (~£3.88 at current prices) in each round trip; however, the vehicle would arrive to the depot almost empty. Companies must evaluate the risk of running with low fuel levels due to congestion and the possibility of getting stranded during extreme weather events. On the plus side, if companies link their refuelling policy to their routing and scheduling software and smart refuelling monitoring systems, they could reduce the fuel consumption across their fleets.

Table 51. Fuel consumption and savings, and travelling time of 15 simulations where weight and speed reductions have been combined, for a round multi drop delivery trip between Basingstoke and Cornwall (Route A).

N	Trip Time (s) Extra Time (%) vs. Baseline (90km/h)	Speed Limiter (Km/h)	GVWR	Vhcl.Distance (km)	PT.Engine.Consump_Abs (L)	Fuel Economy (Km/L)	Average Consumption (L/km)	Weight Fuel in Tank (1L fuel=0.832kg)	FCR vs. Baseline (Simulation 15) (%)
1	31372	70	22415	501.878	137.622	3.647	0.274	200 L = 166.4 Kg	-13.18
2			22499	501.878	137.940	3.638	0.275	300 L = 249.6 Kg	-12.98
3	12.76 %		22582	501.877	138.259	3.630	0.275	400 L = 332.8 Kg	-12.78
4	29932	75	22415	501.878	142.209	3.529	0.283	200 L = 166.4 Kg	-10.29
5			22499	501.875	142.513	3.522	0.284	300 L = 249.6 Kg	-10.1
6	7.58 %		22582	501.874	142.829	3.514	0.285	400 L = 332.8 Kg	-9.9
7	28750	80	22415	501.869	150.352	3.338	0.300	200 L = 166.4 Kg	-5.15
8			22499	501.867	150.655	3.331	0.300	300 L = 249.6 Kg	-4.96
9	3.34 %		22582	501.866	150.970	3.324	0.301	400 L = 332.8 Kg	-4.76
10	27872	85	22415	501.862	157.430	3.188	0.314	200 L = 166.4 Kg	-0.69
11			22499	501.859	157.735	3.182	0.314	300 L = 249.6 Kg	-0.5
12	0.18%		22582	501.880	158.055	3.175	0.315	400 L = 332.8 Kg	-0.29
13	27823	90	22415	501.878	157.898	3.178	0.315	200 L = 166.4 Kg	-0.39
14	Baseline Max		22499	501.875	158.203	3.172	0.315	300 L = 249.6 Kg	-0.2
15	Speed		22582	501.873	158.520	3.166	0.316	400 L = 332.8 Kg	0

Table 52. Fuel consumption of 36 simulations where weight and speeds reductions have been combined (Route B).

N	Time (s) Extra Time (%)	Speed Limit (Km/h)	GVW	Vhcl.Distance (km)	Fuel Consumption (L)	Fuel Economy (Km/L)	Av. Consumption (L/km)	Weight Fuel in Tank (1L=0.832kg)	FCR vs. Baseline (%)
1	17207 18.61 %	65 16%	22329	268.43	80.51	3.3341	0.30	96.1L=80kg	-16.29
2			22449	268.43	80.75	3.3245	0.30	240.4L=200kg	-16.04
3			22499	268.43	80.85	3.3203	0.30	300L=249.6Kg	-15.94
4			22540	268.43	80.93	3.3169	0.30	350L=291kg	-15.85
5			22559	268.43	80.97	3.3153	0.30	372.6L=310kg	-15.81
6			22582	268.43	81.01	3.3134	0.30	400L=332.8Kg	-15.76
7	16294 12.32 %	70 0.10 %	22329	268.43	86.05	3.1197	0.32	96.1L=80kg	-10.53
8			22449	268.44	86.28	3.1111	0.32	240.4L=200kg	-10.28
9			22499	268.43	86.38	3.1074	0.32	300L=249.6Kg	-10.18
10			22540	268.43	86.47	3.1044	0.32	350L= 291kg	-10.09
11			22559	268.43	86.51	3.1030	0.32	372.6L=310kg	-10.05
12			22582	268.43	86.55	3.1014	0.32	400L=332.8Kg	-10.00
13	15539 7.12 %	75 0.08 %	22329	268.44	88.11	3.0467	0.33	96.1L= 80kg	-8.39
14			22449	268.44	88.34	3.0388	0.33	240.4L=200kg	-8.15
15			22499	268.44	88.44	3.0354	0.33	300L=249.6Kg	-8.04
16			22540	268.44	88.52	3.0326	0.33	350L=291kg	-7.96
17			22559	268.44	88.56	3.0313	0.33	372.6L=310kg	-7.92
18			22582	268.44	88.60	3.0297	0.33	400L=332.8Kg	-7.87
19	14934 2.95 %	80 0.04 %	22329	268.42	92.15	2.9128	0.34	96.1L=80kg	-4.18
20			22449	268.42	92.38	2.9056	0.34	240.4L=200kg	-3.94
21			22499	268.42	92.48	2.9024	0.34	300L=249.6Kg	-3.84
22			22540	268.42	92.56	2.8998	0.34	350L=291kg	-3.75
23			22559	268.42	92.60	2.8987	0.34	372.6L=310kg	-3.71
24			22582	268.42	92.65	2.8972	0.35	400L=332.8Kg	-3.67
25	14528 0.15 %	85 0.00 %	22329	268.43	95.44	2.8127	0.36	96.1L=80kg	-0.77
26			22449	268.43	95.67	2.8059	0.36	240.4L=200kg	-0.53
27			22499	268.43	95.77	2.8029	0.36	300L=249.6Kg	-0.42
28			22540	268.43	95.85	2.8006	0.36	350L=291kg	-0.34
29			22559	268.43	95.88	2.7995	0.36	372.6L=310kg	-0.30
30			22582	268.43	95.93	2.7981	0.36	400L=332.8Kg	-0.25
31	14506	90 Baseline	22329	268.43	95.68	2.8055	0.36	96.1L=80kg	-0.51
32			22449	268.44	95.91	2.7988	0.36	240.4L=200kg	-0.27
33			22499	268.43	96.01	2.7959	0.36	300L=249.6Kg	-0.17
34			22540	268.43	96.09	2.7936	0.36	350L=291kg	-0.09
35			22559	268.43	96.13	2.7925	0.36	372.6L=310kg	-0.05
36			22582	268.43	96.17	2.7911	0.36	400L=332.8Kg	0

5.1.2.2 SPEED LIMITATION DEVICES

As speed has such a considerable impact on fuel consumption (for further reference see Equation 3 and Equation 4, page 33), it was reasonable to evaluate whether fitting a speed limiter device could have any noticeable impact on the sponsor's operations and the vehicles' fuel consumption. MB's vehicles have a device similar to the one that appears in Figure 96. This notifies drivers when they are over speeding or when the revolutions of the engine are over an optimal threshold. As the maximum speed is set up at the motorway legal limit of 90 km/h (56mph), the simulations showed that in route 'A', vehicles departing with a full fuel tank could save up to 12.78% of diesel by reducing their speed to 70 km/h (Table 51) and 10% in route 'B' (Table 52). The fuel savings achieved and the extra time needed to cover the same trip's distance appear in both Tables, as well as the extra savings from reducing fuel tank load (lower weight). For example, taking as reference a baseline vehicle on route 'A', reducing the speed from 90km/h (simulation 15) to 70km/h (simulation 1) and loading the fuel tank to half of its capacity yields savings of 13.18%. In route 'B', limiting speed to 70km/h (simulation 8) from 90km/h (simulation 36) and filling the fuel tank to 200kg would save 10.28% of fuel. Reducing the speed of urban lorries was not investigated as reducing vehicle speed too much increases fuel consumption due to the efficiency points on the engine map and there is not much scope to reduce speed in urban areas anyway as the top speed is already low.

Figure 96. Mix Telematics driving assistance device.

Decreasing the vehicle speed limit inevitably increases a trip's time which is very likely going to compromise time windows. In route 'A', the travelling time increased by 12.76% (Table 51), when limiting speed to 70km/h. This in turn compromised time windows and any savings achieved might be cancelled off by the need to deploy further vehicles to provide the expected levels of service to the customers. Moreover, this extra time increased driver's labour costs, as shown in Table 53. In route 'B', the travelling time increased by 12.32% when speed was limited to 70 km/h (Table 52).

A simplistic cost analysis of the impact of reducing speed from 90km/h to 70 km/h for an articulated truck with fully loaded fuel tanks in two different routes (excluding time windows impacts), showed that transportation costs decreased by around 1.9%-2.2%. (Table 53 and Table 54). However, it was more economically efficient to limit the speed of the vehicles to 75 km/h as savings were between 2.49-2.76% (£4.17 and £6.58 per trip for routes 'A' and 'B' respectively). This is consistent with the savings of up to 3% reported by National Research Council (2012). Extrapolating this to the whole fleet and routes, it seems that despite the fact that there is potential for fuel savings and carbon emissions, the economic savings are small unless fuel prices increase. In this evaluation, it was assumed that the fuel cost was £0.96/L and labour cost was of £15/hr. for the drivers and staff refuelling the vehicles. In Tables 53 and 54, it is considered that fuel tanks can be filled up in 10 minutes and the cost of refuelling for vehicles is proportional to the time and the fuel saved. The assumption was that a vehicle that saved a 15% of fuel, decreased refuelling time by the same percentage.

Limiting vehicle speed saves fuel, carbon emissions and potentially transportation costs. The impact on time windows must be studied in detail as this could lead to rebound effects; more vehicles may be needed to meet service levels which could produce the opposite effect. The trade-offs between time and cost are illustrated in Figure 97 (route 'A') and Figure 98 (route 'B'). Limiting vehicle speed in route 'A' yielded higher FCR than in route 'B'; however, the travelling times also increased.

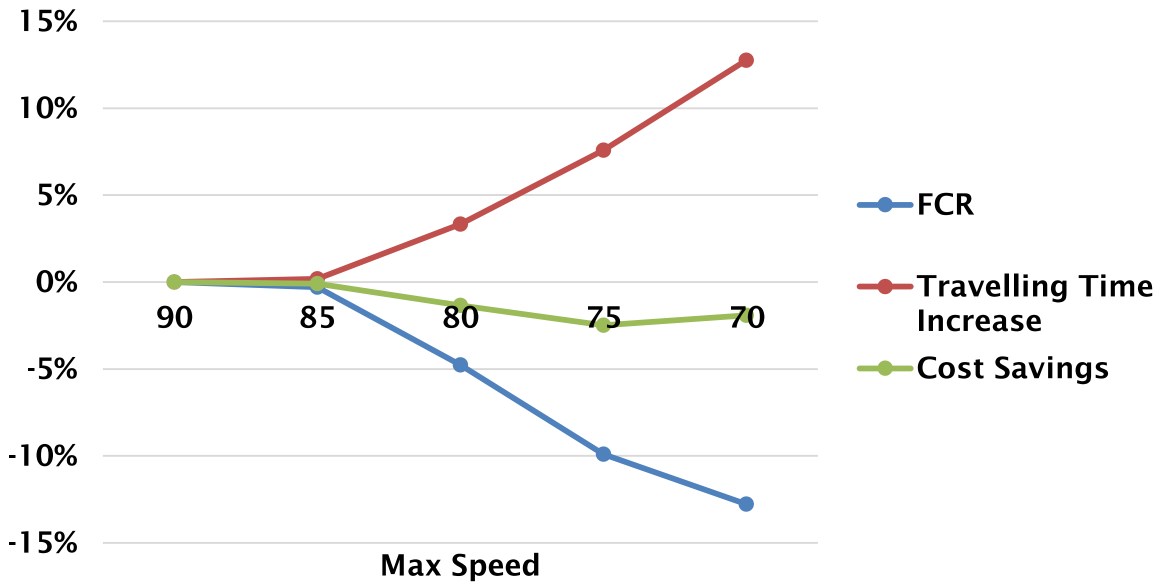


Figure 97. Impacts of Speed Limiters on Fuel consumption, travelling time and total costs for route 'A' (values based on Table 53).

Table 53. Transportation Costs Savings from reducing speed from 90 to 70 km/h, for an articulated truck with a full loaded tank, excluding time-windows impacts for a round trip between Basingstoke and Cornwall (regional roads).

Sim.	Speed	FCR	Fuel Consumption Savings	Fuel Costs Savings	Refuelling Costs Savings	Travelling Time Increase		Labour Costs Increase	Total Trip Costs Change	Cost Savings
N	Km/h	(%)	(L)	(£)	(£)	(%)	Total Min	(£)	(£)	(%)
3	70	-12.78%	-20.26	-19.53	-0.32	12.76%	59.17	14.79	-5.05	-1.91%
6	75	-9.90%	-15.69	-15.12	-0.25	7.58%	35.17	8.79	-6.58	-2.49%
9	80	-4.76%	-7.55	-7.28	-0.12	3.34%	15.47	3.87	-3.53	-1.33%
12	85	-0.29%	-0.47	-0.45	-0.01	0.18%	0.83	0.21	-0.25	-0.09%
Sim. Baseline	Speed	FCR	Fuel Consumption	Fuel Costs	Refuelling costs	Travelling Time (hrs.) (min)		Labour Costs	Total Trip Costs	Cost Savings
15	90	0.00%	158.520	152.77	2.50	7.73	464	115.93	264.36	0.00%

Table 54. Transportation Costs Savings from reducing speed from 90 to 70 km/h for an articulated truck with a full loaded tank, excluding time-windows impacts for a round trip between Basingstoke and Bristol (motorway roads).

Sim.	Speed	FCR	Fuel Consumption Savings	Fuel Costs Savings	Refuelling Costs Savings	Travelling Time Increase		Labour Costs Increase	Total Trip Costs Change	Cost Savings
N	Km/h	(%)	(L)	(£)	(£)	(%)	Total Min	(£)	(£)	(%)
12	70	-10.00%	-9.62	-9.27	-1.50	12.33%	29.8	7.45	-3.32	-2.19%
18	75	-7.87%	-7.57	-7.30	-1.18	7.12%	17.2	4.30	-4.17	-2.76%
24	80	-3.67%	-3.53	-3.40	-0.55	2.94%	7.1	1.78	-2.17	-1.43%
30	85	-0.25%	-0.24	-0.23	-0.04	0.15%	0.4	0.09	-0.18	-0.12%
Sim.	Speed	FCR	Fuel Consumption	Fuel Costs	Refuelling costs	Travelling Time		Labour Costs	Total Trip Costs	Cost Savings
36	90	0.00%	96.174	83.57	2.50	4.03	242	60.44	151.479	0.00%

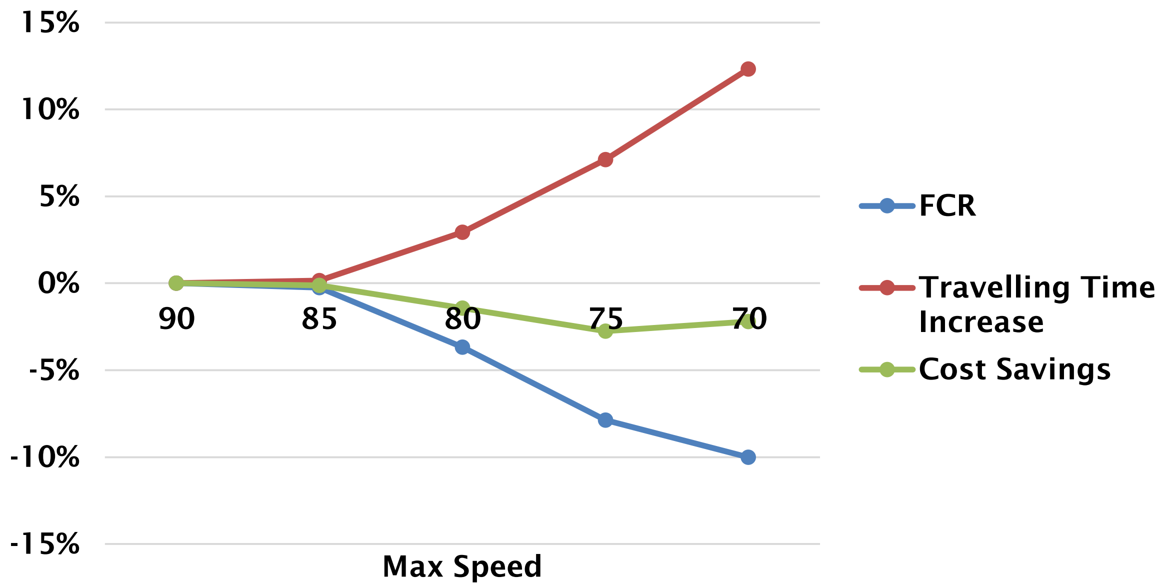


Figure 98. Impacts of speed limiters on fuel consumption, travelling time and total costs for route 'B' (values based on Table 54).

5.2 LIVE TRIAL

A low carbon technology trial was produced to find out the fuel consumption reduction that spray suppression mudflaps could deliver under real world conditions. The trial was conducted with two vehicles (a control and a test vehicles) over two full days running three 100 km round trips each per day. The live trial followed the methodology of the SAE J1321 Type II standard, whose details were described in section 4.3 (page 145).

5.2.1 SPRAY SUPPRESSION MUDFLAPS

According to the literature review (Table 10, Page 55), a patented design of spray suppression mudflaps (Figure 99) sold by Spraydown Ltd. was a cost-efficient investment regardless of duty cycle. The industrial sponsor was considering fitting such a device across the fleet and this presented a good opportunity to validate the supplier claims (fuel savings) and also contrasting the results with the ones found in the literature. Following the SAE J1321 methodology explained in Chapter 4 and under the conditions revealed in Appendices 9 and 10, the trial of this low carbon technology indicated that for the number of trials conducted, fuel savings were 1.5% ±4.85% (Table 55). Unfortunately, such a large confidence interval means that it cannot be concluded with certainty that such device has a real impact on fuel consumption. Despite that the standard SAE J1321 states that the minimum number of runs for each segment is three, the power analyses conducted showed that to achieve a confidence interval of 95%, the number of trips (samples) should be 11 per vehicle during each day of the trial for the F-test and 54 for the t-test. With the three trips underdaken, the confidence of the F-test was 24% and the one of the t-test just 10%. Statistical power analyses for this experiment are illustrated in Appendix 14.

Figure 99. Spray suppression mudflap device (left) and once it is fitted on the vehicle (right).

Table 55. Results of the Spray suppression trial (SPM=spray suppression mudflap technology).

Baseline Segment (Day 1)			
Run Number	Lbs. Diesel Consumed		T/C
	Test HGV (No SPM)	Control (No SPM)	
1	81.24	78.48	1.0351
2	78.37	79.37	0.9875
3	79.26	80.69	0.9822

Test Segment (Day 2)			
Run Number	Lbs. Diesel Consumed		T/C
	Test HGV (With SPM)	Control (No SPM)	
1	79.70	80.42	0.9910
2	80.69	81.35	0.9919
3	84.33	86.31	0.9770

Summary Stats	Baseline	Test
Mean T/C	1.0016	0.9866
Number of Data Points	3	3
Standard Deviations	0.0291	0.0083
Variances	0.0008483	0.0000696
Difference in Means	0.0150	

F-Test for Equal Variances	
Baseline T/C Variance	0.00085
Test T/C Variance	0.00007
F test stat (test/baseline)	0.08210
F low	0.02564
F high	39.00000
Are Variances Equal?	yes

t-Test with Equal Variances (2-tailed)	
Pooled St dev	0.02142
t-critical	2.776
t-stat (t_0)	0.856
Is Fuel Economy Improved?	no
P-value	0.4400
lower CI bound	-0.0335
upper CI bound	0.06354

CI t-critical	2.776
CI std err term	0.01749

Test Result		
	Nominal	Confidence Interval
Fuel Saved	1.50%	± 4.85%
Improvement	1.52%	± 4.92%

The SAE methodology compares the mean fuel consumption between a test and a control vehicle, with a confidence level of 95% (α= 5%). To chose the right statistical test for equality of means, it is necessary to test firstly for equality of variance in the baseline Test/Control (T/C) ration samples and test segment T/C ratio samples. These baseline (day one) and test (day two) segment samples were assumed random observations from normal populations. The null hypothesis (H_0)states that variance in the fuel consumption T/C ratio of baseline segment (σ_B^2) and the test segment (σ_T^2) is equal. The alternative hypothesis (H_1) states the opposite (variances are not equal).

$$H_0: \sigma_T^2 = \sigma_B^2$$

$$H_1: \sigma_T^2 \neq \sigma_B^2$$

Population variances of the T/C ratio for the baseline segment (σ_B^2) and the test segment (σ_T^2) are estimated by sample variances (S^2) which are first calculated for each of the segments. The ratio of the sample variances forms the F-test statistic (F_0).

$$F_0 = \frac{S_T^2}{S_B^2}$$

F_0 must fall between the limits defined by the confidence level (1-α=95%) and the number of samples in the test segment and the baseline segment. If F_0 is not within the interval, the variances are not equal. The outcome of the F-test (0.082) indicated that variances between baseline runs (day 1) and testing runs (day two) were equal (between F low and F high). Next, a t-test for equal variances was conducted.

As the variances are equal, the null hyphotesis (H_0) for equality of means states that the mean fuel consumption T/C ratio of the test segment (μ_T) population, must be equal to the one of the baseline segment (μ_B), and the alternative hyphotesis states the opposite (H_1).

$$H_0: \mu_T = \mu_B$$

$$H_1: \mu_T \neq \mu_B$$

After the test and control trips have been conducted, the test statistic t_0 must be calculated. The numberator represents the difference in T/C means between the trips and denominator an stimated (pooled) of the T/C ratio sample standard deviation (S_p) and the number of samples in each segment (n_B and n_T).

$$t_0 = \frac{\overline{y_B} - \overline{y_T}}{S_P\sqrt{\frac{1}{n_B}+\frac{1}{n_T}}}$$

The estimate of the variance (S_p^2) is calculated by weighing each variance for the baseline and test segments by their degrees of freedom (the number of samples less

one for the estimation of the mean). The overall degrees of freedom for the J1321 test are $v = n_B + n_T - 2$.

$$S_p^2 = \frac{(n_B - 1)S_B^2 + (n_T - 1)S_T^2}{v}$$

For equal variances 2-tailed test with level of significance α=0.05, the difference in means will be significant if $t_0 > t_{\alpha/2,v}$ or $t_0 < t_{-\alpha/2,v}$. This means that we reject H_0 and therefore the fuel consumption T/C ratio between test and baseline segments is different (e.g. it is statistically significant that one vehicle consumes more than the other). Alternatively, not rejecting the null hypothesis means that the average fuel consumption T/C ratio between both vehicles as measured following this standard is equal (e.g. fuel savings cannot be concluded between baseline and test vehicle). As the t-statistic (0.856) was lower than the t-critical value (2.77) the null hypothesis could not be rejected; this means that the T/C average fuel consumption between both vehicles was the same. Also, as the p value was 0.44 this means that the results were not statiscially significant.

A 95% confidence interval (α=0.05) on the difference in means is calculated using as follows:

$$\overline{y_B} - \overline{y_T} \pm (t_{\frac{\alpha}{2},v})\sqrt{\frac{S_B^2}{n_B} + \frac{S_T^2}{n_T}}$$

The results of the statistical test showed a confidence interval larger than the percentage of fuel savings being measured. The nominal value (highlighted in yellow colour in Table 55) reflects the fuel consumption savings as a result of the changes on the test vehicle (the vehicle where the energy efficient technology was being tested). The nominal fuel improvement of 1.52% was much smaller than the confidence interval (±4.92%). Even if this would have been statistically significant, this would have meant that spray suppression mud flaps could increase fuel consumption by as much as 3.4% or reduce it up to 6.44% . As a result, it was not possible to conclude from this live trial that the technology yielded any benefits. Fruther methodological details of the statistics behind this analysis are explained in the SAE J1321 Type II standard (SAE, 2012).

As those trials must be conducted under very controlled circumstances, to obtain statistically significant results, a considerable investment is needed. Table 56 enumerates the costs involved in a two day trial for three trips per vehicle each day. Some of the expenses are accrued just once (e.g. data loggers, installation of these and weather station); this means that further trials cost around £1,814 per day, as of day one trial (baseline segment) does not need to be repeated again, as long as the test and control vehicles are the same and the technology of the test vehicle is uninstalled.

Otherwise, the trials of further technology would represent the outcome of the combined technologies.

Unfortunately, as day 1 was run under optimal conditions (dry, warm and no wind) and day 2 was not (rainy, cold and slightly windy), this trial did not meet SAE J1321 Type II environmental constraints; however, all the other methodological aspects were followed rigorously. The temperature was under the minimum threshold of 4.4˚C until11.20 am (Figure 100), the variation was over 1.1˚C and it rained 5 times. Unfortunately, these conditions breached the mandatory requirements established in the standard.

Table 56. Cost of conducting a low carbon technology trial for a single technology.

Expense Description	Quantity	Unit	Cost / Unit (£)	Total (£)
Data logger	2	Units	139.1	278.3
Drivers (2 drivers x 2 days)	48	Hrs.	15	720
Engineering Assistance	2	Days	700	1400
Fuel (Trial + Trip to trial location)	550.7	L	0.96	528.7
Installation Data logger	2	Times	300	600
Researcher	24	Hrs.	15	360
Scale (fuel tank weighting)	1	Week	70	70
Vehicles (2 HGVs x 2 days)	4	Units	73.37	293.5
Weather station	1	Units	358.9	358.9
Weighing whole vehicle	1	Units	160	160
Travelling expenses (researcher)	348	km	0.28	97.44

Total Spray Suppression Mudflaps Trial £4,867

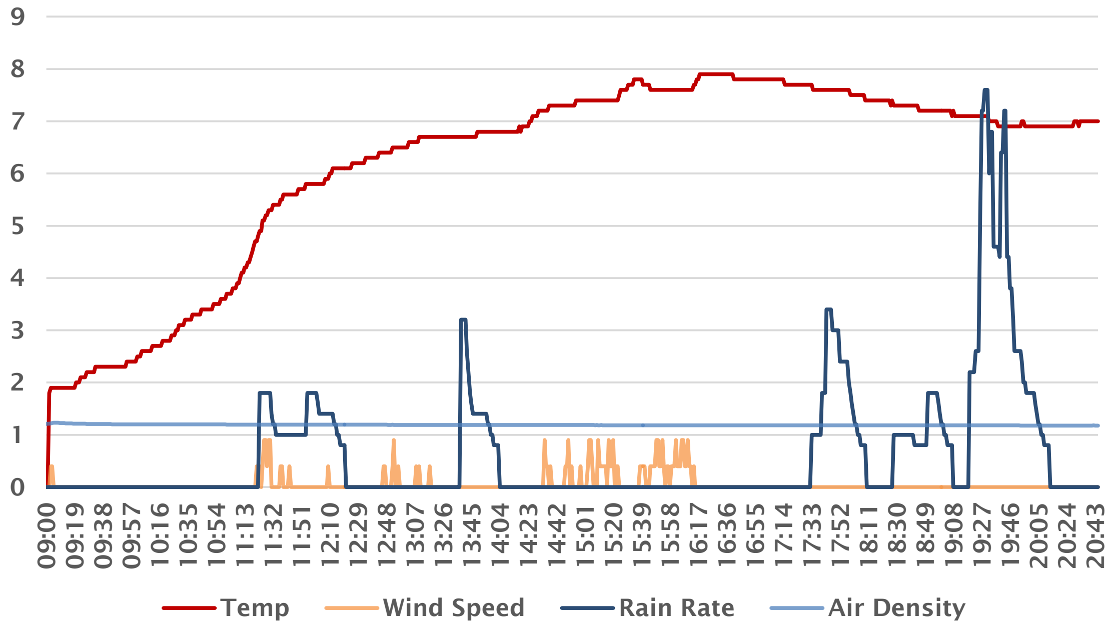


Figure 100. Weather monitoring for filling 'Form D6-Weather summary' at the test site (Theale, UK) on the 25th/11/2014.

5.2.2 ACCURACY OF TELEMATICS UNITS

The trial presented the opportunity of assessing the reliability of the fuel consumption reported by the telematics system (Mix Telematics); as this was used by the industrial sponsor to evaluate the efficiency of vehicles, technologies and drivers. The fuel consumption of the live trials was measured gravimetrically (the fuel tanks were taken out and weighted in a scale before and after each trip) and this was compared with the results reported by the telematics system (Table 57). To do this, the average fuel consumption reported by the telematics for each trip was compared with the outcome of each fuel weight measurement conducted in situ and multiplied by the fuel density (to convert the fuel mass into litres). The fuel density was measured in a laboratory for each fuel sample (one for each day of trial and vehicle).

Immediately after conducting the trial it was evident that there was a discrepancy between the fuel consumption measured gravimetrically and the one reported by the telematics system. It was verified that fuel consumption reported by DAF ECU under reported fuel consumption by an average of 5.47% (around 1.37 l/100km). It could be argued that under reporting the real fuel consumption could benefit some vehicle manufacturer as their vehicles may seem to be more fuel efficient than the ones from their competitors.

These results seem to indicate that conducting technology trials based on telematics information systems may not be a good approach, regardless of how well a trial can be produced; as these fuel consumption readings between trips and vehicles are not consistent enough. In this particular case, after normalising the difference between real fuel consumption and the telematics readings, the in-vehicle fuel measurement system reported 27.55 L less that the real gravimetric fuel consumption for the whole trial.

5.2.3 EVALUATING FUEL SAVINGS FROM DRIVING ASSISTANCE DEVICES

The driving assistance devices fitted in the control and test vehicles (Table 105, page 325) were unplugged from 30th/September/2014 until 26th/June/2015. A statistical test was conducted to ascertain whether there was any significant differences on the fuel consumption that could be attributed to the lack of driving assistance. As the test vehicle was also fitted with spray suppression mudflaps on 25th/November/2014, only the control vehicle fuel consumption was assessed. As gravimetric measurements of fuel consumption are too expensive, the data used for this analysis was downloaded from the telematics historical data for the 3 months before and after disconnecting the driving assistance device (Figure 101). The total fuel consumed and mileage from the 30/June/2014 to 29/September/2014 was 12,667L and 39,662.4 km respectively.

Table 57. Comparison of actual fuel consumption against that reported by the vehicle telematics system.

RUN	GRAVIMETRIC MEASUREMENT						TELEMATICS MEASUREMENT						Difference FC (L/100km)		Average Run
	Test Vehicle			Control			Test Vehicle			Control			Test	Control	Both
DAY 1	Km	Total Litres	L/100 km	Km	Total Litres	L/100 km	Km	Total Litres	L/100 km	Distance	Total Litres	L/100 km			
1	168.4	42.11	25.01	166.3	40.69	24.47	168.2	39.42	23.44	166.0	37.83	22.79	-6.3%	-6.8%	-6.56%
2	168.3	40.63	24.14	166.3	41.14	24.74	168.1	39.16	23.30	166.1	37.94	22.84	-3.5%	-7.7%	-5.60%
3	168.4	41.09	24.40	166.3	41.83	25.15	168.2	39.69	23.60	166.2	39.37	23.69	-3.3%	-5.8%	-4.57%
DAY 2	Distance	Total Litres	L/100 km	Distance	Total Litres	L/100 km	Distance	Total Litres	L/100 km	Distance	Total Litres	L/100 km	%	%	%
1	168.8	41.31	24.48	167.0	41.69	24.96	168.8	39.96	23.67	166.8	38.96	23.36	-3.3%	-6.4%	-4.87%
2	168.8	41.83	24.78	167.0	42.17	25.25	168.8	40.05	23.72	166.8	39.81	23.87	-4.3%	-5.5%	-4.88%
3	168.8	43.71	25.90	167.0	44.74	26.79	168.7	40.91	24.25	166.7	41.85	25.11	-6.3%	-6.3%	-6.32%
	Distance	Total Litres	L/100 km	Distance	Total Litres	L/100 km	Distance	Total Litres	L/100 km	Distance	Total Litres	L/100 km	%	%	%
ALL	1011.5	250.7	24.78	999.9	252.3	25.23	1010.8	239.2	23.66	998.6	235.75	23.61	-4.5%	-6.4%	-5.47%

This produced an average fuel consumption of 31.93 L/100km. After uninstalling the driving assistance device, the fuel consumed from 1st-10-2014 to 31st-12-2014 was 13,617 L for a mileage of 42,050.2 km. This yielded an average fuel consumption of 32.38 L/100 km. The difference between both was around 1.39% (excluding outlier tripsthe difference could increase up to 2.1%). Whether this increase on energy consumption can be attributed to the lack of this device or to changing weather conditions, different route profiles, congestion levels on the roads, schedules, driving styles or loads is uncertain. It is known that the vehicle has an individual fuel tank for heating the cabin and tractor engine and that energy density of the fuel from 30th/September/ 2014 to 25th/November/2014 was the same (0.875 kg/L). This excludes low temperature as a factor but it does not exclude wind speed. It is also relevant to be aware that the telematics seems to under report the fuel consumption by 6.4% which can by itself invalidate the reported savings. The literature reported that fuel savings of up to 17% are possible from training drivers on fuel efficient driving techniques (National Research Council, 2012, Connelly et al., 2011, Hill et al., 2011, Kompfner and Reinhardt, 2008); benefits that tend to decrease to around 7% in the long term. The results here presented suggest that this technology could produce small fuel savings; however, a live test-track trial under controlled conditions should be undertaken to eliminate all the distortions that may affect the results.

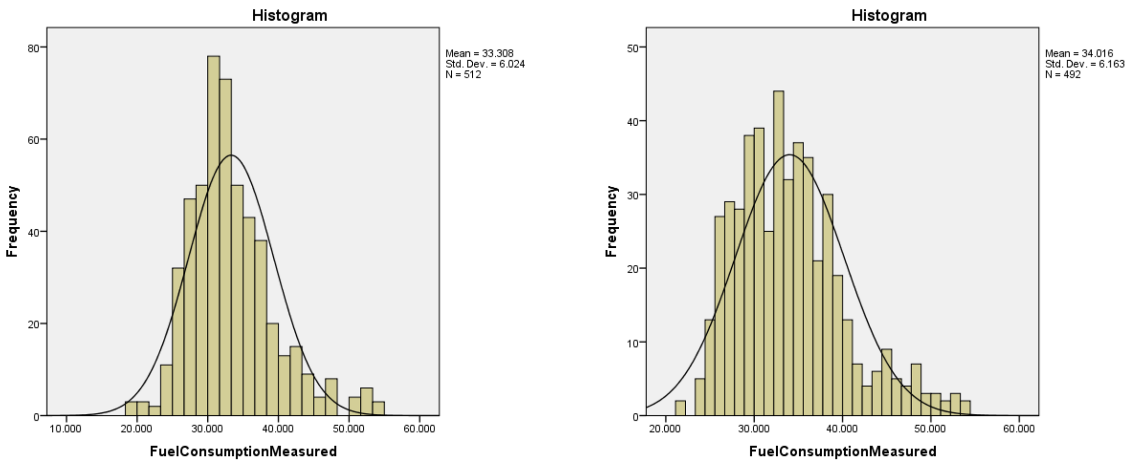


Figure 101. Histogram of fuel consumption (l/100km) before (left) and after (right) unplugging a driving assistance device.

5.3 WASTE-TO-FUELS AUDIT

5.3.1 FEASIBLE WASTE-TO-FUEL PATHWAYS FOR BRITISH QSRs CHAINS

The metaheuristics model quantifies the WTW GHG Emissions (scope 1 and scope 3) of the optimal combination of low carbon technologies during the life span of HGVs. The WTT GHG emission factors of the fuel used by the vehicle has been calculated using as an example waste-to-fuel pathways particular to the industrial sponsor's supply chain.

This has revealed that the fleet of the industrial sponsor can be powered entirely from fuels produced from its own supply chain's waste streams. The biofuels produced had a very low carbon footprint because TTW emissions of biofuels tend to be considered almost negligible as it is assumed that the carbon emissions released in the combustion process are similar to the carbon captured while the feedstock crops were growing. Furthermore, WTT GHG emissions are also very low as waste alone wertr used to produce these biofuels and their carbon intensity was attributed to the first buyer (the restaurants).

The main waste-to-fuel pathways for this supply chain and the HGV engine technologies that can be powered by these are shown in Table 58. There are two main types of powertrains: internal combustion engines (ICE) and electric motors. ICE diesel engines are standard among UK HGV fleets (DECC, 2013b) but there is a growing interest among logistics operators in ICE CNG trucks, vehicles that are also compatible with biomethane, as they can lead to substantial costs and GHG savings. Other ICE engine technologies such as BioDME or Biomethanol also appear in Table 58; however, such HGVs are currently only being tested in small-scale trials by Volvo (BioDME, 2012). HGVs powered by electric motors can use the fuels identified in this study to derive energy by using fuel cells directly or by obtaining electricity from CHP or waste-fired power plants. Solid oxide fuel cells (SOFC) produce hydrogen from the reformation of hydrocarbon fuels (e.g. diesel/biodiesel, biomethane); however, these powertrains are still only at a research stage and are currently being developed just for auxiliary power units (DESTA Consortium, 2014, TOPSOE, 2010). Proton exchange membrane fuel cell (PEMFC) powertrains use the hydrogen that can be generated from the gasification ofbiomass or via stea, reform of biomethane,

Some engine technologies can also reduce GHG emissions through the combination of fuels or hybridisation of powertrains. Typically, dual fuel vehicles use a mix of diesel and methane (or biodiesel/biomethane) and bi-fuel trucks can use either of them but not both simultaneously. Waste feedstocks originating in the FFSC can yield a broad range of fuels depending on the pathway followed (Table 58), as well as other potentially valuable by-products.

The production of FAME biodiesel and biomethane are the simplest pathways to produce renewable fuels in the UK due to the existence of a well-developed market for UCO and tallow collections, and the large number of AD plants installed in the country. In addition, vehicles using either of these fuels meet most of the requirements of hauliers regarding power and range (Cope, 2011). Second generation biodiesel pathways were also studied; however, all commercial plants were located outside the UK and this increased the carbon intensity of such pathways.

Table 58. Main waste-to-fuel pathways in the fast food supply chain and current HGV powertrain technologies that can benefit from these.

Industry	Sectors	Waste Type	Energy Recuperation Processes	Fuel Produced	Powertrain Technology
Food & Drinks	Agricultural Production, Storage & Processing	Product Losses & Waste	Anaerobic Digestion / Gasification	Biomethane	ICE (Natural Gas)
		Non-edible parts	Biomass-to-Liquid/ Gasification	Biodiesel 2^{nd} generation	ICE (Diesel)
		Oil seeds Losses	Transesterification	Biodiesel 1^{st} generation	
			Hydrogenation Vegetable Oil	Biodiesel 2^{nd} generation	
			Anaerobic Digestion	Biomethane	ICE (Natural Gas)
		Water effluent	Anaerobic Digestion	Biomethane	
	Animal Production & Meat Processing	Product Losses & Waste			
		Fat	Trans esterification	Biodiesel 1^{st} gen.	ICE (Diesel)
			Hydrogenation Vegetable Oil	Biodiesel 2^{nd} generation	
		Slurry, Manure	Anaerobic Digestion	Biomethane	ICE (Natural Gas)
	Dairy	Milk			
		Water Effluent			
	Drinks	Water Effluent			
		Fruit Pulp	Anaerobic Digestion / Gasification		
	Quick Service Restaurants	Food waste & leftovers			
		Coffee Grounds	Trans esterification	Biodiesel 1^{st} generation	ICE (Diesel)
		Used Cooking oil & Grease Tap Waste	Hydrogenation Vegetable Oil	Biodiesel 2^{nd} generation	
		Mixed Waste: Paper & Card	Anaerobic Digestion	Biomethane	ICE (Natural Gas)
		Mixed Waste: Plastic & Film	Pyrolysis	Synthetic Diesel, Methane, DME, Methanol, Hydrogen	ICE. (Diesel, DME, Methanol, Hydrogen), Electric (SOFC)
Oil & Plastics	Plastic Packaging	Thermoplastics & Film			
		Bioplastics	Anaerobic Digestion	Biomethane	ICE (Natural Gas)

Industry	Sectors	Waste Type	Energy Recuperation Processes	Fuel Produced	Powertrain Technology
Paper & Wood	Paper & Card packaging, Wood Pallets	Black liquor	Anaerobic Digestion	Biomethane	ICE (Natural Gas)
		Pulp waste	Pyrolysis / Gasification (Syngas)	Synthetic diesel	ICE Diesel
				Bio Dimethyl Ether (BioDME)	Adapted Diesel, Adapted Petrol (70%LPG/30%DME)
				Hydrogen	ICE (Hydrogen)
					Electric (PEMFC)
				Bio Methanol	Electric (Direct Alcohol Fuel Cell) Adapted Diesel (5% additives)
				Bio Ethanol	ICE (Adapted Gasoline) ICE (Diesel with additives)
		Wood residues	Fermentation (Enzyme Hydrolysis) / Gasification	Biodiesel 2nd generation	ICE (Diesel)
Water	Water Treatment	Sewage, sludge	Anaerobic Digestion	Biomethane	ICE (Natural Gas)

5.3.2 WTT EMISSIONS FOR DIFFERENT FEEDSTOCKS AND PATHWAYS

The carbon intensity and GHG savings of different waste-to-fuel pathways are shown in Table 59. Pathways WOFA3a and TOFA3a are the only ones currently followed in this case study. All the other pathways represent other potential alternatives to produce fuels from waste. TTW emission factors (Table 23, page 90) were added to the WTT ones calculated during this research; adding to the total WTW carbon intensity for each pathway (Table 59). The WTW GHG savings of the diesel and biodiesel pathways were then compared to the carbon intensity of the COD1 (conventional diesel), biomethane-to-GMCG1 (compressed natural gas) and bioethanol-to-COG1 (conventional petrol) pathways.

Compared to standard mineral diesel fuel, FAME biodiesel can save almost 85% WTW GHG emissions, a percentage that increases very slightly in the case of second generation biodiesel (88.5%). Biomethane can yield almost 62% WTW GHG savings compared to fossil natural gas fuel and 70% compared to mineral diesel. Bioethanol saves almost 59% compared to gasoline and 59.4% when compared to diesel.

As can be seen in Table 59, WTT carbon intensity from first generation biodiesel are lower than those from second generation; the reason being is that despite their greater efficiency in converting waste to fuel, there are no commercial second generation biofuel production plants in the UK so the feedstock has to be shipped overseas, and the end fuel brought back. These long distances increase the carbon intensity of the TTW chain. If all feedstocks were processed in the domestic market or otherwise sold in the countries where those facilities are located, the WTW GHG savings would increase considerably. Benefiting from these additional carbon savings could be possible by developing an offsetting mechanism similar to Green Certificates applicable to transportation at an EU level. In this way, a feedstock could be processed in one country, shipped to another and bought into the local market without the need for physically importing it.

Table 59. Average carbon intensity and GHG emission savings of different pathways for the food chain studied.

Pathway Code	Waste Feedstock	Fuel	Pathway Carbon Intensity				WTW GHG Savings vs. Fossil fuel pathway
			WTT Fuel	WTT	TTW	WTW	
			(Kg CO_2eq. /t biofuel)	(g CO_2eq./MJ)			
WOFA3a	UCO	FAME Biodiesel	499	13.4	0.2	13.6	84.7% vs. COD1
TOFA3a	Burger Fat	FAME Biodiesel	493	13.3	0.1	13.4	84.9% vs. COD1
WOHY1a	UCO	HVO Biodiesel	666	15.1	-4.9	10.2	88.5% vs. COD1
TOHY1a	Burger Fat	HVO Biodiesel	654	14.9	-5.2	9.7	85.1% vs. COD1
FFCG1	Food Waste	Biomethane	1,030	22.9	3.5	26.4	61.9% vs. CMCG1
WWET1	Wood Waste	Bioethanol	714	35.8	0.2	36	58.7% vs. COG1

When considering the WTW emissions, with the exception of the WWET1 pathway, all others deliver the sustainability criteria as defined by the EU Directive 2009/28/EC which states that a biofuel must save at least 60% GHG emissions to be classified as renewable and benefitting from any European subsidies for these (DfT, 2013c, European Commission, 2013a). The results in Table 59 differ from those reported in Table 22 (Page 89), as they are specific to the supply chain studied. In Figures 102-106, the haulage distances are expressed in km while the percentages represent the contribution of each stage to the total TTW carbon intensity. The percentages shown represent the contribution of a particular stage to the overall GHG emissions for the waste-to-fuel pathway. Road and nautical distances were converted to kilometres and quoted on top of the arrows representing the distance between origin and destination. The pathways from plastics to synthetic diesel were excluded as no GHG emissions savings were expected. Percentages in Figures 102-106 represent the contribution of each stage of the waste-to-fuel process to the total carbon intensity of the waste-to-fuel pathway.

5.3.2.1 WTT EMISSIONS OF UCO AND FAT TO BIODIESEL

Across all the case study restaurants, UCO and fat were collected in the QSRs, consolidated in a DC and converted into FAME biodiesel following the chain illustrated in Figure 102. Under WOFA3a and WOHY1a pathways, the oil was collected in an oil tank built into the HGVs' chassis. In theTOFA3a and TOHY1a pathways, tallow was collected and transported in barrels from QSRs to the conversion plant. This reduced the carbon intensity, as there was no energy consumption for transferring from/to and maintaining feedstock in the storage tanks.

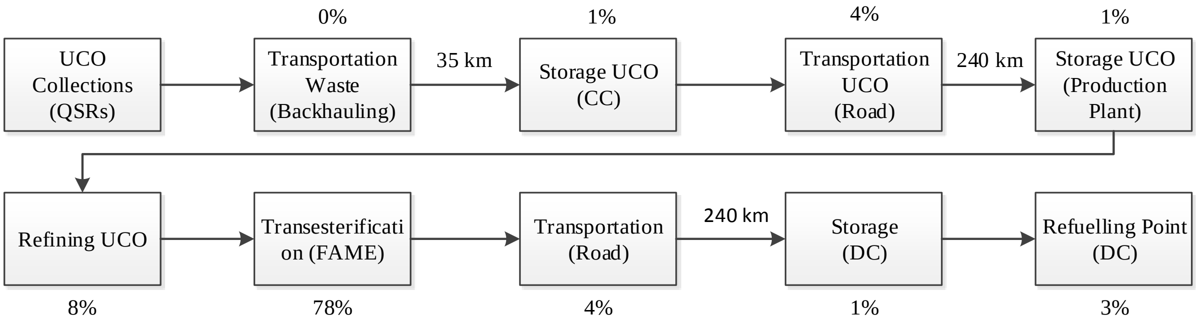


Figure 102. UCO to FAME biodiesel chain (WOFA3a pathway).

Initially, the UCO was collected in small storage tanks located in the QSRs and pumped into larger 300 L oil tanks fitted in the delivery trailer's chassis. Once these arrive at the DC, the UCO was stored in two tanks with a capacity of several thousand litres each (Figure 103), awaiting for collection from a third party biofuel processing organisation located at an average distance of 240 km. The UCO was stored at the processing plant until it is refined and transesterified. The conversion process stages represent 86% of the total carbon emissions of the chain. The first generation biofuel was sent back to the DC were it was stored and ready to be used by the logistics fleet. In this case the WTT carbon intensity calculated (13.4 g CO_2eq./MJ) is very similar to the one reported by Edwards et al. (2014) in Table 22.

TOFA3a pathway represents the conversion of tallow (burger fat) to FAME biodiesel. The stages are the same as the WOFA3a pathway with the only difference that fat is stored in barrels until it reaches the processing plant. There is thus no additional energy demand associated with its initial storage. This reduced the carbon intensity by 0.1 g to 13.3 g CO_2eq. /MJ, around half of the value reported in Table 22 (Page 89), Refining and transesterification represented 87% of the total carbon intensity of this waste-to-fuel chain.

Figure 103. Used cooking oil storage tank.

While first generation biofuels was produced in the UK, second generation biodiesel (e.g. HVO) was processed in the Netherlands, hence shipping waste overseas and bringing it back explains the increase in carbon emissions for the WOHY1a and TOHY1a pathways.

The conversion of UCO and tallow into second generation biofuel was feasible; however, the producer contacted for this study indicated that a chemical analysis should be undertaken before accepting these types of feedstocks. Figure 104 illustrates the chain for conversion of UCO into HVO biodiesel (WOHY1a). The WTT carbon intensity for this pathway is 15.1 g CO_2eq. /MJ, a value very similar to the one reported in Table 22. In this chain, waste is consolidated in the DC and transported an average distance of 267 km by road to the port of Felixstowe where it is shipped to Rotterdam (134 nautical miles) by a ship tanker. Once in the Netherlands, after a short trip by road, it reaches the Neste Oil processing plant. After the hydrogenation process, a high quality biodiesel is produced and it is assumed that this is shipped back to the DC in the UK where it can be stored and supplied to the fleet.

The TOHY1a pathway (fat to HVO biodiesel) chain is similar to Figure 104; however, tallow is transported in barrels all the way through. This means that the lorry carries dry product and that the ship is an ocean bulk carrier. On the way back, the liquid fuel is transported by sea tankers and trucks for liquids. The contribution that each stage in the chain represents on the total carbon intensity appears in percentage over each step (%). Aggregating the percentages that each step represents, it was calculated that storage contributed to around 5%, transportation 18% and processing 75% of the total carbon footprint of this pathway (Figure 104).

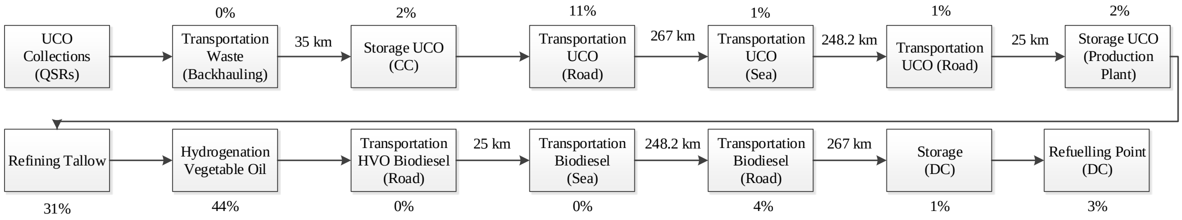


Figure 104. UCO to HVO biodiesel chain (WOHY1a pathway). Percentages represent the contribution of each stage to the total carbon intensity of the waste-to-fuel pathway.

5.3.2.2 WTT EMISSIONS OF FOOD WASTE TO BIOMETHANE

Following the methodology explained in section 4.4 (page 150), data from waste collections from the industrial sponsor were assessed and the results suggested that biomethane from organic waste could reduce GHG emissions by up to 70%. This pathway (FFCG1) is illustrated in Figure 105. Food waste was collected in QSRs and stored in the DC where it was shipped to the clossest AD plant. After the digestion of the waste, the biogas was upgraded to 95% biomethane and it was injected into the UK natural gas network. The biomethane could also be consumed in the DC by natural gas HGVs. Refuelling represents a substantial percentage of the energy intensity of the chain (13%) as the gas had to be pressurised from 85 bar (national grid) to 250 bars (vehicle gas tank pressure). This was necessary as a higher pressure meant lower fuel tank volume (at the same temperature) which minimised the impact on vehicle volumetric payload. Using LNG instead of CNG would increase vehicle range (for the same gas tank volume). However, this would add an additional step where the gas would have to be kept at cryogenic temperature, and part of the boiled off gas recovered, compressed and stored. This would have increased the carbon intensity of the chain even further and therefore reduced the GHG savings.

Consolidating food waste in the DCs and shipping such waste to the nearest AD plant generates 26.4 g CO_2eq. /MJ of energy output (as shown in Table 59). This represents 70.2% lower carbon emissions than those reported in Table 22 for mineral diesel (88.6 g CO_2eq. /MJ) and almost 62% lower than those for fossil natural gas. This result is slightly lower than the savings of 83% reported in Table 23 for the OWCG1 pathway; there, however, the organic fraction included all municipal wastes whilst in the FFCG1 pathway only fast food waste was considered, with the yields reported in Table 33 (page 152). The energy required for the pasteurisation of the digestate to meet PAS110 regulations was not been included in this chain, as it did not directly relate to the production of the fuel itself. The emissions associated to this were atributed to the buyer of the fertilizer (digestate).

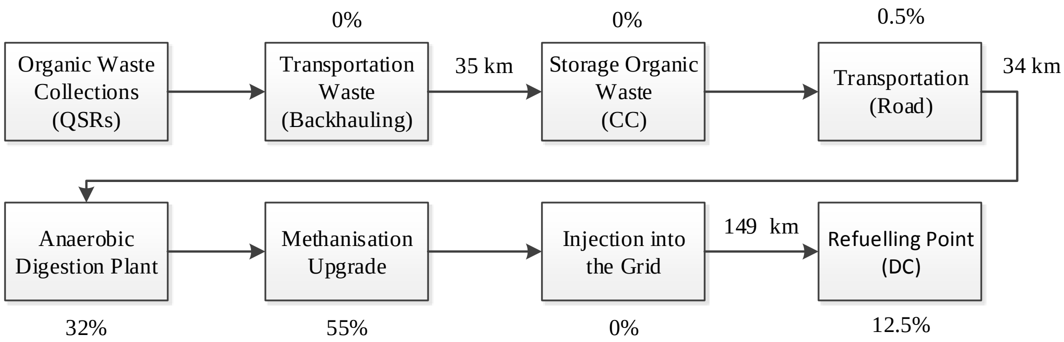


Figure 105. Restaurant food waste to biomethane chain (FFCG1 pathway).

Additional modelling showed that if the food waste would be shipped to an AD plant 100 km, 200 km, 300 km and 400km far away (instead of the clossest one to the DC), the total GHG savings would decrease to 55.3%, 38.5, 21.8% or 5% respectively. This means that the carbon intensity of the FFCG1 pathway is highly sensitive to the distance between feedstock production and AD plant location.

5.3.2.3 WTT EMISSIONS OF WOODEN PALLETS TO BIOETHANOL

Wood waste is mainly generated through wear-and-tear on wooden pallets. Wood waste could be converted into liquid or gas biofuels through BTL or biomass-to-gas processes, such as Fischer-Tropsch biodiesel (FT Diesel) and bioDME respectively. Both pathways were very promising with GHG savings of 98% reported from wood waste to BioDME (BioDME, 2012, Edwards et al., 2014) and 97% for wood waste to FT Diesel (Edwards et al., 2014). Producing ligno-cellulosic ethanol from paper and cardboard waste also seemed feasible; however, this was excluded from the current assessment as no such processing plants were found to operate in Europe. Only two commercial wood processing plants were found in Europe (as of 2014) capable of producing fuels (bioethanol) and for this reason, all the other pathways for this feedstock were excluded. Bioethanol can be used in adapted petrol engines; it is also possible to adapt diesel engines to run on 95% ethanol plus a 5% of ignition enhancing additives (ignition improver, lubricant and corrosion) as developed by Sekab and used by Scania (Sekab, 2013).

A WTW carbon intensity of 35.8 g CO_2eq. /MJ was estimated and WTT GHG savings around 57% for pathway WWET1 were found. This differed from the 72% GHG savings reported by Edwards et al. (2014). The reason is that the shipping of wood chips to the locations of the processing plants (Norway) and bringing the output back to the UK represented a very high percentage of the overall emissions of this chain. This pathway was below the 60% required to meet the EU sustainability criteria for renewables.

Figure 106 represents the WWET1 pathway where wasted wood (e.g. wooden pallets) was converted into bioethanol. In this pathway, it was assumed that wasted wood was stored in the DC, collected by a third party that crushed the wood into pellets and shipped them from the Port of Felixstowe to the Port of Havneholmen (Norway) by bulk carrier. There, after an 18 km trip, they reached their destination in the Borregaard Synthesis plant where they were processed and converted into bioethanol.

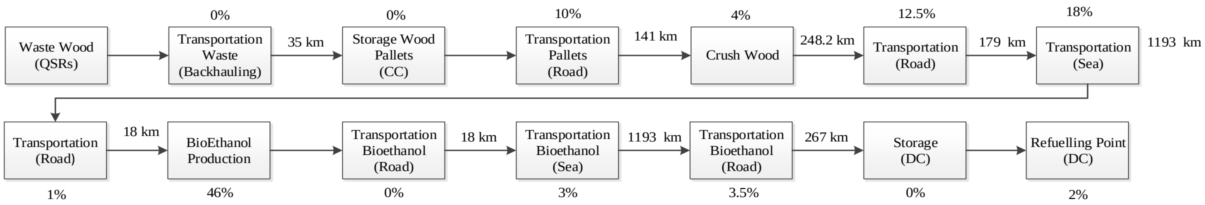


Figure 106. Restaurant wood waste (pallets) to bioethanol chain (WWET1 pathway).

Despite the fact that using wood pallets from the logistics industry to produce fuels is technically feasible, it is always better to reuse pallets as embedded emissions from procuring reused pallets are just under 7% of the emissions of making pallets from primary wood, as stated in Defra (2013b) emission factors. Also, this pathway has economic implications as removing usable pallets would impact market prices of second hand ones.

5.3.3 QUANTIFYING THE POTENTIAL FUEL GENERATION FROM QSR WASTE ARISINGS ACROSS THE UK

5.3.3.1 MAIN WASTE FRACTIONS

Based on the case study data obtained from a QSR chain over 3 years, the potential for fuel production from QSR waste were estimated (Table 60). The results suggested that British QSRs and their DCs generate around 24.9 tonnes of waste per outlet each year that can be used to produce fuels. Cardboard and paper fractions represented over half the tonnage generated, with food waste making up the second largest fraction with a quarter, and fats and UCO the third with 17% of the total. Plastic represented just 2% of the total tonnage produced (Figure 107). In Table 60, each pathway represents the fuel produced by a specific feedstock and conversion process, considering the energy yields shown in Table 33 (page 152) and LHV from Table 61. The total fuel availability has been converted into GJ to allow an easy comparison of the effectiveness of each pathway and contrast this with the demand of diesel from British HGVs.

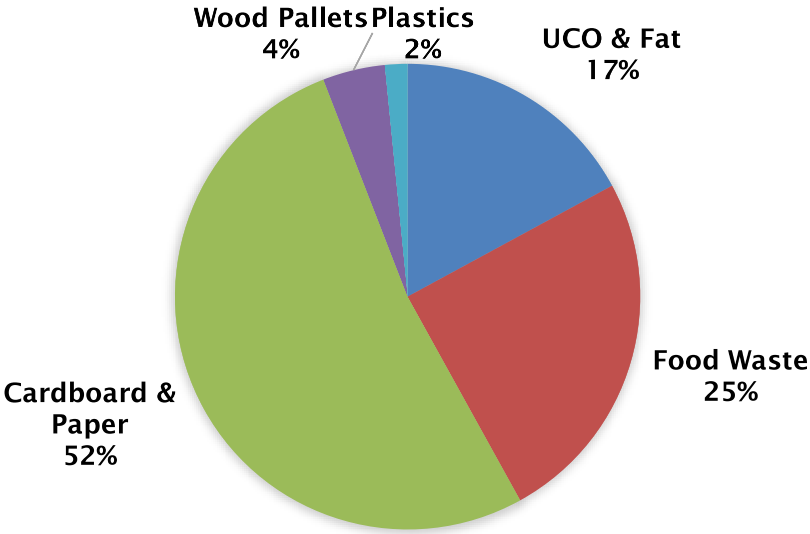


Figure 107. Separated collections of QSRs and DCs plus mixed food waste with potential for producing fuels (% in weight)

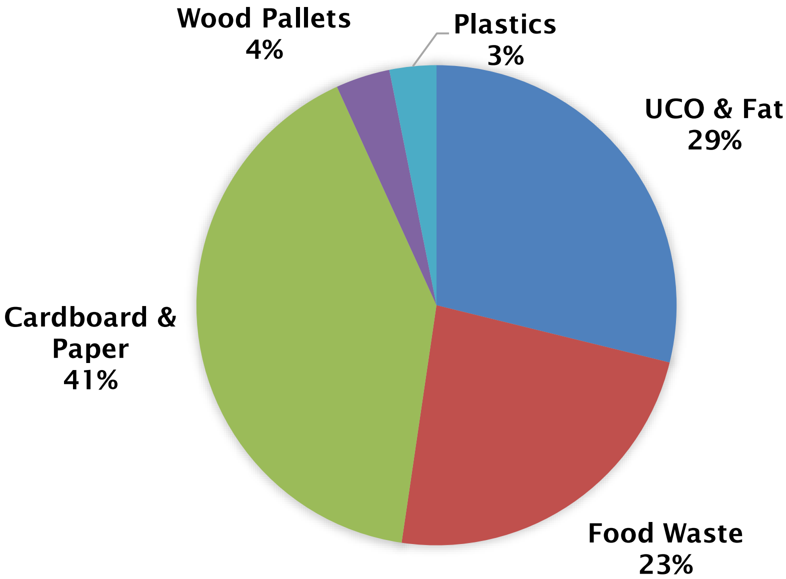


Figure 108. Energy content available in the main separated waste fractions plus mixed food waste from QSRs and DCs with potential for producing transportation fuels (% of total GJ).

When QSRs and DCs separated waste collections and QSRs mixed food waste collections were consolidated, cardboard and paper represented over 50% of all weight, food waste a quarter, UCO and fat 17%, wood pallets 4% and plastics just 2%. Based on the energy content of each feedstock (Table 61), an average restaurant had the potential to produce 537 GJ of energy per year. From this, cardboard and paper represented around 41% of the total energy, while UCO and fats represented 29%, followed by food waste with 23%, wood pallets with 4% and plastics with a mere 3%

(Figure 108). However these yields were much lower when waste is finally converted into liquid or gas fuels.

Table 60. Waste-to-fuel potential from British QSRs (assuming 3 DCs for each 1,000 outlets).

Pathway Code	Feedstock	Waste generation per year	U.	Total GJ (LHV)	Resulting Fuel	U.	Final Total GJ (LHV)	Fuel
WOFA3a	UCO	120,629	m^3	4,101,387	113,362,870	L	3,753,218	FAME
WOHY1a					45,580,232	L	1,564,314	HVO
WOCG1					52,271,583	kg	2,571,762	Biomethane
TOFA3	Fat (Tallow)	60,612	m^3	2,063,241	56,961,247	L	1,885,873	FAME
TOHY1a					22,902,621	L	786,018	HVO
TACG1					40,500,868	kg	1,992,643	Biomethane
FFCG1	Food Waste	242,586	t	5,021,524	122,099,674	kg	6,007,304	Biomethane
CACG1	Cardboard	508,224	t	8,731,290	98,555,880	kg	4,848,949	Biomethane
PACG1	Paper	543	t	7,144	54,019	kg	2,658	Biomethane
WWET1	Pallets	42,182	t	780,364	8,642,498	L	183,905	Bioethanol
PFSD	Plastics (Film PP)	9,190	t	404,366	8,638,136	L	296,461	Synthetic Diesel
PBSD	Plastics (HDPE)	6,135	t	269,951	5,766,745	L	197,915	Synthetic Diesel

5.3.3.2 WASTE-TO-FUEL SCENARIOS

The tree scenarios proposed delivered GHG emissions savings of 68.5%, 63.9% and 59.5% (Table 62). Further details showing the kilometres that could be run with fuel made from British QSRs waste and the number of vehicles that could be powered by these fuels appear in Table 63.

Table 61. Carbon intensity of each scenario (in kg CO_2eq. /GJ).

Carbon Intensity	Scenario 1 - UCO/Fat to FAME B100	Scenario 2 - UCO/Fat to HVO B100	Scenario 3 - UCO/Fat to Biomethane
Before	76.4	73.5	70.1
After	24.1	26.5	28.4
Savings	68.5%	63.9%	59.5%

The scenarios represent the outcomes of pathways FFCG1, CACG1, PACG1, WWET1 and PFSD and PBSD in combination with another two pathways more (TOFA3A and WOFA3a or TOHY1a and WOHY1a) depending on the final use of UCO and fat. In

addition to the conversion of paper and cardboard to biomethane, wood to bioethanol and plastics into synthetic diesel in all three scenarios, the only differences are:

- **Scenario 1 represents the conversion of UCO and fat into FAME biodiesel (WOFA3a, and TOFA3a pathways).**
- **Scenario 2, represents the conversion of UCO and fat into HVO biodiesel (WOHY1a and TOHY1a pathways).**
- **Scenario 3, represents the conversion of UCO and fat into biomethane (WOCG1 and TACG1 pathways).**

Table 62. Energy content of different feedstocks.

Product	LHV	Unit	Source
Standard Diesel	43.10	GJ/tonne	Edwards et al. (2014)
FAME	33.11	GJ/m^3	Edwards et al. (2014)
HVO	34.32	GJ/m^3	Edwards et al. (2014)
Biomethane	49.20	GJ/tonne	Edwards et al. (2014)
Bioethanol	21.28	GJ/m^3	Edwards et al. (2014)
Synthetic Diesel	34.32	GJ/m^3	Edwards et al. (2014)
UCO (refined oil)	34.00	GJ/m^3	Edwards et al. (2014)
Fat (Tallow)	34.04	GJ/m^3	Edwards et al. (2014)
Food Waste	20.70	GJ/tonne	Banks and Zhang (2010)
Cardboard	17.18	GJ/tonne	Banks and Zhang (2010)
Paper	13.16	GJ/tonne	Banks and Zhang (2010)
Pallets (Wood Logs)	18.50	GJ/tonne	Edwards et al. (2014)
Plastics (Film PP)	44.00	GJ/tonne	Themelis and Mussche (2014)
Plastics (Bottles HDPE Natural)	44.00	GJ/tonne	Themelis and Mussche (2014)

Assuming that each HGV runs 85,000 miles/year (136,794 km) and an average fuel consumption for biomethane lorries of 25.3 kg/100km (17.1 MJ/km), 32 L/100km (10.6 MJ/km) for diesel and biodiesel lorries, and 86.9 L/100km (18.5 MJ/km) for bioethanol fuelled trucks, the results suggested that the main waste feedstocks of the FFSC would be enough to run between 910 and 1,221 million km per year. This means that between 6,659 and 8,928 HGVs could potentially be powered with fuels from waste streams (Table 63).

Excluding PFSD and PBSD pathways from these values due to their lack of GHG savings, British fast food fleets could run between 864 and 1,174 million km per year with very low carbon fuels, this is between 6,317 and 8,587 HGVs depending on the scenario chosen. These numbers are considerably superior to the number of HGVs distributing to British QSRs.

Table 63. Potential energy produced from wastes, km replaced with alternative fuels and number of vehicles powered by these (assuming 136,000 km year[-1]). Quantities are in litres, except biomethane that is in kg.

Fuel	Scenario 1 - UCO/Fat to FAME B100				Scenario 2 - UCO/Fat to HVO B100				Scenario 3 - UCO/Fat to Biomethane			
	Potential Production	GJ	Million km	Vehicles	Potential Production	GJ	Million km	Vehicles	Potential Production	GJ	Million km	Vehicles
Biodiesel (L)	170,324,117	5,639,091	532.3	3,891	68,482,853	2,350,332	221.8	1,622	-	-	-	-
Biomethane (kg)	220,709,573	10,858,911	632.4	4,623	220,709,573	10,858,911	632.4	4,623	313,482,024	15,423,316	898.2	6,566
Bioethanol (L)	8,642,498	183,905	9.9	73	8,642,498	183,905	9.9	73	8,642,498	183,905	9.9	73
Synthetic Diesel (L)	14,404,880	494,375	46.7	341	14,404,880	494,375	46.7	341	14,404,880	494,375	46.7	341
Total		17,176,283	1,221.3	8,928		13,887,523	910.8	6,659		16,101,597	954.8	6,980

Table 64. GHG Savings for each scenario

	Fuel	Emission Factors (Kg CO_2eq. /GJ)	Scenario 1 - UCO/Fat to FAME B100			Scenario 2 - UCO/Fat to HVO B100			Scenario 3 - UCO/Fat to Biomethane		
			GJ	Scope 1&3 (t CO_2eq.)	Savings (t CO_2eq.)	GJ	Scope 1&3 (t CO_2eq.)	Savings (t CO_2eq.)	GJ	Scope 1&3 (t CO_2eq.)	Savings (t CO_2eq.)
Before	Diesel (average biofuel blend)	88.6	5,639,091	499,623	-	2,350,332	208,239	-	-	-	-
Before	CNG/LNG	69.3	10,858,911	752,523	-	10,858,911	752,523	-	15,423,316	1,068,836	-
Before	Petrol (average biofuel blend)	87.1	183,905	16,018	-	183,905	16,018	-	183,905	16,018	-
Before	Diesel (average biofuel blend)	88.6	494,375	43,802	-	494,375	43,802	-	494,375	43,802	-
			17,176,283	1,311,966	-	13,887,523	1,020,582	-	16,101,597	1,128,656	-
After	Biodiesel	13.6-13.4	5,639,091	76,692	422,932	2,350,332	31,494	176,745	0	0	0
After	Biomethane	26.4	10,858,911	286,675	465,847	10,858,911	286,675	465,847	15,423,316	407,176	661,660
After	Bioethanol	36.0	183,905	6,621	9,398	183,905	6,621	9,398	183,905	6,621	9,398
After	Synthetic Diesel	88.6	494,375	43,802	0	494,375	43,802	0	494,375	43,802	0
Total			17,176,283	413,789	898,177	13,887,523	368,592	651,990	16,101,597	457,598	671,058

In Scenario 1, the conversion of UCO and burger fat into FAME biodiesel yields 5.6 million GJ, more than double compared to when the same feedstocks are converted into HVO biodiesel in the second scenario. In this scenario, the conversion of feedstocks into FAME biodiesel (B100), biomethane and bioethanol, yields the largest energy production of all three scenarios with over 17 million GJ, enough to drive almost 1.2 million km with renewable fuels. Under scenario 2, UCO and fat are converted into second generation biodiesel (HVO). Under this scenario, 6,659 vehicles could run with a mix of different fuels. As the conversion efficiency is lower, scenario 2 presents the lowest energy yield of all three scenarios with 3.3 million GJ/year less energy than scenario 1 and 2.2 GJ/year than scenario 3.

Scenario 3 was developed after interviews conducted with truck manufacturers who indicated that new sales of HGVs from January 2014 had to meet the Euro 6 emission standard and that these vehicles would see their warranty made void if vehicles use biodiesel in concentrations exceeding the EN590 standard (Mercedes-Benz, 2013, Cattley, 2013, DAF Trucks Ltd., 2013). This means that concentrations beyond 7% of FAME biodiesel or 30% of HVO biodiesel are not allowed in Euro 6 trucks. If the FFSC wants to convert all waste streams into transportation fuels and consume all of it, scenario 3 represent the only alternative. In the scenarios 1 and 2, the production of fuel exceeds the potential demand of Euro 6 vehicles owned by the FFSC. Under scenario3, UCO and fat are co-digested to produce biomethane. This approach would yield 15.4 million GJ of biomethane; enough to run 898 million km/year and power 6,566 biomethane vehicles in addition to the yields of bioethanol and synthetic diesel common to all three scenarios.

Ethanol is a fuel that is found in concentrations of up to 10% in European conventional petrol following the EN228 fuel standard. It is also possible to use pure ethanol in some engines. It is estimated that such an alternative would produce enough energy to power a total of almost 9.9 million km each year or 73 trucks. As bioethanol has a lower energy intensity than biodiesel, long haul routes may require larger fuel tanks which could potentially impact on the vehicle payload. As previously mentioned, bioethanol can also be used in diesel engines with the addition of certain additives or in direct-ethanol fuel cell vehicles.

The use of plastics was common to all three scenarios and it could power 341 HGVs each year. However, this would not lead to any GHG savings as plastics are made from fossil hydrocarbons. Furthermore, it is difficult to guarantee that only end of life plastics are used. As procuring virgin plastic is more expensive and carbon intensive than recycling it, the GHG emissions of pathways PFSD and PBSD are likely to increase carbon emissions and plastic prices if not managed well.

5.3.3.3 TOTAL WTW GHG EMISSIONS

Since October 2013, the Companies Act 2006 Regulations 2013 oblige all UK quoted companies to report on their GHG emissions (Defra, 2013b). Based on the UK Government methodology for company reporting (Hill et al., 2013), assuming that the fleets are owned or controlled by the logistics operators, and using the emission factors reported in Table 60 (Page 219), the carbon emissions and savings for each scenario have been calculated as appear in Table 64.

Scenario 1 (UCO and fat is used to produce FAME B100) produced the most energy and therefore could displace more conventional diesel, producing higher GHG savings. Scenario 1 revealed that replacing 17.1 million GJ of conventional diesel for biodiesel, biomethane and bioethanol would reduce GHG emissions by almost 900 thousand tonnes of CO_2eq. per year (almost 32% less). Similarly, scenario 2 (UCO and fat is used to produce HVO B100) shows savings of almost 652 thousand tonnes per year (36% less). Scenario 3 (UCO and fat is co-digested to produce biomethane) indicated that 671 thousand tonnes per year (over 40% less than using conventional natural gas) could be saved by using most of the waste feedstocks to produce biomethane. This suggests that Scenario 1 will yield the highest carbon savings overall. Looking at the carbon intensity of each scenario normalising to tonnes of CO_2eq. /GJ, Scenario 1 carbon intensity is the lowest of all three scenarios with 24.1 kg CO_2eq. /GJ (Table 64).

Detailed fuel consumption data of QSR distribution fleets in British districts is unavailable. Extrapolating the number of vehicles of the case study and considering that Euro 6 diesel vehicles can only use low percentages of biofuels (up to 30% for second generation B100), it is evident that the fuel potential production from wastes from the British FFSC exceeds the fuel demand of their fleets (Velazquez Abad et al., 2015). The percentage of fuel consumption from HGVs that could be powered by wastes produced by QSRs according to scenario 1 is shown in Figure 109; this includes the fuel consumption from all British HGVs as reported by DECC (2013b), not just QSR distribution fleets. The fuel consumption of HGVs (excluding buses) in the UK was around 7 million tonnes in 2011, a quantity that decreased to almost 6.9 in 2012 (DECC, 2013b). Assuming that all HGVs consumed a standard average biodiesel blend (7%) and that the fuel density was 43.1 GJ/ton, this translates to a demand of 303.27 and 296.6.5 million GJ in 2011 and 2012 respectively. This indicates that around 5.7%, 4.6% and 5.3% of the energy could be supplied by wastes from the FFSC for scenarios 1, 2 and 3 respectively in 2011 and 5.8%, 4.7% and 5.4% in 2012. If we exclude non-biogenic feedstock, the percentages were slightly lower at 5.5%, 4.4 % and 5.1% in 2011 and 5.6%, 4.5% and 5.2% in 2012. Based on scenario 1, Table 65 shows the British districts where fuel from waste could provide over 20% of the energy needs of the area. Greater London presented the highest waste-to-fuel energy output due to the concentration of 7,313 QSRs. Under scenario 1, London could produce 3.1 million GJ of fuels, representing 24% of the energy needs of the area (13.1 million GJ). This percentage decreased to 19.4% and 22.5% under scenarios 2 and 3, respectively. Blackpool's waste-to-fuel potential indicated that over two thirds of all its diesel consumption could be covered by fuels from waste streams. At the opposite extreme were the Isles of Scilly where no QSRs were found and therefore no fuels could be produced.

Table 65. Top 20 districts with the highest percentages of energy demand from HGVs' fleets that could potentially be covered by fuels produced by British QSRs waste each year.

Ranking	District	Num. Outlets	Annual Fuel Potential (in GJ averaged over a 40 months period)	Fuel Demand in 2012 (GJ)	% Demand
1	Blackpool	187	80,780	119,464	67.6
2	Southend-On-Sea	144	62,205	156,288	39.8
3	Reading	139	60,045	161,560	37.2
4	Bournemouth	144	62,205	170,931	36.4
5	Brighton and Hove	259	111,883	330,582	33.8
6	Torbay	104	44,926	149,302	30.1
7	Manchester	583	251,844	885,212	28.5
8	City Of Leicester	294	127,002	480,631	26.4
9	Isle Of Wight	76	32,830	125,218	26.2
10	Liverpool	390	168,472	658,621	25.6
11	Newcastle Upon Tyne	266	114,907	466,053	24.7
12	Greater London Authority	7,313	3,159,070	13,173,082	24.0
13	Southampton	192	82,940	354,605	23.4
14	Bradford	416	179,704	776,637	23.1
15	Wolverhampton District	167	72,141	322,485	22.4
16	City of Nottingham	275	118,795	549,733	21.6
17	City of Portsmouth	176	76,028	365,925	20.8
18	Poole	107	46,222	224,029	20.6
19	South Tyneside District	121	52,270	253,625	20.6
20	Sheffield	531	229,381	1,123,263	20.4

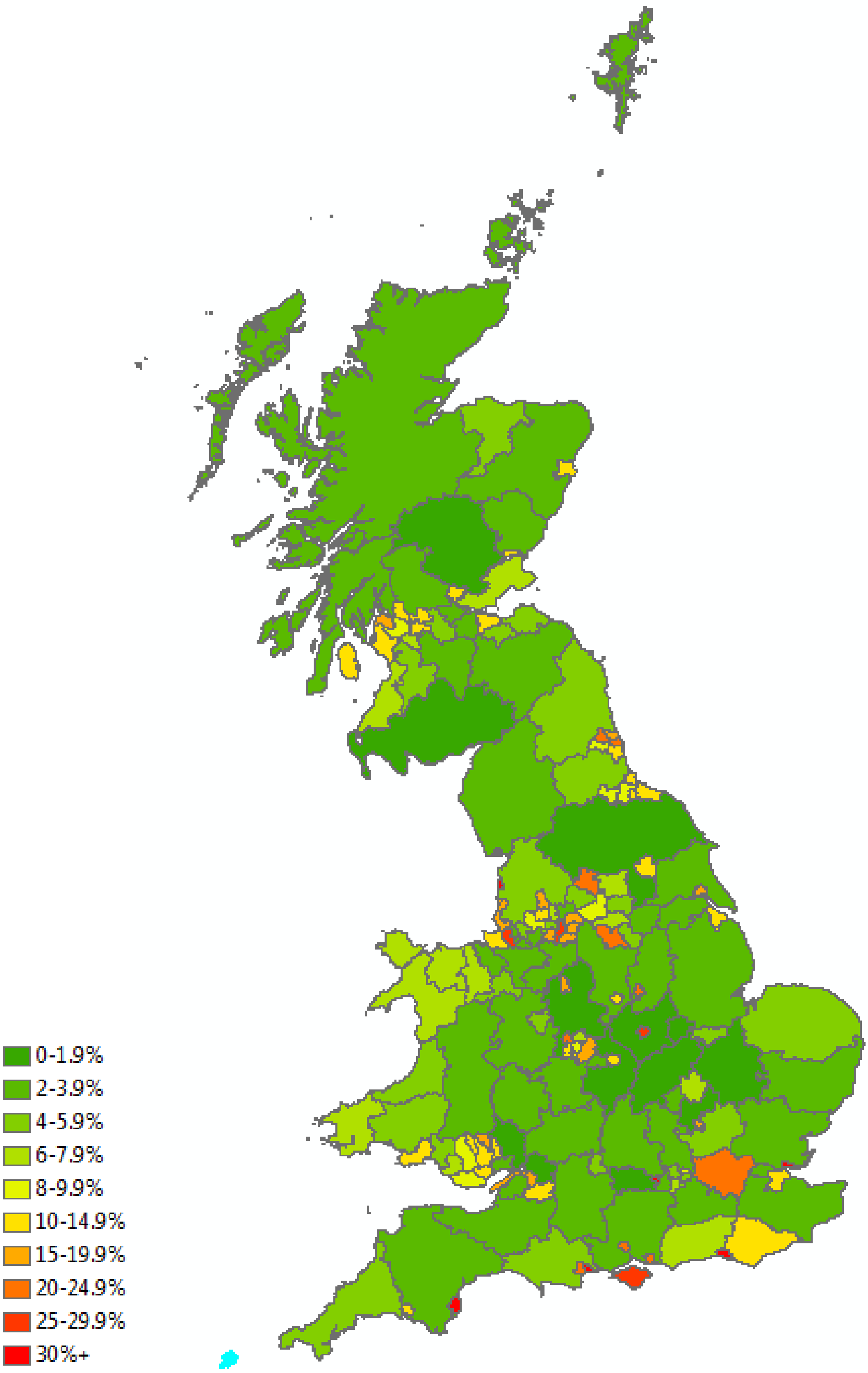


Figure 109. Percentage of the British freight HGVs fuel demand that could potentially be covered by fuels produced from British QSRs (Scenario 1).

5.4 METAHEURISTICS QUANTITATIVE MODEL: OPTIMAL VEHICLE CONFIGURATION

In the methodology, the framework was divided in four main blocks or stages (Figure 69, page 123). Block one included a literature review and block two included all the practical work (simulated experiments, a live trial and carbon footprinting audits). This section (block three), used the previous blocks' findings as inputs (Figure 71, page 125) in a bespoke quantitative metaheuristics model to generate optimal vehicles' configurations according to different objective functions and scenarios. As explained in the methodology, the model uses evolutionary algorithms for solving a combinatorial problem that yields a vehicle specification that minimises total net present cost (under several risk profiles) or carbon emissions during the life span of a HGV. The outcomes of this model are used in the next section (block 4) to produce a qualitative suggestion for a vehicle specification based on the objectives chosen by the industrial sponsor following a multicriteria decision analysis approach.

In this section, the results of the metaheuristics model are presented. For each duty cycle (urban, regional and long-haul), four different strategies were compared:

- Strategy 1 (S1) consists in the optimisation of the vehicle specification by yielding the lowest net present cost (NPC) possible, regardless of any other objectives.
- Strategy 2 (S2) optimises the vehicle configuration with the aim of minimising GHG emissions, regardless of costs and risks.
- Strategy 3 (S3) minimises the NPC allowing only technologies with a risk level of technology maturity of 6 or higher. This means that just technologies that have been previously trialled with HGVs' fleets can be chosen.
- Strategy 4 (S4) minimises NPC by considering technologies that do not present additional safety issues or higher limitations than the incumbent technologies; this strategy constraints the risk of safety and limitations to technologies with a level 6 or higher .

A range of scenarios have been created for each strategy. In all of them the rate of return is 9.7%, the rate of interest of leasing the vehicles is 3% and the life span of the investment is 5 years, as specified by the industrial sponsor. The baseline assumption for each strategy considers that the price of biodiesel is 80.51 p/L (excluding VAT), red diesel 57.95 p/L and electricity is 13.02 p/kWh. The nomenclature for these scenarios is UB (urban), RG (regional) and LH (long-haul) plus a word that represents the strategy and a number from 1 to 3. The word 'UNLTD' represents strategy S1, 'GHG' strategy S2, 'RTM' strategy S3, 'RS' strategy S4. Number 2 represents the scenarios with current fuel prices; number '1' with prices 20% lower and number '3' with prices 20% higher. Table 66 explains the meaning of each scenario for urban vehicles. Regional and long-haul ones use the RG and LH prefixes, respectively.

All scenarios are compared with a baseline vehicle represented in the Tables by strategy S0 (no low carbon technologies are fitted in those vehicles). The nomenclature of the baseline scenarios follows a similar format: UG/RG/LH-BASE plus a number depending on the assumption taken for fuel prices (1, 2 or 3). It is assumed that a baseline vehicle uses a conventional mechanical refrigeration unit with R-404A refrigerant gas. The fuel's emission factors (B65) from the model come from the WOFA3a pathway presented in Table 60 (page 219); a pathway based on the industrial sponsor's supply chain where used cooking oil from chip fryers is used to produce biodiesel. As B65 fuel and red diesel have different GHG emission factors, the percentage of fuel reduction does not translate to a similar reduction in carbon emissions.

The metaheuristics model is run three times (to reflect variations of ±20% in energy prices) for each one of the four strategies (S0 to S4). S1, S3 and S4 have the same objective function (cost minimisation) with changes in the constraints (risk levels) while S2 involves a change in the objective function from cost to all scopes carbon footprint minimisation. The outcomes of each strategy are used in the multicriteria decision analysis section to propose a ranking of preferred alternatives according the industrial sponsor goals.

5.4.1 SELECTION OF LOW CARBON TECHNOLOGIES FOR URBAN LORRIES

The vehicle in the urban scenarios (Tables 67-69) represents an 18 tonne rigid DAF CF65 lorry running on biodiesel (B65) with a 9 m refrigerated box with a 7.5 kW refrigeration unit. In this duty cycle, the vehicles run an average 113,909 km/year and carry 2,822 tonnes/year (excluding the reverse logistics of waste). The typical average fuel consumption of these vehicles is around 28.63 L/100km. TRUs are assumed to work 2,130 hrs. /year and consume around 1.75 L/hr. (red diesel).

Table 66. Scenarios evaluated for urban duty HGVs. Regional and long-haul scenarios use the prefix RG and LH instead of UB, respectively.

Strategy Code	Objective Function	Scenario Code	Descriptor (duty cycle, objective function, energy prices assumption)
S0	Baseline vehicle (no LCTs fitted)	UB-BASE1	Urban, baseline scenario (no objective), energy prices 20% lower than current ones
		UB-BASE2	Urban, baseline scenario (no objective), current energy prices.
		UB-BASE3	Urban, baseline scenario (no objective), energy prices 20% higher than current ones
S1	Minimisation of NPC	UB-UNLTD1	Urban, minimisation of NPC, energy prices 20% lower than current ones
		UB-UNLTD2	Urban, minimisation of NPC, current energy prices.
		UB-UNLTD3	Urban, minimisation of NPC, energy prices 20% higher than current ones
S2	Minimisation of GHG Emissions	UB-GHG1	Urban, minimisation of GHG emissions, energy prices 20% lower than current ones
		UB-GHG2	Urban, minimisation of GHG emissions, current energy prices.
		UB-GHG3	Urban, minimisation of GHG emissions, energy prices 20% higher than current ones
S3	Minimisation NPC with low RITM[16]	UB-RITM1	Urban, minimisation of NPC with risk of technology maturity level 6 or over, energy prices 20% lower than current ones
		UB-RITM2	Urban, minimisation of NPC with risk of technology maturity level 6 or over, current energy prices.
		UB-RITM3	Urban, minimisation of NPC with risk of technology maturity level or over, energy prices 20% higher than current ones
S4	Minimisation of NPC with low RISL	UB-RISL1	Urban, minimisation of NPC with risk of safety and limitations 6 or over, energy prices 20% lower than current ones
		UB-RISL2	Urban, minimisation of NPC with risk of safety and limitations 6 or over, current energy prices.
		UB-RISL3	Urban, minimisation of NPC with risk of safety and limitations 6 or over, energy prices 20% higher than current ones

[16] Only technologies with a risk level of 6 or higher are part of the solution. This means that the risk is low.

All the strategies developed for urban lorries consider that light weighing materials, spray suppression mudflaps and automated manual transmissions (AMT) are good value for money (Table 67). Spray suppression technologies are always chosen despite that in urban HGVs, they yield a mere 0.5% of fuel savings, due to the fact that they are very inexpensive (£120/vehicle). In contrast, aerodynamic irregular body shape boxes and aerodynamic fairings, hydraulic powertrains and stop-start engines are not selected by the metaheuristics model. This is consistent with the literature (National Research Council, 2010, Baker et al., 2009a, Hill et al., 2011) as city logistics vehicles do not benefit greatly from aerodynamic improvements. The model only selects some of these aerodynamic technologies when minimising GHG emissions (strategy S2), as cost-efficiency is irrelevant under this objective function. Predictive cruise control and controllable air compressors are not feasible technologies as these do not yield any fuel savings under the urban delivery duty cycle.

Stop-start engines are not selected in strategy S1 because their function is redundant when a flywheel is also fitted and the latter is a more cost efficient technology. Both technologies are not selected under S2 because electric hybrid powertrains yield higher higher carbon savings and they both include a stop-start function. Stop-start engines are not selected under S4 because they present a serious limitation; when the vehicle is in congestion, the engine could stop long enough as to impact negatively on the performance of the three phase auxiliary alternator refrigeration unit, when this technology is also selected.

Regarding refrigeration technologies only auxiliary alternator technologies and vacuum insulated panels get selected under some of the scenarios. Due to the amount of working hours and fuel consumption for TRUs, there is not a business case for other more sophisticated refrigeration technologies.

Under S1 (cost minimisation strategy), exhaust heat recovery systems and electrical drive turbo compound (Table 13, page 64) are never selected as they are too expensive for the savings that they generate. New generation single wide base tyres are preferred over lower rolling resistance (LRR) tyres despite being twice as expensive as they save four times more fuel (4% vs. 1%). Kinetic energy recovery flywheels are chosen over other types of hybrid technologies due to their favourable fuel savings/cost ratio. The main differences between the three urban scenarios (UB-UNLTD 1,2 and 3) is that under UB-UNLTD2 (current energy prices) and UB-UNLTD3 (energy prices 20% more expensive) tyre pressure monitoring systems and 3 phase alternator refrigeration units become cost efficient; however, with fuel prices down by 20% (scenario UB-UNLTD1), these technologies would become too costly and are not selected by the model.

Table 67. Optimisation of low carbon technologies selection for different scenarios for urban deliveries HGV (using B65).

Financial Parameters	Vehicle Parameters		Operating Parameters - Urban Deliveries	
Rate of Return 9.7%	GVW 18 tonnes	Conventional Diesel TRU	Tonnes delivered (5 years): 14,111	Price B65 (2015) 80.51 p/L
Interest Rate Leasing 3%	Tractor 4x2 Rigid	Initial Fuel: Red Diesel	Total Km (5y): 569547	Price Red Diesel (2015) 57.95 p/L
Life Investment 5 Years	(DAF CF65)	Initial Refrigerant Gas: R-404A	Refrigeration (hrs./year):2,130	Price Electricity (2015) 13.02 p/kWh
GDP Central Growth	Tractor Fuel (65 % biodiesel)	Semi-Trailer: 10.4/61.14 m^3		

Results			Urban														
			Baseline (S0)			Optimisation with Unlimited Risk (S1)			Minimisation GHG Emissions (S2)			Risk Maturity >= 6 (S3)			Risk Safety & Limitations > 6 (S4)		
			-20%	Fuel Price Medium	+20%	-20%	Fuel Price Medium	+20%	-20%	Fuel Price Medium	+20%	-20%	Fuel Price Medium	+20%	-20%	Fuel Price Medium	+20%
			UB-BASE1	UB-BASE2	UB-BASE3	UB-UNLTD1	UB-UNLTD2	UB-UNLTD3	UB-GHG1	UB-GHG2	UB-GHG3	UB-RITM1	UB-RITM2	UB-RITM3	UB-RISL1	UB-RISL2	UB-RISL3
Vehicle Technologies	Reduced Aerodynamic Resistance	Aerodynamic Trailers	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
		Aerodynamic Irregular body shape	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Aerodynamic Fairings	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Spray Reduction Mud Flaps	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
	Reduced Rolling Resistance	Low rolling resistance tyres	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
		New generation wide-base single tyres	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0
		Automatic tyre pressure adjustment	0	0	0	0	1	1	1	1	1	0	1	1	1	1	1
	Vehicle Mass	Lightweighting Materials	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
	Intelligent VT	Predictive Cruise Control	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Auxiliary Systems	Controllable air compressor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Powertrain Technologies	Exhaust Heat Recovery	Heat Recovery (in general)	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
		Electrical Drive Turbo compound	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
	Transmissions	Automated Manual Transmission	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
	Mild Hybrid	Flywheels Hybrid	0	0	0	1	1	1	0	0	0	1	1	1	0	0	0
		Stop-Start: Electric Hybrid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Pneumatic Booster - Air Hybrid	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0
	Alternative PT	Full Hybrid: Series / Parallel Electric	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
		Series / Parallel hydraulic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total FCR (Vehicle & Powertrain)		0.0%	0.0%	0.0%	27.8%	28.5%	28.5%	35.1%	35.1%	35.1%	24.6%	25.3%	25.3%	9.4%	9.4%	9.4%
TRU	Refrigeration Technologies	3 Phase Aux. Alternator Unit (R410A)	0	0	0	0	1	1	1	1	1	0	1	1	0	0	0
		Hybrid Refrigeration Unit	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Cryogenic Nitrogen (LIN)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Cryogenic CO_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Cryogenic Air (LAIR)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Lower GWP Gas Unit (R744)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Vacuum Isolated Panels	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
	Total FCR (TRU)		0%	0%	0%	0%	100%	100%	100%	100%	100%	0%	100%	100%	0%	0%	0%
	Combined FCR % (Vehicle, Powertrain & Refrigeration)		0.0%	0.0%	0.0%	-25.0%	-30.7%	-30.7%	-36.9%	-36.9%	-36.9%	-22.0%	-27.9%	-27.9%	-8.4%	-8.4%	-8.4%
	New Average Fuel Consumption (L/ 100km)		28.63	28.63	28.63	20.67	22.10	22.10	20.14	20.14	20.14	21.59	23.01	23.01	25.94	25.94	25.94
	New TRU Fuel Consumption (L/hrs.)		1.75	1.75	1.75	1.75	0.00	0.00	0.00	0.00	0.00	1.75	0.00	0.00	1.75	1.75	1.75
	Improvement in Costs		0.0%	0.00%	0.00%	7.8%	9.8%	11.5%	-4.3%	-0.2%	3.1%	6.6%	8.5%	10.0%	2.3%	3.0%	3.5%

Table 68. Outcome of the meta-heuristics optimisation of the vehicle specification based on different strategies for an urban duty cycle HGV.

Output for Multicriteria Decision Analysis	STRATEGY 0			STRATEGY 1			STRATEGY 2			STRATEGY 3			STRATEGY 4		
	-20%	Fuel Price Medium	20%	-20%	Fuel Price Medium	20%	-20%	Fuel Price Medium	20%	-20%	Fuel Price Medium	20%	-20%	Fuel Price Medium	20%
	UB-BASE1	UB-BASE2	UB-BASE3	UB-UNLTD1	UB-UNLTD2	UB-UNLTD3	UB-GHG1	UB-GHG2	UB-GHG3	UB-RITM1	UB-RITM2	UB-RITM3	UB-RISL1	UB-RISL2	UB-RISL3
Net Present Cost	224,679	250,895	277,112	207,142	226,318	245,131	234,322	251,473	268,624	209,748	229,675	249,270	219,481	243,408	267,336
GHG Emissions (t CO_2 eq.)	317	317	317	252	187	187	171	171	171	259	195	195	295	295	295
Risk Technology Maturity	10	10	10	4	4	4	4	4	4	6	6	6	7	7	7
Risk Safety & Limitations	6	6	6	4	4	4	3	3	3	4	4	4	6	6	6

Table 69. Emissions (ton CO_2 eq.) and KPIs for urban duty scenarios.

GHG Emissions (t CO_2 eq.)	Urban														
	Baseline (S0)			Optimisation with Unlimited Risk (S1)			Minimisation GHG Emissions (S2)			Risk Maturity >= 6 (S3)			Risk Safety & Limitations > 6 (S4)		
	-20%	Fuel Price Medium	20%	-20%	Fuel Price Medium	20%	-20%	Fuel Price Medium	20%	-20%	Fuel Price Medium	20%	-20%	Fuel Price Medium	20%
	UB-BASE1	UB-BASE2	UB-BASE3	UB-UNLTD1	UB-UNLTD2	UB-UNLTD3	UB-GHG1	UB-GHG2	UB-GHG3	UB-RITM1	UB-RITM2	UB-RITM3	UB-RISL1	UB-RISL2	UB-RISL3
Scope 1[17]	220.6	220.6	220.6	179.0	121.0	121.0	110.8	110.8	110.8	183.9	125.8	125.8	206.6	206.6	206.6
Difference	0%	0%	0%	-18.8%	-45.1%	-45.1%	-49.8%	-49.8%	-49.8%	-16.7%	-43.0%	-43.0%	-6.4%	-6.4%	-6.4%
Scope 2[18]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Scope 3[19]	96.6	96.6	96.6	72.6	66.4	66.4	60.5	60.5	60.5	75.4	69.2	69.2	88.5	88.5	88.5
Difference	0%	0%	0%	-24.8%	-31.2%	-31.2%	-37.3%	-37.3%	-37.3%	-21.9%	-28.4%	-28.4%	-8.4%	-8.4%	-8.4%
All Scopes	317.2	317.2	317.2	251.7	187.4	187.4	171.4	171.4	171.4	259.3	195.0	195.0	295.0	295.0	295.0
Difference	0%	0%	0%	-20.7%	-40.9%	-40.9%	-46.0%	-46.0%	-46.0%	-18.2%	-38.5%	-38.5%	-7.0%	-7.0%	-7.0%
Outside Scopes [20]	270.0	270.0	270.0	195.2	207.5	207.5	189.2	189.2	189.2	204.0	216.1	216.1	244.7	244.7	244.7
Difference	0%	0%	0%	-27.7%	-23.1%	-23.1%	-29.9%	-29.9%	-29.9%	-24.5%	-20.0%	-20.0%	-9.4%	-9.4%	-9.4%
Total Emissions (Inside/Outside)	587	587	587	447	395	395	361	361	361	463	411	411	540	540	540
Difference	0%	0%	0%	-23.9%	-32.7%	-32.7%	-38.6%	-38.6%	-38.6%	-21.1%	-30.0%	-30.0%	-8.1%	-8.1%	-8.1%
g CO_2eq./km (all scopes)	557	557	557	442	329	329	301	301	301	455	342	342	518	518	518
g CO_2eq./tonne-km (all scopes)	0.039	0.039	0.039	0.031	0.023	0.023	0.021	0.021	0.021	0.032	0.024	0.024	0.037	0.037	0.037
g CO_2eq./cage-km (all scopes)	0.010	0.010	0.010	0.008	0.006	0.006	0.006	0.006	0.006	0.009	0.006	0.006	0.010	0.010	0.010
g CO_2eq./case-km (all scopes)	0.0004	0.0004	0.0004	0.0003	0.0002	0.0002	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004

[17] Tank-to-well GHG emissions (direct emissions).
[18] GHG emissions from electric power consumption (energy indirect)
[19] Well-to-Tank GHG emissions (other indirect emissions)
[20] Emissions from biofuels combustion outside scopes 1, 2 and 3. As scope 1 emissions of biodiesel is considered to be almost negligible (e.g. 20 g CO_2/L), outside scopes reflect the direct CO_2 impact of burning the fuel.

S1 shows that with the right combination of low carbon technologies and at current prices, GHG emissions can be reduced by 41% (UB-UNLTD2) while decreasing NPC by £24,577 (9.8%). This results suggest that over a fleet of 39 rigid CF65 vehicles not fitting any LCT, the industrial sponsor could save 5,064 tonnes of CO_2 eq. whilst reducing NPC by £958k. This is possible by decreasing fuel consumption from 28.63 L/100 km to 22.1 L/100km. With fuel prices 20% cheaper (UB-UNLTD1), net present savings of £17k compared to UB-BASE1 can be achieved per vehicle, halving the carbon savings to 20.7% as a result of not including a 3 phase alternator refrigeration unit and a tyre pressure monitoring system (TPMS), as reflected in Table 68. This represent savings of 2,554 kg CO_2 eq. and £683,943 over the next 5 years for the whole fleet of urban lorries. With lower fuel prices, it is more likely that fewer LCTs are cost-efficient and therefore chosen by the model and GHG emissions reduced. When comparing UB-BASE3 with UB-UNLTD3, the company could save over the life span of the lorries 5,064 tonnes of CO_2 eq.; however as the energy prices would be 20% higher, savings of up to £1.25 Million could be achieved.

Under S2 (the strategy seeking to minimise GHG emissions), aerodynamic trailers and electric hybrid powertrains are selected as these reduce tractive fuel consumption by 1% and 20% respectively, as their costs are irrelevant. The same reason applies to vacuum insulated panels. S2 is insensitive to changes in electricity and red diesel prices, and the technologies that increase fuel consumption are not penalised as long as they reduce all scopes carbon emissions. In contrast with other duty cycles, urban rigid lorries cannot minimise GHG emissions whilst saving money unless energy prices increase by 20%. When this happens, reducing carbon emissions at the highest level leads to a 3% reduction on NPCs as well. The combination of low carbon technologies is common among all three S2 scenarios which leads to GHG avoidances of 146 tonnes over 5 years (46% lower than UB-BASEx scenarios). As it can be observed in Table 68, S2 is the strategy with the highest associated risks (level 4 for risk of technology maturity and level 3 for technology safety and limitations). The three scenarios under S2 would save 5,686 ton CO_2 over 5 years almost cost-neutrally, as the increased cost would be just £578 for the whole fleet. However, if energy prices would decrease by 20% the NPC would increase up to £376,077. On the other hand, if fuel prices would increase by 20%, the strategy would save the company £331,020.

Strategies S3 and S4 are the least risky ones. Accepting technologies with a technology maturity risk level of 6 or over, yields the solutions of the S3 strategy. Strategy S4 reflects the optimal vehicle specification that includes technologies that do not present any relevant technological limitation or safety issues (level 6 or over). The main differences between the solutions for both strategies, is that while S3 choses new generation WBST and none of hybridisation technologies, S4 selects LRR tyres and flywheels. TPMS technologies (Table 6, page 48) are chosen under both strategies; however, in S3 when fuel prices are 20% lower (UB-RITM1), this technology is not cost effective. Under S3, auxiliary alternator units are the most cost efficient refrigeration technology with current and 20% higher energy prices. In S4, due to the limitations of the technology, auxiliary alternator refrigeration units are not chosen. Depending on the scenario, S3 yields NPC savings of over £21k (UB-RITM2), while S4 just £7.5k (UB-RISL2); roughly 8.5% and 3% cheaper respectively. Compared to UB-BASE1, under the UB-RITM1 scenario, the fleet of 39 CF65 lorries could save 58 t CO_2 eq. over 5 years and £582,309. At current and 20% more expensive fuel prices, selecting the suggested vehicle specification results in carbon savings of 122 t CO_2 eq. with NPC savings of £827,580 and over £1 Million respectively. Because there are fewer technologies available to reduce carbon emissions under S4, all three scenarios yield just 22t of carbon savings over the life span of the fleet. Depending on the energy prices, NPC savings are in the range between £202,722 (energy prices 20% lower) to £381,264 (energy prices 20% higher). These results mean that even the most risk averse companies (choosing strategies S3 or S4) could still save money and GHG emissions by choosing the optimal vehicle specification suggested by the metaheuristics model.

Assuming current energy prices, efficient frontier analyses of strategy S1 when different levels of risk aversion are considered, are illustrated in Figures 110 and 111. It can clearly be appreciated that higher risks (RITM level 5 or RISL level 6 or lower) lead to higher rewards (NPC is lower). Figure 110 illustrates that the willingness to accept technologies with a risk level of technology maturity of 8 instead of 9, reduces NPCs by £6.6k (over 5 years)[21]. Similarly, Figure 111 shows that the risk aversion from a technology limitation of level 6 instead of level 5 results in a £10k more expensive solution. Each one of the solutions corresponds to a specific combination of low carbon technologies for a particular scenario; for example, in Figure 110, the combination of technologies that represent a RITM level of 6, correspond to the technologies chosen under scenario UB-RITM2 (Table 68).

[21] This excludes the monetary losses of vehicle breakdowns and consequential unmet service level agreements.

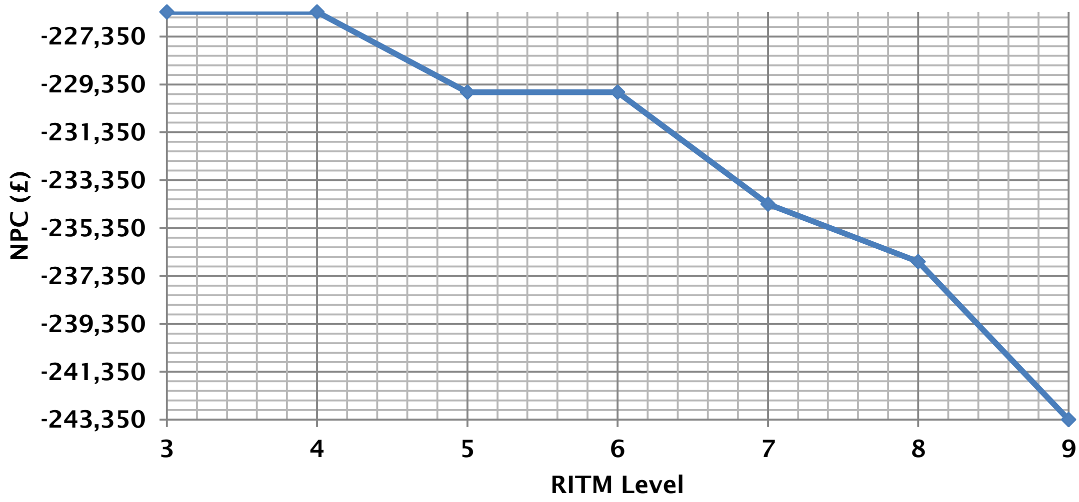


Figure 110. Efficient frontier of the impact of technology maturity risk acceptance (RITM) over NPC for an urban HGV under strategy S1.

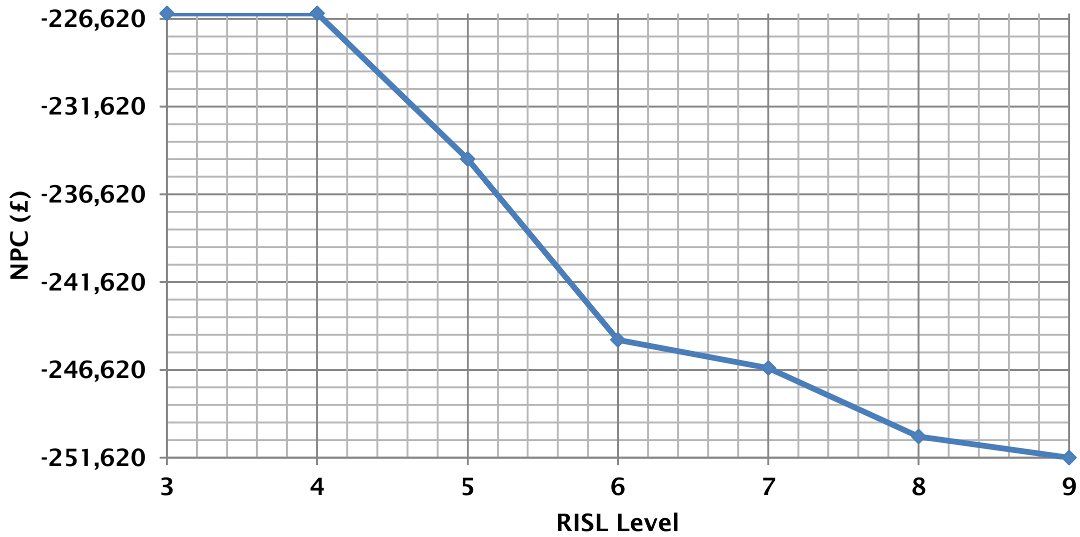


Figure 111. Efficient frontier of the impact of technology safety and limitations risk acceptance (RISL) over NPC for an urban HGV under strategy S1.

In the context of this research, an efficient frontier is a set of optimal solutions that minimise the net present costs (or GHG emissions) for a defined level of risk. The solutions that lie underneath the efficient frontier are sub-optimal, as their cost (or carbon emissions) are higher than the optimal technology package for the same level of risk.

The efficient frontier of strategy S2 represents different carbon emissions for each level of risk[22]. The efficient frontier of each technology maturity risk (RITM) is illustrated in Figure 112 while the one for the risk of technology safety and limitations appears in Figure 113. GHG emissions can be reduced considerably by accepting less mature technologies (Figure 112). When technologies with a level 7 are accepted (technologies that have just enter into the market), instead of level 8 (technologies that have been in the market for a while), more than 40t CO_2 can be reduced. Similar savings are materialised when accepting lower levels of technology safety and limitations risks (Figure 113); this means riskier technologies. By accepting technologies with a level 4 (technologies that present some limitations or safety concerns), 120 t CO_2 eq. can be saved over 5 years compared to the solution that only accept technologies with a level 7 of RISL (technologies that do not present new safety issues and that are less limited and therefore are more advantageous than incumbent ones) .

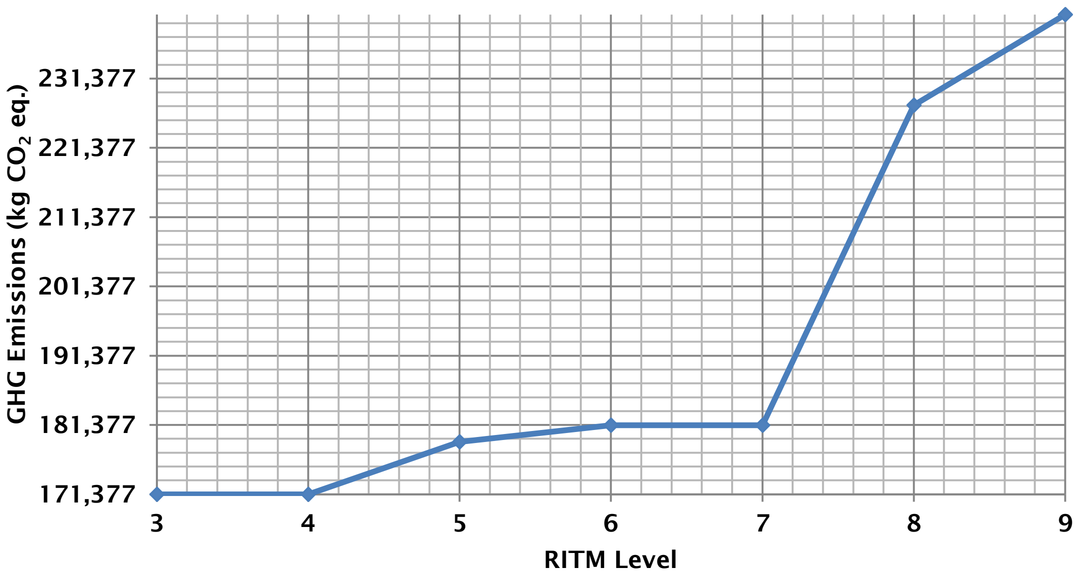


Figure 112. Efficient frontier of the impact of technology maturity risk acceptance (RITM) over GHG emissions for an urban HGV under strategy S2.

Excluding S0 (do-nothing scenario), S1 yields always the lowest cost solution and S2 the solution with the lowest GHG emissions and the highest costs for each one of the scenarios evaluated in Table 68 (Page 232). Despite that S3's aim is to produce a solution with the lowest cost for a risk of technology maturity over 6 (technologies that have at least being trialled in HGVs), this strategy is always dominated by S4 as this one always yields the solution with the lower risks

[22] The description of the different levels of RITM and RISL appear in Tables 26 (page146) and Table 27 (page 129-130, respectively).

(including both; risks of technology maturity and safety and limitations). It also represents the second most expensive solution. As companies have multiple targets, the range of alternative strategies justifies the need to use a method that can consider different criteria to propose a solution that best reflects the priorities of the decision making organisation. This evaluation is conducted in section 5.5, where the results of the analytic hierarchy process (AHP) are presented.

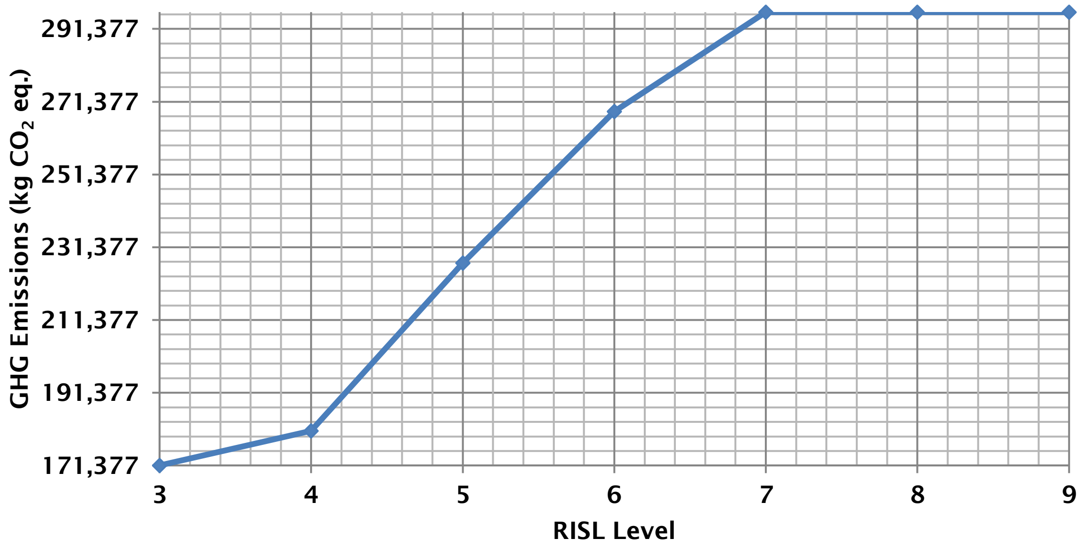


Figure 113. Efficient frontier of the impact of technology safety and limitations risk acceptance (RISL) over GHG emissions for an urban HGV.

None of the urban scenarios produce scope 2 emissions (Table 69, page 232). The reason for this is that the technologies that could use electric power (e.g. hybrid refrigeration units), are not chosen in any of the solutions. Scope 1 emissions include the combustion of fuels and refrigerant gas leakages. TRUs using R410-A (e.g. 3 phase auxiliary alternator units) have almost half of the emission factors and leakage rates than conventional units using R-404A gas. Scope 3 emissions represent the well-to-tank emissions of the fuels used, as well as the lifecycle emissions of the cryogenic gases (production and delivery). As none of those are chosen in urban scenarios, scope 3 emissions are slightly lower than in the scenarios where cryogenic gases are used. As it can be seen in Table 69 (Page 232), outside scope emissions are higher than scope 1 emissions. The reason for this is that the fuel used by the industrial sponsor has a high biogenic content. As all biofuels, scope 1 emissions (tank to wheel) are almost negligible and most of the carbon footprint represents scope 3 and outside scope emissions for the reasons explained in section 5.3. Excluding the do-nothing scenario, the quantity of CO_2 produced by all strategies is between 301 and 518 g CO_2 eq. /km

(Table 69). Normalising by tonne-km, GHG emissions are certainly low (21 to 37 mg CO_2 eq. /tonne-km). As the tonnage moved by the industrial sponsor is an estimate (based on average recorded weights), the KPI that reflects most accurately the GHG emissions of the sponsor is g CO_2 eq. /cage-km as there is precise and accurate information regarding the cases transported (urban vehicles deliver an average 10,650 cages and run between 112,776 km in year 1 to 115,624 in year 5). The results suggested that the GHG emissions for this KPI fluctuated between 6 to 10 mg CO_2 eq. / cage-km. These small differences of 4 mg per cage/km add up to savings of 146 t CO_2 eq. / 5 years for S2 (UB-GHG2) and 22 t CO_2 eq. for S4 (UB-RISL2) that over a fleet of 39 lorries is 5,694 and 858 t CO_2 eq. for the fleet under each scenario.

When this research started in 2010, it seemed that energy prices were always going to rise. By 2012, DECC (2012) projected that fuels for private vehicles' prices would always grow (up to 2030). Nevertheless, by 2014 DECC (2014e) projected that prices would decrease and would not pick up until 2020. By 2015 and 2016 oil prices were in decline. To reflect these fluctuations in fuel prices, the scenarios shown in Table 69 included scenarios with prices up to 20% higher and lower than the baseline price. These assumptions have been expanded to accommodate larger energy cost variances in Figure 114. This illustrates the impact of theoretical fuel prices being 70% of their current prices (biodiesel B65 cost of £ £0.564/L) to 30% higher (biodiesel B65 cost of £1.04/L) than now under strategy S1 (the one that minimises costs). Despite that the trend line appears to indicate a linear relationship between energy prices and NPC, in reality this is not the correct, as the trend line (black) does not match perfectly the blue curve (Figure 114). The reason for this, is that different energy prices may result in some cases in a different combination of vehicle technologies being most appropriate. Based on S1, a difference in fuel prices of ±30% (from 70% to 130% of current prices) leads to an increase on NPC of 28.79%.

A sensitivity analysis of the impact of mileage on NPC for urban HGVs (scenario UB-UNLTD2) was conducted as illustrated in Figure 115. In this case study, the sensitivity analyses of mileage is not very relevant as the industrial sponsor does not expect to increase the distance run per vehicle significantly in the coming years. The reasons for this include the fact that thanks to the efficient routing and scheduling optimisation system used by the sponsor, the vehicles are highly utilised (the loading factor of the vehicles is 93.3%). As it can be seen in Figure 115, changes of ±20% on the mileage run each year, vary NPC from under £247.6k to over £255.3k. Details of the intermediate values appear in Appendix 15. As it can also be appreciated, the mileage for year 2016 has the highest impact. The reason for this is that the mileage is expected to grow a little bit each year, the value time of money increases the sensitivity values early in time and more importantly because the prices of fuel in 2015 are considerably lower than the prices expected for 2016 and onwards.

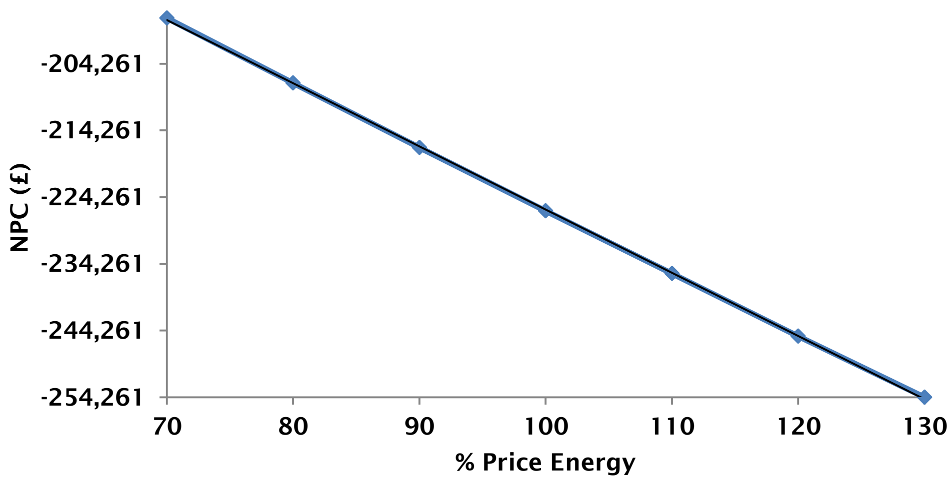


Figure 114. Relationship between NPC (strategy S1; scenario UB-UNLTD2) and cost of energy for an urban HGV (e.g. B65 price between £0.564/L to £1.04/L).

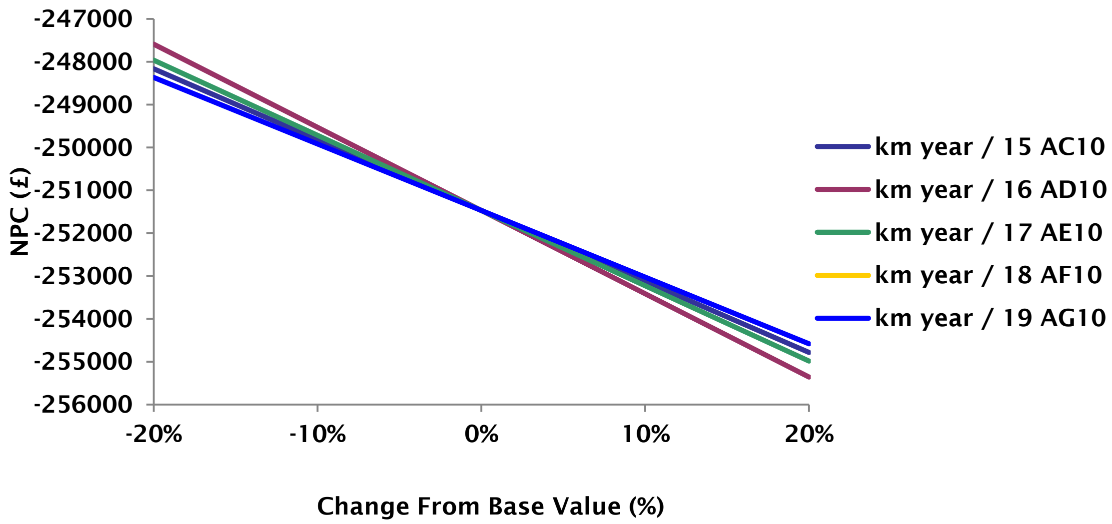


Figure 115. Relationship between NPC (strategy S1; scenario UB-UNLTD2) and mileage (in km) for an urban HGV (baseline mileage for year 2015 was 112,776).

5.4.2 SELECTION OF LOW CARBON TECHNOLOGIES FOR REGIONAL SEMI-ARTICULATED TRAILERS

The vehicle in the regional scenarios (Table 70-72) represents a DAF CF85 32t 4x2 semi-articulated vehicle running on biodiesel (B65) with a semi-trailer (13.4 m) that uses a 9.6 kW refrigeration unit. Based on the business case of the industrial sponsor, under this type of duty, the vehicles run around 152,991 km/year and carry 3,763 tonnes/year (excluding the reverse logistics of waste). The typical average fuel consumption of these vehicles is 34.13 L/100km. TRUs consume 2.87 L/hr. and run for 3,550 hrs. /year. The strategies evaluated are the same as appear in Table 67 (Page 231); however, instead of urban they represent regional duty, which results in very different vehicles, operations and therefore scenarios.

With prices 20% below current levels and up to 20% higher, all strategies (S1, S2, S3 and S4) consider that aerodynamic trailers, spray suppression mudflaps, lower rolling resistance technology (LRR or SWBT), automatic tyre pressure monitoring systems (ATPMS), lightweight materials and predictive cruise control represent good value for money and all contribute to achieve the goals sought by all four strategies (Table 70); this also means that all these technologies are common to all scenarios. The only technologies that are consistently excluded from all strategies (and therefore scenarios) are irregular body shape trailers (teardrop shaped boxes), aerodynamic fairings (side skirts), and hydraulic hybrid powertrains.

Regarding refrigeration technologies, the only ones that are selected under different strategies and scenarios are three phase auxiliary alternator units, LAIR and vacuum insulated panels. Three-phase auxiliary alternator units represent the best alternative for strategies S1, S2 and S3, with the exception of scenario RG-UNLTD3 (energy prices are 20% more expensive and the objective function seeks cost minimisation regardless of emissions or risks). The savings returned by this technology more than offset its costs. LAIR TRU represent the most cost efficient refrigeration technology under scenario RG-UNLTD3. This technology cannot be included under S3, as it is still under development (immature).

Under strategy S1, the selection of energy efficient vehicle technologies is quite insensitive to variations of ±20% in the price of fuel and the only differences between scenarios relate to the refrigeration technology chosen (Table 71). In addition to the technologies common to all four strategies, S1 scenarios (RG-UNLTD1, 2 and 3) select new generation WBST, controllable air compressors, flywheels and pneumatic boosters. Regional duty HGVs should not fit LRR tyres, exhaust heat recovery systems, electrical drive turbo compound, automated manual transmissions (AMT), stop start engines and electric hybrid powertrains. The reasons for not selecting heat recovery, turbo compound systems and electric hybrids powertrains are simple; they are too expensive for the amount of fuel that they save. AMT and stop-start technologies benefits are greater under urban duty cycles where multiple stops and gear changes maximise fuel savings (1.5% and 3% respectively); benefits that under regional and long-haul are much smaller.

Under RG-UNLTD3, the fuel consumption of the tractor unit is 22.84L/100km. Under RG-UNLTD1 and 2, selecting a 3 phase alternator unit increases the fuel consumption of the tractor unit by 3.36 L/100km. This is the result of multiplying the fuel consumption of this type of TRU by the amount of hours that the vehicle works each year and divided by the number of km.Considering the results that appear in Table 71, strategy S1 reduces the NPC of the investment by between £43.4 k to £74 k compared to the do-nothing scenarios (RG-BASE1, 2 and 3) and GHG emissions by between 187-269 t CO_2 eq. over 5 years with technologies that have been developed at least as prototypes for HGVs (maturity risk level 4) which are also considered as safe and present a few limitations (limitation risk level 4). Considering that the industrial sponsor has a fleet of 78 DAF CF85, with low energy prices, savings could be in the range of £3.4 M and 21 kt CO_2 eq. over 5 years. With high energy prices, fuel savings would increase up to almost £5.8M and 14.6 kt CO_2 eq.

Strategy S2 choses the technologies that contribute the most to reduce GHG emissions (not just fuel consumption reduction). For example, a technology with a higher fuel consumption reduction than another may not be selected, as it may produce higher carbon emissions when gas leakages or scope 3 emissions are taken in consideration. Table 72 shows that strategy S2 can reduce emissions of regional HGVs by 56.2% (scope 1) while delivering net present savings between 5% (RG-GHG1) and 11.4% (RG-GHG3). This strategy can reduce the average fuel consumption of the HGVs from 34.13 L/100 km (S0) to 24 L/100km (Table 70). On the negative side, S2 is the riskier strategy, with levels of risk of 4 and 3 for technology maturity and safety and limitations respectively (Table 71), a trait common to all vehicle duties. These levels of risk mean that some of the technologies chosen have not reached a commercial stage yet and they are more limited in some aspects than the incumbent technologies that they could replace. Strategy S2 is the only one choosing vacuum insulated panels, as these can yield some energy savings due to better thermal insulation, despite that they are very cost inefficient (5% fuel savings of the refrigeration system at an additional cost of £8,590 for this size of trailer).

The three energy cost scenarios under S3 yield the same combinations of technologies; this means that a company accepting only this strategy would find that the solution suggested is insensitive to fuel price changes (±20%). This strategy is very similar to S1, with the exception of pneumatic boosters that are not chosen due to their poor level of technology maturity (Table 70). Regarding TRUs, the difference in respect to S1 is that LAIR cannot be chosen under S3 due to the fact that this technology is still immature. Compared to S0, S3 scenarios can expect a NPC reduction by between 11% (RG-RITM1) and 15% (RG-RITM3) with all scopes GHG emissions avoidances of 46% (Table 72). Taking forward strategy S3 could save the sponsor 20.3 Kt CO_2 eq. over the life of the investment.

Under regional duty, strategy S4 scenarios represent the solution with the lowest risks (a risk level of technology maturity of 7 and safety and limitations of 6). S4 swaps NGSWT in favour of LRR tyres, as it is assumed that the former represent higher limitation risks as the infrastructure to maintain these is not well developed (e.g. in case of a puncture) as not all garages keep them in stock. S4 also excludes controllable air compressors and flywheels. The most relevant variation among all three S4 scenarios is that RG-RISL3 choses ATM while the other two do not. In combination with the other technologies chosen under this scenario, ATM can save around £753 of fuel per year at a cost of £3,250. This presents a payback period of 53 months, slightly below the 60 months of life expectancy of the HGV and way above of the payback period typically required by industrial sponsors when deciding on what technologies to invest. Following the payback approach, AMT would not be chosen. However, based on the NPV technique, selecting AMT decreases NPC of RG-RISL3 by £73 and for this reason the heuristics model selects this technology (a cost of £402,225 instead of £402,298 per vehicle). Across the fleet the savings from this technology would be a modest £5,694 over 5 years.

Under S4 (the strategy that minimises costs by only using technologies that are at least as safe and that present fewer limitations than the incumbent technologies that they could replace), no lower carbon refrigeration technologies are selected either because their level of safety and limitations is under 6 (e.g. LIN, LAIR, cryogenic CO_2) or because they are not cost efficient (e.g. hybrid TRUs, lower GWP refrigerant gas units and vacuum insulated panels). For example, in the model it has been assumed that hybrid TRUs are plugged 10% of the time in the grid. Even if they would save 10% of red diesel, the £590 saved per year would require almost 6 years to recover the £3,234 of on top costs compared to conventional TRUs. The case of vacuum insulated panels is quite simple; they cost £8,590 per year and they save just 5% of a total fuel cost of £25,237 per refrigerator. This means that their payback is almost 7 years. In the case of cryogenic refrigeration gases, even if the technologies would cost the same, the effect is even more dramatic, as while the NPC of red diesel would accrue over 5 years £25,237, excluding any potential energy costs, cryogenic LIN units gas would exceed £50k over the same period and cryogenic CO_2 units gas would reach £92 K. This justifies why these units are not chosen under any scenario.

Table 70. Optimisation of low carbon technologies selection for different scenarios for regional duty HGV (using B65).

Financial Parameters	Vehicle Parameters		Operating Parameters - Regional	
Rate of Return 9.7% Interest Rate Leasing 3% Life Investment 5 Years GDP Central Growth	GVW 32 tonnes Tractor 4x2 Semi-articulated (DAF CF85) Trailer 2 axles Tractor Fuel (65 % biodiesel)	Conventional Diesel TRU Initial Fuel: Red Diesel Initial Refrigerant Gas: R-404A Semi-Trailer: 13.4/78.79 m3	Tonnes delivered (5 years): 18815 Total Km (5y): 764955 Refrigeration (hrs./year):3550	Price B65 (2015) 80.51 p/L Price Red Diesel (2015) 57.95 p/L Price Electricity (2015) 13.02 p/kWh

Results

			Regional														
			Baseline (S0)			Optimisation with Unlimited Risk (S1)			Minimisation GHG Emissions (S2)			Risk Maturity >= 6 (S3)			Risk Safety & Limitations > 6 (S4)		
			-20%	Fuel Price Medium	+20%	-20%	Fuel Price Medium	+20%	-20%	Fuel Price Medium	+20%	-20%	Fuel Price Medium	+20%	-20%	Fuel Price Medium	+20%
			RG-BASE1	RG-BASE2	RG-BASE3	RG - UNLTD1	RG - UNLTD2	RG - UNLTD3	RG - GHG1	RG -GHG2	RG - GHG3	RG - RITM1	RG - RITM2	RG - RITM3	RG - RISL1	RG -RISL2	RG - RISL3
Vehicle Technologies	Reduced Aerodynamic Resistance	Aerodynamic Trailers	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
		Aerodynamic Irregular body shape	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Aerodynamic Fairings	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Spray Reduction Mud Flaps	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
	Reduced Rolling Resistance	Low rolling resistance tyres	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
		New generation wide-base single tyres	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0
		Automatic tyre pressure monitoring	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
	Vehicle Mass	Lightweighting Materials	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
	Intelligent VT	Predictive Cruise Control	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
	Auxiliary Systems	Controllable air compressor	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0
Powertrain Technologies	Exhaust Heat Recovery	Heat Recovery (in general)	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
		Electrical Drive Turbo compound	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
	Transmissions	Automated Manual Transmission	0	0	0	0	0	0	1	1	1	0	0	0	0	0	1
	Mild Hybrid	Flywheels Hybrid	0	0	0	1	1	1	0	0	0	1	1	1	0	0	0
		Stop-Start: Electric Hybrid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Pneumatic Booster - Air Hybrid	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0
	Alternative PT	Full Hybrid: Series / Parallel Electric	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
		Series / Parallel hydraulic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total FCR (Vehicle & Powertrain)		0.0%	0.0%	0.0%	33.1%	33.1%	33.1%	39.0%	39.0%	39.0%	30.9%	30.9%	30.9%	21.8%	21.8%	23.0%
TRU	Refrigeration Technologies	3 Phase Aux. Alternator Unit (R410A)	0	0	0	1	1	0	1	1	1	1	1	1	0	0	0
		Hybrid Refrigeration Unit	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Cryogenic Nitrogen (LIN)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Cryogenic CO_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Cryogenic Air (LAIR)	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
		Lower GWP Gas Unit (R744)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Vacuum Isolated Panels	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
	Total FCR (TRU)		0%	0%	0%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%	0%	0%
	Combined FCR % (Vehicle, Powertrain & Refrigeration)		0.0%	0.0%	0.0%	-35.8%	-35.8%	-44.0%	-41.2%	-41.2%	-41.2%	-34.1%	-34.1%	-34.1%	-18.2%	-18.2%	-19.2%
	New Average Fuel Consumption (L/ 100km)		34.13	34.13	34.13	26.17	26.17	22.84	23.97	23.97	23.97	26.90	26.90	26.90	26.70	26.70	26.30
	New TRU Fuel Consumption L/hrs.)		2.87	2.87	2.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.87	2.87	2.87
	Improvement in Costs		0.0%	0.00%	0.00%	12.0%	14.2%	16.5%	5.0%	8.5%	11.4%	11.3%	13.3%	15.0%	8.2%	9.4%	10.4%

Table 71. Outcome of the meta-heuristics optimisation of the vehicle specification based on different strategies for a regional haul duty cycle HGV.

Output for Multicriteria Decision Analysis	STRATEGY 0			STRATEGY 1			STRATEGY 2			STRATEGY 3			STRATEGY 4		
	-20%	Fuel Price Medium	+20%	-20%	Fuel Price Medium	+20%	-20%	Fuel Price Medium	+20%	-20%	Fuel Price Medium	20%	-20%	Fuel Price Medium	+20%
	RG-BASE1	RG-BASE2	RG-BASE3	RG-UNLTD1	RG-UNLTD2	RG-UNLTD3	RG-GHG1	RG-GHG2	RG-GHG3	RG-RITM1	RG-RITM2	RG-RITM3	RG-RISL1	RG-RISL2	RG-RISL3
Net Present Cost	360,815	404,885	448,956	317,386	347,313	374,917	342,883	370,297	397,711	320,175	350,938	381,700	331,155	366,726	402,225
GHG Emissions (t CO_2 eq.)	564	564	564	295	295	377	271	271	271	303	303	303	481	481	477
Risk Technology Maturity	10	10	10	4	4	4	4	4	4	6	6	6	7	7	7
Risk Safety & Limitations	6	6	6	4	4	4	3	3	3	4	4	4	6	6	6

Table 72. Emissions (ton CO_2 eq.) and KPIs for regional duty scenarios.

GHG Emissions (t kg CO_2 eq.)	Regional														
	Baseline (S0)			0ptimisation with Unlimited Risk (S1)			Minimisation GHG Emissions (S2)			Risk Maturity >= 6 (S3)			Risk Safety & Limitations > 6 (S4)		
	-20%	Fuel Price Medium	+20%	-20%	Fuel Price Medium	+20%	-20%	Fuel Price Medium	+20%	-20%	Fuel Price Medium	+20%	-20%	Fuel Price Medium	+20%
	RG-BASE1	RG-BASE2	RG-BASE3	RG-UNLTD1	RG-UNLTD2	RG-UNLTD3	RG - GHG1	RG -GHG2	RG - GHG3	RG -RITM1	RG-RITM2	RG-RITM3	RG-RISL1	RG-RISL2	RG-RISL3
Scope 1	397.0	397.0	397.0	189.2	189.2	160.2	173.8	173.8	173.8	194.3	194.3	194.3	344.9	344.9	342.0
Difference	0	0	0	-52.3%	-52.3%	-59.6%	-56.2%	-56.2%	-56.2%	-51.1%	-51.1%	-51.1%	-13.1%	-13.1%	-13.8%
Scope 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Scope 3	166.5	166.5	166.5	105.6	105.6	216.5	96.8	96.8	96.8	108.6	108.6	108.6	136.5	136.5	134.9
Difference	0	0	0	-36.6%	-36.6%	30.0%	-41.9%	-41.9%	-41.9%	-34.8%	-34.8%	-34.8%	-18.0%	-18.0%	-19.0%
All Scopes (baseline)	563.5	563.5	563.5	294.8	294.8	376.7	270.5	270.5	270.5	302.9	302.9	302.9	481.4	481.4	476.9
Difference	0	0	0	-47.7%	-47.7%	-33.2%	-52.0%	-52.0%	-52.0%	-46.2%	-46.2%	-46.2%	-14.6%	-14.6%	-15.4%
Outside Scopes (baseline)	433.7	433.7	433.7	330.0	330.0	288.1	302.3	302.3	302.3	339.3	339.3	339.3	339.9	339.9	334.8
Difference	0	0	0	-23.9%	-23.9%	-33.6%	-30.3%	-30.3%	-30.3%	-21.8%	-21.8%	-21.8%	-21.6%	-21.6%	-22.8%
Total Emissions (Inside/Outside)	997	997	997	625	625	665	573	573	573	642	642	642	821	821	812
Difference	0	0	0	-37.3%	-37.3%	-33.3%	-42.6%	-42.6%	-42.6%	-35.6%	-35.6%	-35.6%	-17.6%	-17.6%	-18.6%
g CO_2eq./km (all scopes)	737	737	737	385	385	492	354	354	354	396	396	396	629	629	623
g CO_2eq./tonne-km (all scopes)	0.04	0.04	0.04	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03
g CO_2eq./cage-km (all scopes)	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01
g CO^2eq./case-km (all scopes)	0.0004	0.0004	0.0004	0.0002	0.0002	0.0003	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0004	0.0004	0.0004

Cryogenic CO_2 units and mechanical units using CO_2 as refrigerant gas use very different technologies; while the former are rather limited as they need large storage tanks and refilling stations, the second ones are mature technologies with the same level of safety and limitations as conventional TRUs but producing less GHG emissions. Lower GWP units, such as the ones described here that use CO_2, also present the advantage of future proofing the refrigeration system against changes in regulations regarding fluorinated gases. These new regulations will see some refrigerant gases phased out to meet international environmental agreements (European Commission, 2012a). As S4 is the strategy that limits the range of potential low carbon technologies the most, GHG savings are the lowest of all do-something strategies, at around 15% compared to S0 (Table 72). The NPC under the S4 scenarios yield NPC savings of between 8% (RG-RISL1) and 10% (RG-RISL3) as it can be calculated from Table 71; well below the savings achieved by strategies S1 and S3.

S1 regional scenarios always yield the lowest cost and S2 the lowest GHG emissions. S4 always produce the solution with the lowest risks and in contrast with urban HGVs, it is also the most expensive (instead of S2) when energy prices are 20% more expensive (RG-RISL3). Regional HGVs' GHG emissions can be reduced by around 15% under S4 and up to 52% with the most favourable strategy (S2). In this case, none of the scenarios produce scope 2 emissions (Table 72). The reason for this is that no electric power is used by any of the selected technologies and the electric power needed by the supplier to produce LAIR under scenario RG-UNLTD3, following carbon accounting practices, constitutes scope 3 emissions for the industrial sponsor.

Despite that scenario RG-UNLTD3 (the scenario where NPC is minimised regardless of GHG emissions and risks) shows a lower fuel consumption than scenarios RG-UNLTD1 and 2, its all scopes GHG emissions are reduced by 33%, while the other two scenarios can reduce GHG emissions by almost 50% compared to the baseline scenarios in S0. The reason for this is that producing LAIR is a very high energy intensive process, and despite that scope 1 emissions at the point of use are zero, scope 3 emissions include the production of the liquid air, plus the storage and delivery to the firm's premises. This is common to LIN, and cryogenic CO_2 TRU as well. The impact of using 3-phase auxiliary alternator unit was already explained in the previous section regarding urban delivery vehicles and it relates to the fuel consumption penalty applied to the tractor unit.

The opportunity to reduce GHG emissions for the industrial sponsor is lower than for other logistics firms, as their vehicles use B65 and as a result, most of the emissions of the HGVs are outside scopes. Compared to S0, S2 can reduce

424.3 t of CO_2 eq. over 5 years (including all scopes and outside scope emissions). The quantity of CO_2 produced by all strategies (excluding S0) is between 354 (S2) and 629 g CO_2 eq. /km under the S4 scenarios (Table 72). Normalising by tonne-km, GHG emissions are certainly low; in the range of 18.8 to 33.4 mg CO_2 eq. /tonne-km. This is slightly lower than the emissions of urban deliveries, despite that the average fuel consumption of regional HGVs is 19% higher as these vehicles carry higher tonnage[23]. Using cage-km as KPI, carbon emissions are between 5.4 and 8.9 mg CO_2 eq. / cage-km. Considering that the sponsor has a fleet of 78 vehicles, S2 could save 22,854 t CO_2 eq. (Scope 1 and 3) over 5 years while saving the company between £1.4 M under RG-GHG1 (scenario of low energy prices) to 4M under RG-GHG3 (scenario of high energy prices).

Based on S1 (scenario RG-UNLTD2), Figures 116 and 117 illustrate the sensitivity of different levels of risk over NPC. Assuming current energy prices, constraining the possible technologies to those that have a maturity level over 6 has a significant impact on NPC (Figure 116), overall when only technologies over level 8 are allowed (technologies that have entered the market more than one year ago), this can incur an additional cost of almost £30k over the life time of the vehicle. A slightly higher cost is incurred when the accepted technologies must present fewer limitations than the incumbent technologies (Figure 117). Both Figures illustrate the importance of risk aversion for the selection of low carbon technologies and their financial impact.

Based on S2 (scenario RG-GHG2), sensitivity analyses of the levels of risk that a company is willing to accept versus the impact of that decision on GHG emissions are illustrated in Figure 118 and 119. By allowing technologies that have just entered into the market (level 7), instead of those that are slightly more mature (level 8), 53.6 t of CO_2 eq. could be avoided (Figure 118); a reduction of 15.8%.

The impact of the risk of technology safety and limitations over GHG emissions is illustrated in Figure 119. The efficient frontier represents the minimum GHG emissions found by the heuristics model over each RISL level and it corresponds to a particular combination of technologies. All the scenarios under S2 represent the solution (combination of low carbon technologies) where RITM is 4 (Figure 118) or where RISL is 3 (Figure 119). Incumbent technologies have a level of 6. When the optimised solution can include technologies that are slightly more limited than the incumbent technologies (e.g. level 5 instead of 6), GHG

[23] Regional vehicles are assumed to deliver 14,200 cages and run from 151,469 km in year 1 to 154,521 in year 5.

emissions can decrease by more than 167 t over 5 years; a reduction of 34.5%. In contrast with urban deliveries, allowing riskier level 4 technologies could reduce GHG emissions by 13% while in urban duty, the same strategy reduced emissions by 20% compared to level 5.

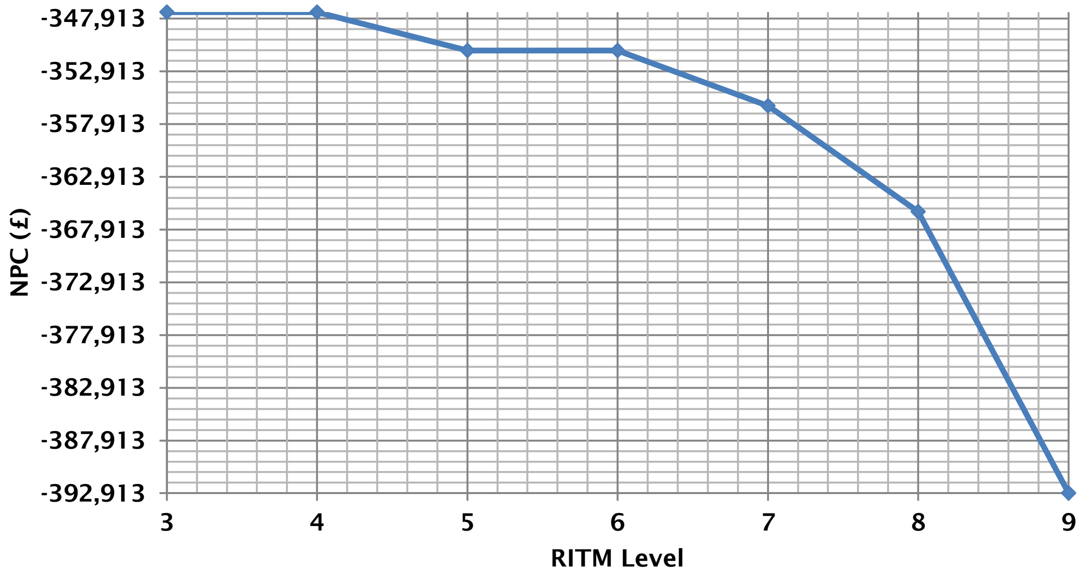


Figure 116. Efficient frontier of the impact of technology maturity risk acceptance (RITM) over NPC for a regional HGV.

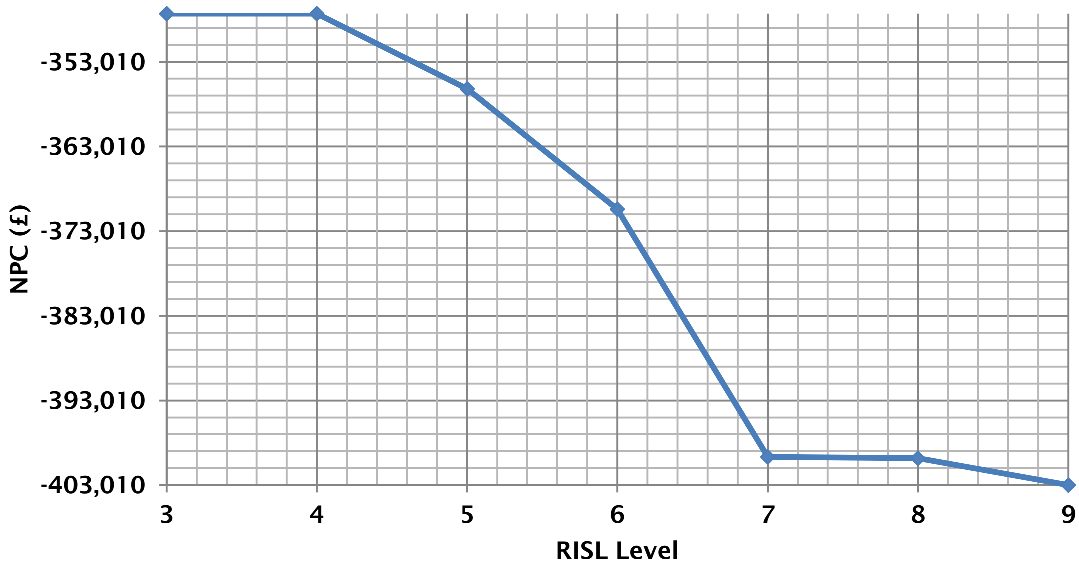


Figure 117. Efficient frontier of the impact of technology safety and limitation risk (RISL) aversion on NPC for a regional HGV (Strategy S4, scenario RG-RISL2).

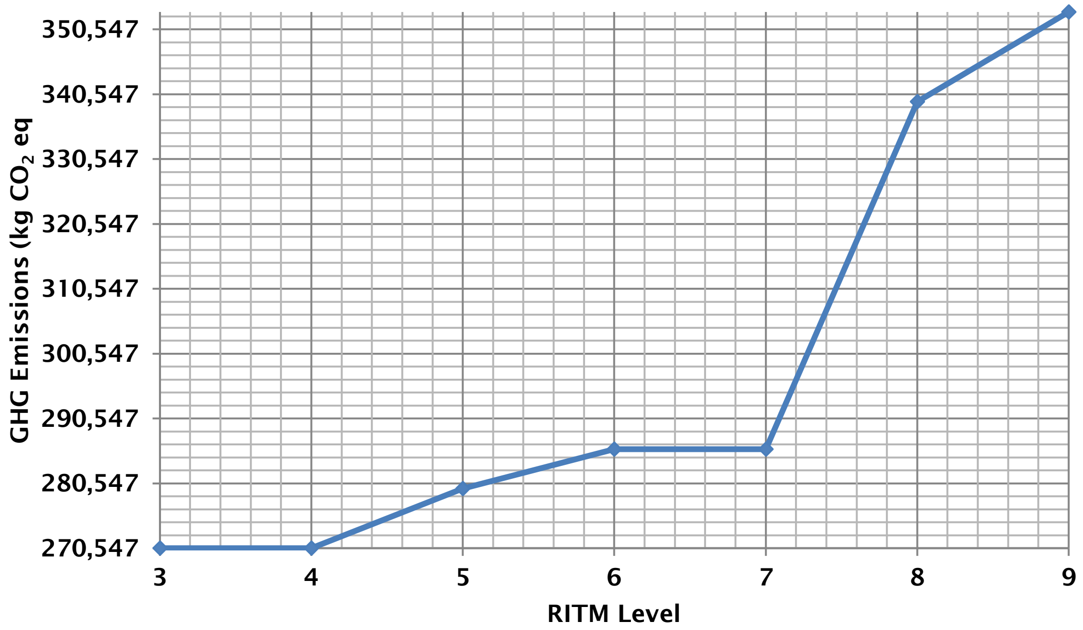


Figure 118. Efficient frontier of the impact of technology maturity risk acceptance (RITM) over GHG emissions for a regional HGV.

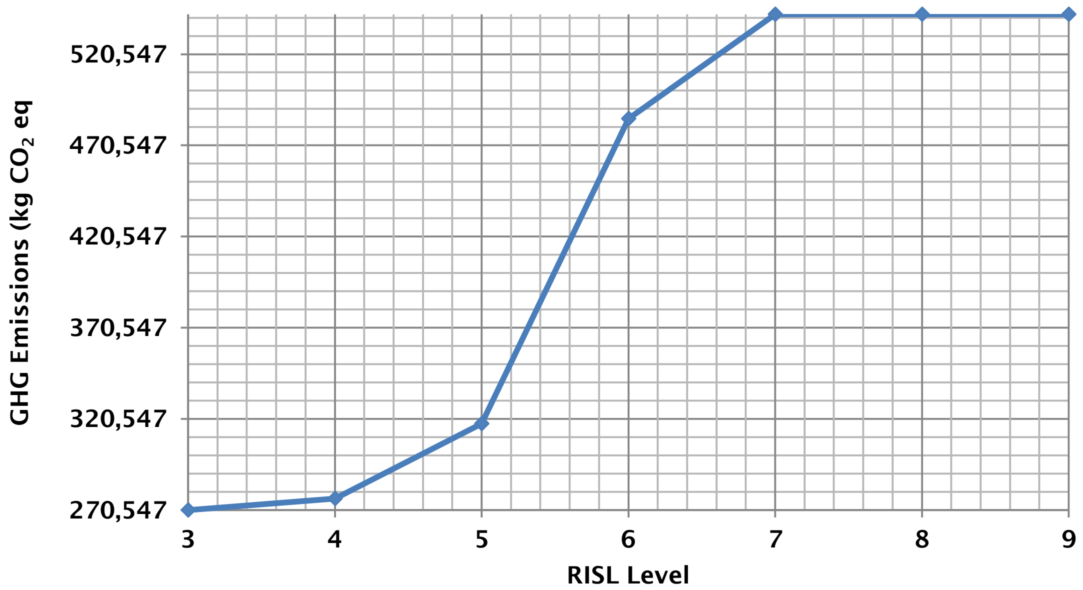


Figure 119. Efficient frontier of the impact of technology safety and limitations risk acceptance (RISL) over GHG emissions for a regional duty HGV.

A more exhaustive sensitivity analysis of the impact of energy costs over NPC has been illustrated in Figure 120. When fuel prices are 30% lower than current prices, the NPC of strategy S1 is £85,552 cheaper than when prices are 30% higher. In contrast with urban deliveries, the trend line in Figure 120 shows more clearly that the relation between the cost of fuel and NPC is not linear. Figure 120 illustrates that an increase on fuel prices of 60% (±30% from current prices) results in an increase on NPC of 28.29%; a slightly lower increment than urban duty cycle vehicles. The combination of low carbon technologies suggested by the model is quite sensitive to variances on energy prices; however, for regional vehicles the differences on vehicle specification are rather minimal for variations ±20%, as seen in Table 70 (Page 243). This can give decision makers the confidence that the vehicle procured will deliver the best possible outcome even if prices vary during the life of the investment by this percentage. Similarly to urban HGVs, the NPC of regional duty HGVs following S1 is more sensitive to mileage run in 2016 than any other year (Figure 121).

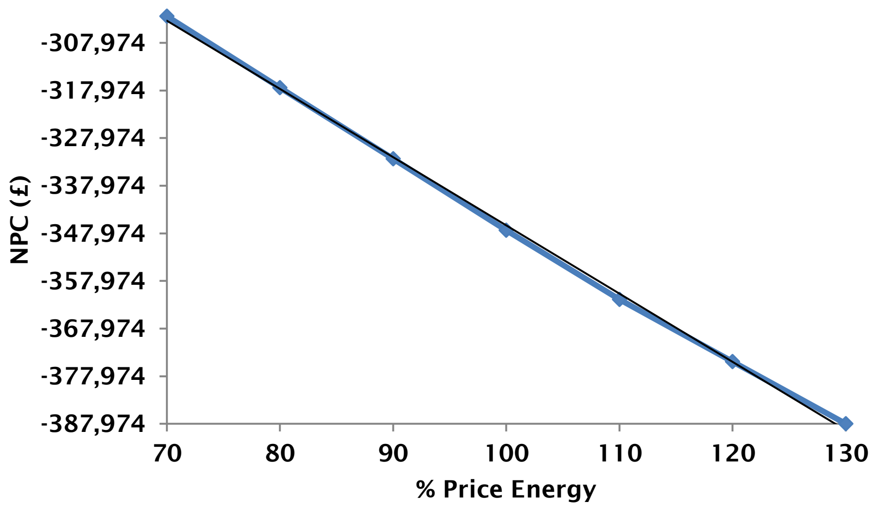


Figure 120. Relationship between NPC (strategy S1; scenario RG-UNLTD2) and cost of energy for a regional HGV (e.g. B65 price between £0.564/L to £1.04/L).

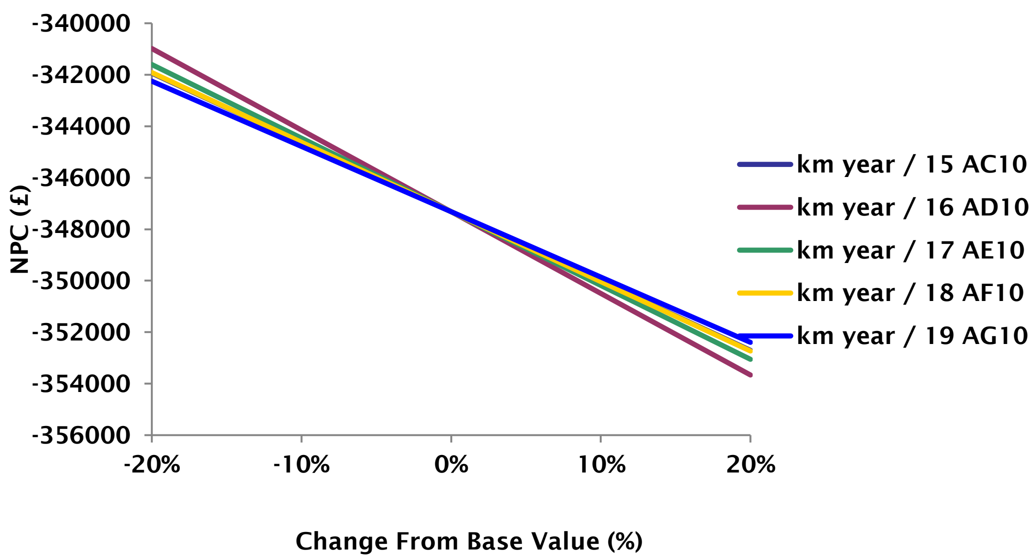


Figure 121. Relationship between NPC (strategy S1; scenario RG-UNLTD2) and mileage (in km) for a regional HGV (baseline mileage for year 2015 was 151,469).

5.4.3 SELECTION OF LOW CARBON TECHNOLOGIES FOR LONG-HAUL SEMI-ARTICULATED TRAILERS

Long-haul HGVs' scenarios (Table 73 - 75) represent a DAF XF105 32t 4x2 semi-articulated vehicle running on biodiesel (B65) with a semi-trailer (13.4 m) that uses a 9.6 kW refrigeration unit. It is assumed that the vehicle runs around 172,119 km/year and it transports 3,763 tonnes/year (excluding the reverse logistics of waste). The typical average fuel consumption of these vehicles is around 32.91 L/100km. TRUs consume 2.87 L/hr. and work for 3,550 hrs. /year. The scenarios evaluated are the same as appear in Table 67 (page 231); however, instead of urban they represent long-haul duty vehicles.

All scenarios consider that aerodynamic trailers, spray suppression mudflaps, any of the lower rolling resistance tyre technologies, automatic tyre pressure monitoring systems, light weighting materials and controllable air compressors represent good choices to contribute to achieving the goals sought. On the other hand, irregular body shape trailers (teardrop shaped boxes) and aerodynamic fairings (side skirts) are never selected because either individually or combined, they yield lower fuel savings at a higher cost than aerodynamic trailers. Stop-start engines and hydraulic hybrid powertrains are not recommended in any of the strategies either as the first technology saves just 1% of fuel and the latter nothing at all. Looking at the refrigeration system, hybrid units, cryogenic LIN or CO_2, and lower GWP refrigeration units using CO_2 as a refrigerant gas, they do not represent good choices.

Based on current fuel prices, strategy S1 (LH-UNLTD2) shows that costs can be reduced by 13% and GHG by 45.5% (Table 74) by using the combination of energy efficient technologies that appear in Table 73. Considering that the industrial sponsor has a fleet of 6 DAF XF105 dedicated almost exclusively to long haul deliveries, the results indicate that the company could benefit from cost savings of £347,790 while reducing GHG emissions by 1,632 t over the next 5 years, when comparing this scenario to the baseline one (LH-BASE2). Under S1, controllable air compressors, flywheels and pneumatic boosters are also selected as they contribute to cost minimisation. While the use of aerodynamic improvements is consistent with what is expected from higher speed duty cycles, selecting flywheels for a duty cycle where there are not many stops start operations is unexpected. As this technology can reduce fuel consumption by 5%, it can save £2,213/year; meaning that it has a 37

Table 73. Optimisation of low carbon technologies selection for different scenarios for a long-haul duty HGV.

Financial Parameters	Vehicle Parameters		Operating Parameters - Long Haul	
Rate of Return 9.7%	GVW 32 tonnes	Conventional Diesel TRU	Tonnes delivered (5 years): 18815	Price B65 (2015) 80.51 p/L
Interest Rate Leasing 3%	Tractor 4x2 Semi-artic	Initial Fuel: Red Diesel	Total Km (5y): 860,593	Price Red Diesel (2015) 57.95 p/L
Life Investment 5 Years	Trailer 2 axles	Initial Refrigerant Gas: R-404A	Refrigeration hrs./year):3550	Price Electricity (2015) 13.02 p/kW
GDP Central Growth	Tractor Fuel (65 % biodiesel)	Semi-Trailer: 13.4/78.79 m3		

Results			Long Haul														
			Baseline (S0)			Optimisation with Unlimited Risk (S1)			Minimisation GHG Emissions (S2)			Risk Maturity >= 6 (S3)			Risk Safety & Limitations > 6 (S4)		
			-20%	Fuel Price Medium	20%	-20%	Fuel Price Medium	+20%	-20%	Fuel Price Medium	+20%	-20%	Fuel Price Medium	+20%	-20%	Fuel Price Medium	+20%
			LH-BASE1	LH-BASE2	LH-BASE3	LH-UNLTD1	LH-UNLTD2	LH-UNLTD3	LH-GHG1	LH-GHG2	LH-GHG3	LH-RITM1	LH-RITM2	LH-RITM3	LH-RISL1	LH-RISL2	LH-RISL3
Vehicle Technologies	Reduced Aerodynamic Resistance	Aerodynamic Trailers	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
		Aerodynamic Irregular body shape	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Aerodynamic Fairings	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Spray Reduction Mud Flaps	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
	Reduced Rolling Resistance	Low rolling resistance tyres	0	0	0	1	1	1	0	0	0	1	1	1	1	1	1
		New generation wide-base single tyres	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
		Automatic tyre pressure monitoring	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
	Vehicle Mass	Lightweighting Materials	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
	Intelligent VT	Predictive Cruise Control	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
	Auxiliary Systems	Controllable air compressor	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0
Powertrain Technologies	Exhaust Heat Recovery	Heat Recovery (in general)	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
		Electrical Drive Turbo compound	0	0	0	0	0	0	1	1	1	0	0	1	0	0	0
	Transmissions	Automated Manual Transmission	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
	Mild Hybrid	Flywheels Hybrid	0	0	0	1	1	1	0	0	0	1	1	0	0	0	0
		Stop-Start: Electric Hybrid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Pneumatic Booster - Air Hybrid	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0
	Alternative PT	Full Hybrid: Series / Parallel Electric	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
		Series / Parallel hydraulic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total FCR (Vehicle & Powertrain)		0.0%	0.0%	0.0%	31.1%	31.1%	31.1%	38.8%	38.8%	38.8%	29.8%	29.8%	28.3%	24.9%	24.9%	24.9%
TRU	Refrigeration Technologies	3 Phase Aux. Alternator Unit (R410A)	0	0	0	1	1	0	1	1	1	1	1	1	0	0	0
		Hybrid Refrigeration Unit	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Cryogenic Nitrogen (LIN)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Cryogenic CO_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Cryogenic Air (LAIR)	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
		Lower GWP Gas Unit (R744)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Vacuum Isolated Panels	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
	Total FCR (TRU)		0%	0%	0%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%	0%	0%
	Combined FCR % (Vehicle, Powertrain & Refrigeration)		0.0%	0.0%	0.0%	-34.0%	-34.0%	-41.6%	-40.9%	-40.9%	-40.9%	-32.9%	-32.9%	-31.6%	-21.1%	-21.1%	-21.1%
	New Average Fuel Consumption (L/ 100km)		32.91	32.91	32.91	25.64	25.64	22.68	22.96	22.96	22.96	26.07	26.07	26.56	24.70	24.70	24.70
	New TRU Fuel Consumption (L/hrs.)		2.87	2.87	2.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.87	2.87	2.87
	Improvement in Costs		0.0%	0.00%	0.00%	11.0%	13.1%	15.3%	5.1%	8.6%	11.4%	10.6%	12.6%	13.5%	9.3%	10.7%	11.8%

Table 74. Outcome of the meta-heuristics optimisation of the vehicle specification based on different strategies for a long-haul duty cycle HGV.

Output for Multicriteria Decision Analysis	STRATEGY 0			STRATEGY 1			STRATEGY 2			STRATEGY 3			STRATEGY 4		
	-20%	Fuel Price Medium	20%	-20%	Fuel Price Medium	20%	-20%	Fuel Price Medium	20%	-20%	Fuel Price Medium	20%	-20%	Fuel Price Medium	20%
	LH-BASE1	LH-BASE2	LH-BASE3	LH-UNLTD1	LH-UNLTD2	LH-UNLTD3	LH-GHG1	LH-GHG2	LH-GHG3	LH-RITM1	LH-RITM2	LH-RITM3	LH-RISL1	LH-RISL2	LH-RISL3
Net Present Cost	394,274	441,658	489,041	350,710	383,693	414,353	374,099	403,641	433,183	352,396	385,943	422,971	357,448	394,271	431,094
GHG Emissions (t CO_2 eq.)	596	596	596	324	324	406	291	291	291	330	330	336	493	493	493
Risk Technology Maturity	10	10	10	4	4	4	4	4	4	6	6	7	7	7	7
Risk Safety & Limitations	6	6	6	4	4	4	3	3	3	4	4	4	6	6	6

Table 75. GHG Emissions (ton CO_2 eq.) and KPIs for long-haul duty scenarios.

GHG Emissions (t CO_2 eq.)	Long Haul														
	Baseline (S0)			0ptimisation with Unlimited Risk (S1)			Minimisation GHG Emissions (S2)			Risk Maturity >= 6 (S3)			Risk Safety & Limitations > 6 (S4)		
	-20%	Fuel Price Medium	20%	-20%	Fuel Price Medium	20%	-20%	Fuel Price Medium	20%	-20%	Fuel Price Medium	20%	-20%	Fuel Price Medium	20%
	LH-BASE1	LH-BASE2	LH-BASE3	LH-UNLTD1	LH-UNLTD2	LH-UNLTD3	LH-GHG1	LH-GHG2	LH-GHG3	LH-RITM1	LH-RITM2	LH-RITM3	LH-RISL1	LH-RISL2	LH-RISL3
Scope 1	417.3	417.3	417.3	208.0	208.0	179.0	186.8	186.8	186.8	211.4	211.4	215.3	352.5	352.5	352.5
Difference	0	0	0	-50.2%	-50.2%	-57.1%	-55.2%	-55.2%	-55.2%	-49.3%	-49.3%	-48.4%	-15.5%	-15.5%	-15.5%
Scope 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Scope 3	178.2	178.2	178.2	116.4	116.4	227.3	104.3	104.3	104.3	118.4	118.4	120.6	140.9	140.9	140.9
Difference	0	0	0	-34.7%	-34.7%	27.5%	-41.5%	-41.5%	-41.5%	-33.6%	-33.6%	-32.3%	-20.9%	-20.9%	-20.9%
All Scopes (baseline)	595.6	595.6	595.6	324.4	324.4	406.3	291.1	291.1	291.1	329.8	329.8	335.9	493.5	493.5	493.5
Difference	0	0	0	-45.5%	-45.5%	-31.8%	-51.1%	-51.1%	-51.1%	-44.6%	-44.6%	-43.6%	-17.1%	-17.1%	-17.1%
Outside Scopes (baseline)	470.2	470.2	470.2	363.8	363.8	321.8	325.8	325.8	325.8	370.0	370.0	376.9	353.7	353.7	353.7
Difference	0	0	0	-22.6%	-22.6%	-31.6%	-30.7%	-30.7%	-30.7%	-21.3%	-21.3%	-19.8%	-24.8%	-24.8%	-24.8%
Total Emissions (Inside/Outside)	1,066	1,066	1,066	688	688	728	617	617	617	700	700	713	847	847	847
Difference	0	0	0	-35.4%	-35.4%	-31.7%	-42.1%	-42.1%	-42.1%	-34.3%	-34.3%	-33.1%	-20.5%	-20.5%	-20.5%
g CO_2eq./km (all scopes)	692	692	692	377	377	472	338	338	338	383	383	390	573	573	573
g CO_2eq./tonne-km (all scopes)	0.04	0.04	0.04	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03
g CO_2eq./cage-km (all scopes)	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01
g CO_2eq./case-km (all scopes)	0.0004	0.0004	0.0004	0.0002	0.0002	0.0003	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003

months payback period when working on its own. When this technology is evaluated in conjunction with the others, as the fuel consumption of the vehicle is much lower, the 5% of fuel saved represents savings of just £1,525/year, rising the payback period to 54 months, just 6 months under the life span of the vehicle (5 years). Using flywheels reduces net present costs during the 5 year period of the vehicle life by over £2,000 and it makes this technology a financially sound choice. This highlights again the weaknesses of the payback period as an investment technique, as that technique would exclude this technology. Auxiliary alternator refrigeration units are an excellent choice when the prices of B65 and red diesel are 80-100% of current prices. When prices increase by 20% to 96.61pence/L, the model indicates that cryogenic air (LAIR) represent better value for money under S1.

Scenarios LH-UNLTD1 and LH-UNLTD2 can save 34% fuel (including B65 and red diesel), while scenario LH-UNLTD3 can save 41.6% (Table 73). When fuel prices are 20% lower and 20% higher than the baseline (S0), strategy S1 can deliver NPC savings between £261k and 448k while reducing GHG emissions by 1.1Kt to 1.6Kt over the next 5 years, respectively (compared to LH-BASE1 and LH-BASE3). Fuel savings do not translate to similar reductions on carbon emissions and as it is shown in Table 75, where LH-UNLTD3 yields lower GHG savings than the other two scenarios (when all scopes are considered). Fuel savings of 41.6% (under LH-UNLTD3) and 34% (under LH-UNLTD1 and 2), translate to GHG savings of 31.8% and 45.5%, respectively. The reason for this is that when LAIR is chosen, producing liquid air is a very energy intensive process.

In Appendix 16, a sensitivity analysis of the chosen technologies and their impact on NPC is included. The analysis shown for illustrative purposes represents the optimal combination of technologies under scenario LH-UNLTD2 and the yellow cells represent a technology that was chosen but that it is excluded to asses how sensitive is the optimal solution. This illustrates how the model behaves when it is forced to exclude a particular technology that otherwise would be ideal. In Appendix 16, we can see that not allowing aerodynamic trailers results in the selection of aerodynamic fairings and an increase of NPC of £8.402. A similar situation occurs when LRR tyres are excluded; resulting in the selection of SWBT and an increase on NPC of £736. If the auxiliary alternator unit is excluded, this allows LAIR to be chosen, resulting in an increase on NPC of almost £1,500. In this particular situation, GHG emissions get reduced by almost 32%; however, with the imposition of all the other individual constraints GHG remain between 42.3% and 45.5%. The results of the constrained LH-UNLTD2 scenario are not very sensitive in regards to NPC, finding that all the solutions save between

11.6-13.1%. The biggest expenses would arise from excluding aerodynamic trailers (£8,402) despite the fact that the model would chose aerodynamic fairings instead and from excluding predictive cruise control, as this would increase the cost of the solution by £6,715 over the life of the vehicle.

Strategy S2 represents the combination of technologies that minimise GHG emissions (regardless of other objectives). S2 scenarios yields GHG savings of 51.1% (Table 75), and cost savings between 5% (LH-GHG1) and 11% (LH-GHG3) compared to S0 (Table 73). Under this strategy, aerodynamic trailers are selected instead of irregular bodies and fairings, as the first has a higher FCR than the other two combined. SWBT are chosen over LRR resistance tyres. The parallel hybrid powertrain is favoured over a hydraulic one and stop-start systems are excluded as they are considered not compatible with 3 phase alternator units, and the latter have a much higher impact on carbon emissions. It is interesting to notice that vacuum insulated panels are selected despite that the fuel savings of the refrigeration system under S2 is already 100%. The reason for this is that when auxiliary alternator units are selected the energy improvement applies to the fuel penalty that this technology imposes on the tractor unit. It is interesting to observe that the combination of both technologies has the highest potential for reducing GHG emissions from refrigeration.

Strategy S3 constraints the type of technologies that can be included in the solution by allowing only those technologies that have at least have been trialled by other fleets (risk of technology maturity 6 or above). Scenarios LH-RITM1 and 2 are very similar to scenarios LH-UNLTD1 and 2 with the only exception that pneumatic boosters are not chosen under S3. The reason for this is that pneumatic boosters were trialled by 2010; however, personal communication with the supplier in September 2015 (Knorr-Bremse AG, 2015) revealed that this technology had been discontinued due to a lack of interest from the market and as a result, it was given a level 4 of risk maturity (first prototype) and is not included among the feasible technologies under strategy S3. In addition to pneumatic boosters, the scenario that represents higher energy prices (LH-RITM3) also excludes flywheels as these are still considered as immature in the realm of HGVs. On the other hand, this scenario recommends the use of electrical drive turbo compound for long-haul vehicles. Other technologies are not chosen under S3 including heat recovery and hydraulic hybrids systems, as both have a level of risk of technology maturity of 5.

Regarding refrigeration technologies, all three S3 scenarios (LH-RITM1, 2 and 3) indicate that 3 phase alternator refrigeration units are the preferred technology. LAIR could not be chosen this time as this is a technology that is still being developed by the supplier (Dearman, 2015). The same occurs with the vacuum insulated panels. According to personal communications with Kevothermal (2015), despite that this technology could be fitted in refrigerated trailers, the main focus nowadays is towards insulation in the construction industry. For this reason it is considered as an inmature technology at the moment. As shown in Table 73, S3 scenarios yield NPC savings between 10.6% (LH-RITM1) and 13.5% (LH-RITM3) while avoiding the emission of 260-266 t CO_2 eq. over the life span of the vehicle, compared to S0. Extrapolating this results to the fleet of 6 HGVs under this duty cycle, the industrial sponsor could save 1.6 kt CO_2 eq. and between a £250k when energy prices are 20% lower than currently to almost £400k if prices increase by 20%.

Strategy S4 constraints the technologies that can be selected by disregarding the ones that present safety concerns or higher limitations than the incumbent technologies. This excludes half of the potential tractor technologies, allowing just aerodynamic improvements, spray suppression mudflaps, low rolling resistance tyres, automatic tyre inflation monitoring systems, lightweight materials, predictive cruise control and automatic manual transmissions. SWBT are not allowed as they are typically not stocked by tyre workshops and replacing the tyres would not be possible on remote routes; also according to Reading (2015) fitting this tyres would require a wing expansion to spat on the body of the tractor to cover the part of the tyre that otherwise would stick out, for the vehicle to pass the MOT. Other technologies that are not selected due to their limitations include flywheels (as they cannot sustain power for long); pneumatic boosters (as they can reduce vehicle volumetric payload for the compressed air tank); mild hybrids (stop-start, electric and hydraulic powertrains) in the sense that they restrict the possibility of using auxiliary alternator units (as they draw their power from the engine). Under S4, auxiliary alternator units are also excluded as it has been considered that these could not work standing alone as conventional diesel units do and limit the type of operations that can be undertaken with such trailers (e.g. cross-docking). The outcome of this is that S4 includes all the technologies that appear in S1 with a risk level of 6 or higher (technologies with the same of fewer limitations and safety concerns than incumbent technologies). As a result, the potential for reducing fuel consumption under S4 is considerably inferior than S1. The solution found under scenario LH-RISL2 is £10,578 more expensive than under LH-UNLTD2 but £47,387 cheaper than LH-BASE2. Compared to S0, the fleet of 6 XF105 vehicles can save £284,322 and 618 t CO_2 eq. over 5 years.

There is clearly a trade-off between NPC and risk. An analysis of the efficient frontier of the risk seeking attitude of the purchasing organisation towards the risk of technology maturity, illustrates that the NPC increases when the level of risk aversion is higher. Based on S1, Figure 122 shows clearly that allowing technologies that have just entered INTO the market can reduce NPCs by around £43k over 5 years compared to just using predominant technologies (levels 9-10). Riskier technologies than level 7 (e.g. levels 1-6) yield marginally lower NPC solutions (very similar NPC). From this, it can be concluded that to obtain significant gains, companies must choose innovative technologies. Focusing on the level of safety and limitations risk, Figure 123 illustrates that higher levels of risk lead to lowest costs. Selecting technologies that do not present new safety issues and fewer limitations that the incumbent technologies (level 7 or over) is £26k more expensive than allowing riskier level 6 technologies (technologies with no additional safety concerns or limitations). This also shows that risk aversion results in higher costs.

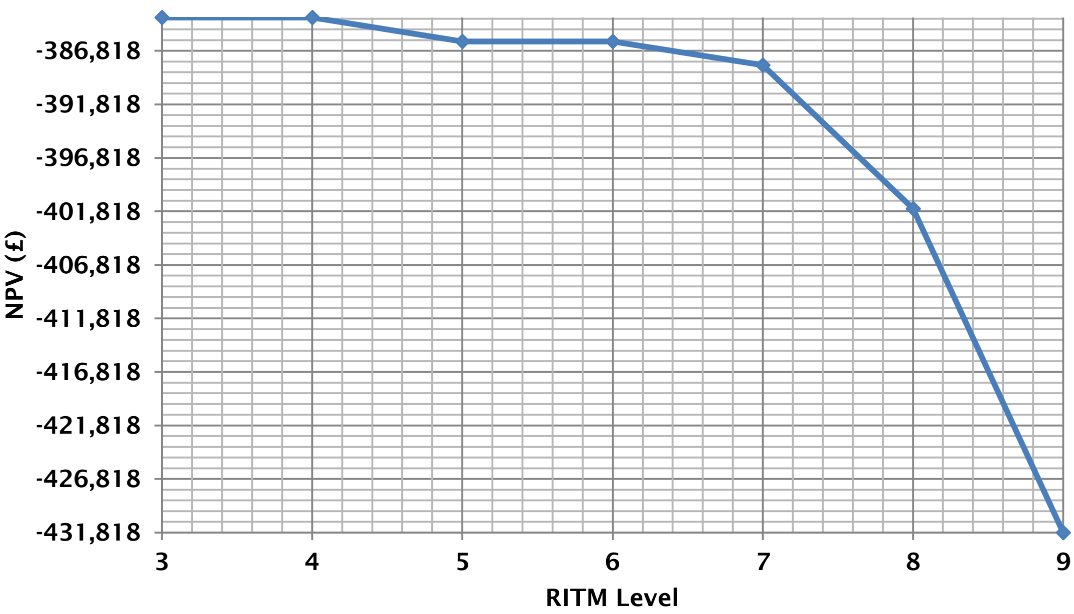


Figure 122. Efficient frontier of the impact of technology maturity risk acceptance (RITM) over NPC for a long-haul HGV

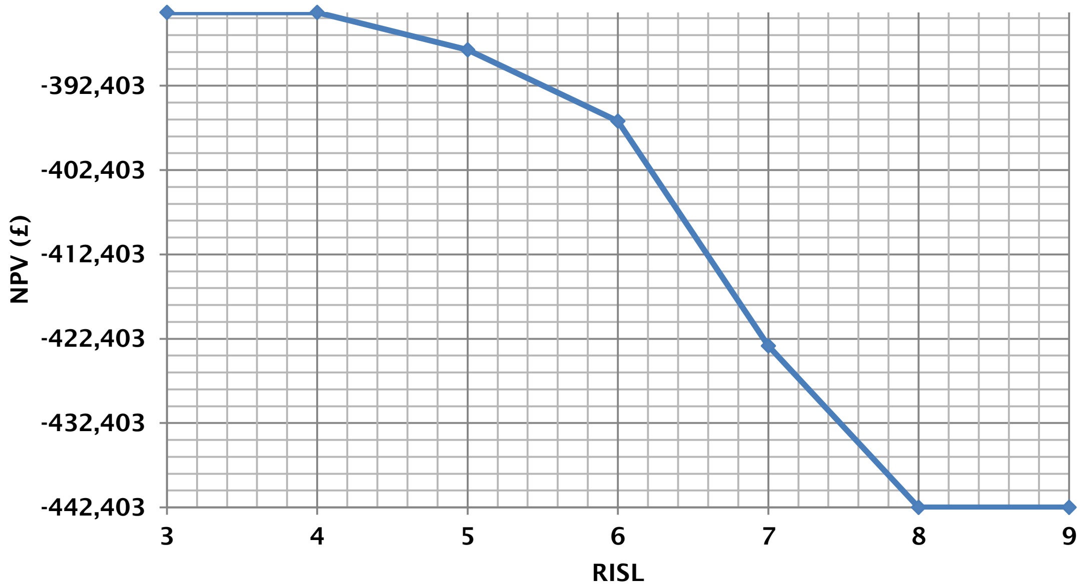


Figure 123. Efficient frontier of the impact of technology safety and limitation risk acceptance (RISL) over NPC for a long-haul HGV.

Based on S2, Figures 124-125 illustrate the impact of risk aversion on GHG emissions. When the risk of technology maturity allows changes from level 8 to level 7 (technologies that have just entered into the market), this results in a decrease in carbon emissions of 72 t CO_2 eq. (Figure 124). As with urban and regional duty cycles, constraining the risk level of technology maturity has a negative impact on GHG emissions. When considering the risk of technology safety and its limitations, the biggest impact on GHG emissions occurs when only technologies that do not represent any additional limitation are allowed (level 6). In this case, GHG emissions can improve by 179 t CO_2 eq. by allowing as well technologies that are somehow slightly more limited (level 5) than the incumbent ones (level 6).

Following strategy S1, an efficient frontier analysis of the impact of energy prices on NPC is presented in Figure 126. A variation of fuel prices of ±30%, shows that NPC increase by 28.23%. In contrast, NPC of urban vehicles would vary by 28.73%. In this Figure it is visually more evident than with the other duty operations (Figure 114, page 239 and Figure 120, page 249) that the relation between NPC and the price of energy is not linear.

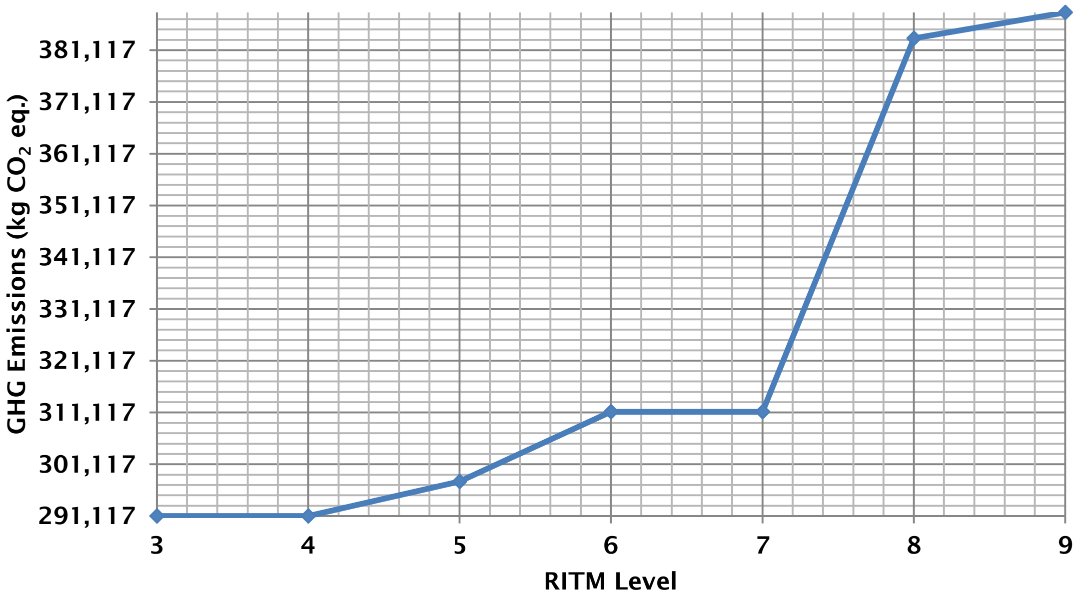


Figure 124. Efficient frontier of the impact of technology maturity risk acceptance (RITM) over GHG emissions for a long-haul HGV.

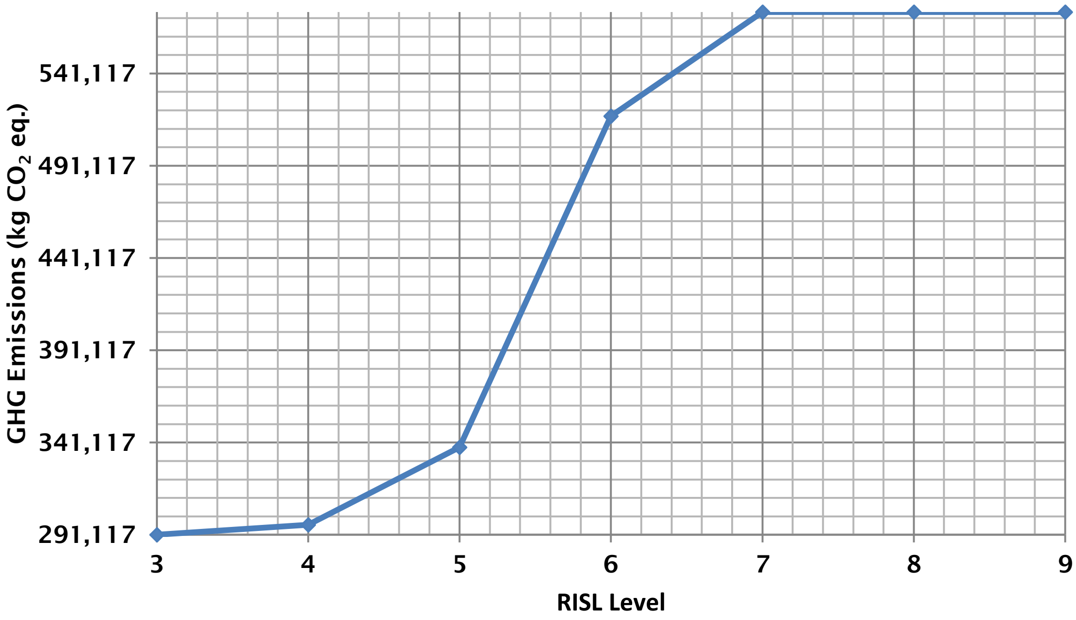


Figure 125. Efficient frontier of the impact of impact of technology safety and limitations acceptance (RISL) over GHG emissions for a long-haul HGV.

Running a hypothetical scenario where energy prices double current ones, it has been observed that the solution of S1 scenarios is the same as the S2 ones. This means that the higher the prices of fuel, the more likely that all the technologies that can contribute to reduce fuel consumption will be chosen, as they become cost effective.

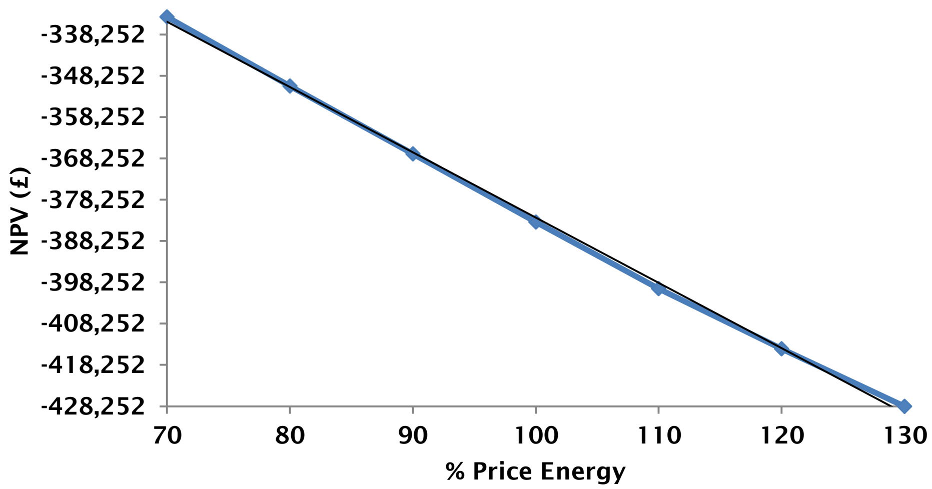


Figure 126. Relationship between NPC (strategy S1; scenario LH-UNLTD2) and energy prices for an long-haul HGV (e.g. B65 price between £0.564/L to £1.04/L).

For the same reasons as explained with the duty cycles, the NPC of long-haul HGVs following S1 is more sensitive to the mileage run in 2016 than any other year. Details of the calculations of the sensitivity analysis for this scenario are included in Appendix 17. Figure 127 shows that by choosing the combination of technologies suggested by the model for the strategy S1, scenario LH-UNLTD2, the NPC may vary from £377.7k if the mileage would be 20% lower than expected to £390.7, if mileage was increased by 20%.

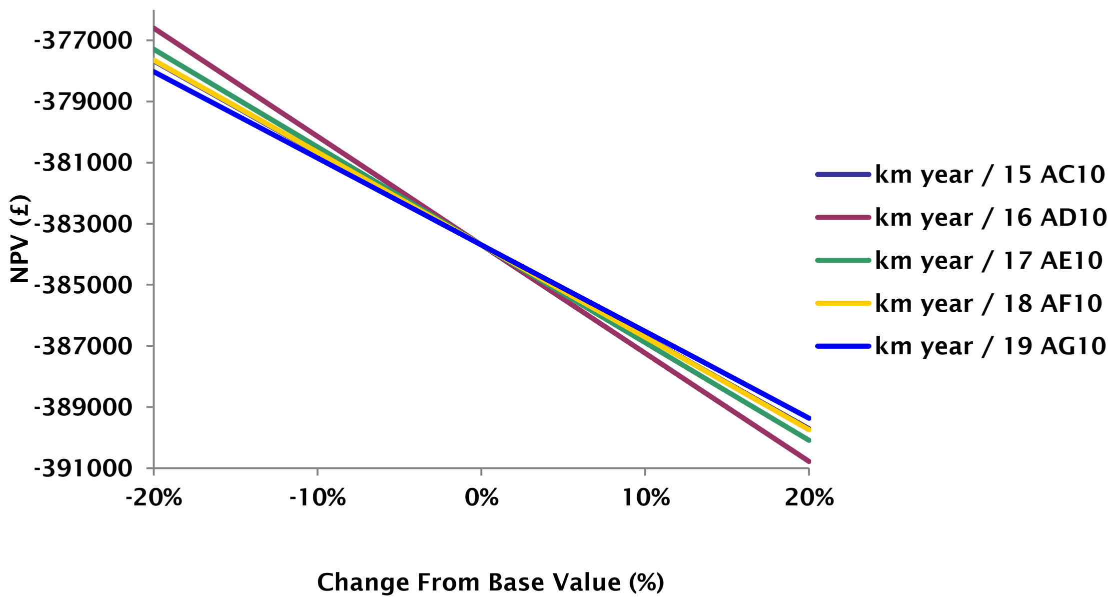


Figure 127. Relationship between NPC (strategy S1; scenario LH-UNLTD2) and mileage (in km) for a long-haul HGV (baseline mileage for year 2015 was 170,405).

5.4.4 SENSITIVITY OF NPC OVER THE MINIMAL ACCEPTABLE RATE OF RETURN AND CARBON PRICES

Two further analyses have been conducted to evaluate the robustness of the solutions (optimal combinations of technologies) towards different minimum acceptable rates of return (MARR) and the prices of carbon. The MARR expected by the industrial sponsor was 9.6%. All the strategies and scenarios use this value. Using the metaheuristics model, Table 76 shows how the NPC changes for some scenarios when the MARR decreases to 5%. It has been found that for an MARR from 0% to 100%, the combinations of technologies suggested by the model for the S1 (cost minimisation) and S4 (cost minimisation eliminating technologies with a risk of safety and limitation level under 6) strategies always remain the same for the scenarios[24] that assume current energy prices. This means that a company using the metaheuristics framework can have the confidence that when they order a new vehicle fitted with the combination of technologies suggested by the model, this will be the optimal vehicle specification even if the MARR expected by its organisation changes considerably. These changes on MARR could happen as a reaction to changes on public monetary policy such as changes in the interest rates determined by the Bank of England, the European Central Bank or similar institution of the country where the model takes its inputs from.

Table 76. Sensitivity of NPC over different MARR for urban, regional and long-haul HGVs.

SCENARIOS	STRATEGY	NPC MARR 9.6%	NPC MARR 5%	% Change
UB-BASE2	S0	250,895	285,320	13.72%
UB-UNLTD2	S1	226,318	257,232	13.66%
UB-RISL2	S4	243,408	276,758	13.70%
RG-BASE2	S0	404,885	460,446	13.72%
RG-UNLTD2	S1	347,313	394,771	13.66%
RG-RISL2	S4	366,726	416,918	13.68%
LH-BASE2	S0	441,658	502,255	13.72%
LH-UNLTD2	S1	383,693	436,126	13.67%
LH-RISL2	S4	394,271	448,200	13.67%

A sensitivity analysis of the impact of carbon prices over NPC for some scenarios was conducted (Table 77). In this Table, only the scenarios of strategy S1 are considered (with current energy prices); as the objective functions of strategy S2 (GHG minimisation) is insensitive towards costs, and S3 and S4 are the

[24] **Scenarios are defined in**Table 66**, page 231.**

same as S1 but with harder constraints in regards to the technologies that can be accepted in the final vehicle specification. So far, only energy producers and large consumers are obliged to pay for their carbon emissions withing the EU ETS scheme; however, future policy changes may enforce carbon quotas and carbon emission prices to other sectors of the economy.

Table 77. Sensitivity of NPC over carbon prices (from £0 to £200/t CO2 eq.) for urban, regional and long-haul HGVs.

SCENARIOS	£0/t CO_2	£27/t CO_2	£50/t CO_2	£100/t CO_2	£200/t CO_2	% Change over NPC (£0-£200)
UB-BASE2 (S0)	250,895	257,423	262,983	275,070	299,245	19.27
UB-UNLTD2 (S1)	226,318	230,174	233,458	240,598	254,877	12.62
RG-BASE2 (S0)	404,885	416,485	426,366	447,487	490,809	21.22
RG-UNLTD2 (S1)	347,313	353,378	358,545	369,777	392,242	12.93
LH-BASE2 (S0)	441,658	453,916	464,358	487,059	532,460	20.56
LH-UNLTD2 (S1)	383,693	390,336	396,050	408,407	432,498	12.72

By assigning a price to the production of GHG emissions, three main conclusions have been reached. The first one is that the higher the price of carbon, the larger the NPC savings between the baseline scenario and the optimised one. For example, with the price of carbon emissions at £0/t, the differences between the baseline S0 and S1 scenarios from Table 77 reveals that urban, regional and long-haul HGVs can reduce NPCs by 9.8%, 14.22% and 13.12% respectively. However, when the prices of carbon is £200/t, these differences are even higher at 14.8%, 20% and 18.8% respectively. The second conclusion is that using low carbon technologies mitigates the impact of carbon taxation. Under each duty cycle, the baseline scenarios (no low carbon technologies are used), result in an increase of NPC of 19-21%. In contrast, under the UNLTD scenarios, NPC increases are muc more moderate (under 13%). Both points demonstrate that low carbon technologies have a positive impact on reducing carbon emissions' costs. The third conclusion is that higher prices of carbon do not seem to benefit the uptake of low carbon technologies. Low carbon technologies are chosen primarily for their impact of fuel consumption and their reductions on fuel costs. As illustrated in Figure 128, the impact of carbon prices on NPC is rather moderate. Even when carbon prices reach £200/t, the combinations of technologies proposed by the heuristics model always remain the same for all scenarios except for LH-UNLTD2 (highlighted in yellow in Table 77). When the price of carbon is £144/ton, exhaust heat recovery is added to the vehicle specification and when the price is £196/t, electrical drive turbo compound also becomes part of the final solution. No other technologies change in the scenarios from Table 77. Bearing in mind that currently the spot carbon emissions price of the EU ETS is around £6.77/t, the fact that the model can deal with fluctuating carbon prices and that these are unlikely to change drastically during the life span of the vehicle, the results suggest that the solution given by the model is very robust as it is unlikely to change the combination of technologies proposed, due to the implementation or changes on carbon prices. Assuming that a tonne of CO_2 eq. is produced when burning 387.6 L of diesel (1000 L/2.58 kg CO2 eq/L). The price per tonne of CO_2 must be higher than the cost of fuel . For example, if the cost of diesel is £1/L, for the carbon taxation being more important than the fuel savings, the price per tonne must be equal to £387.6.

The reason for this insensitivity is that the difference between the most (do-nothing scenario) and less carbon emitting scenario (S2) is 130 t, 293t and 305t of CO_2 eq. for urban, regional and long-haul deliveries respectively, and this limits the cost that carbon tax represent per vehicle. At current carbon prices, the potential savings that could be achieved by using all the LCTs represent just £880, £1,983 and £2,064 for each duty cycle respectively. There is therefore little scope to recover the cost of investment on low carbon technologies based purely on carbon emissions savings.

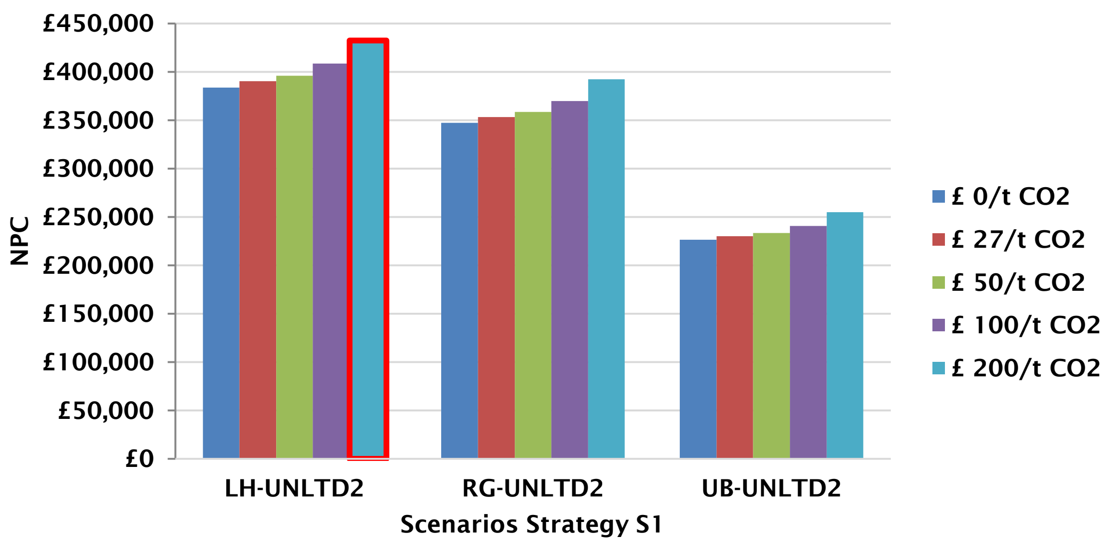


Figure 128. NPC of the UNLTD2 scenarios for urban, regional and long-haul deliveries with carbon prices from £0 to £200/tonne CO_2 eq.

The UK Government considers that a carbon price of £27/t by 2020 and higher thereafter would incentivise investment in low carbon technologies. This means that the maximum savings achievable from avoiding GHG emissions at that price would be £3,510, £7,911 and £8,235 for urban, regional and long-haul HGVs.

As the technologies chosen when the price of carbon is zero already minimise fuel consumption and NPC, the prices of carbon making a real difference is very nlikely. The only change on vehicle specification occurs under scenario LH-UNLTD2 and when the price of carbon reaches £144/t. Assuming that a tonne of CO_2 eq. is produced when burning 387.6 L of diesel (1000 L/2.58 kg CO2 eq/L). The price per tonne of CO_2 must be higher than the cost of fuel saved . For example, if the cost of diesel is £1/L, for the carbon taxation being more important than the carbon cost, the price per tonne must be equal to £387.6.

The results here presented indicate that carbon prices should reach a much higher value than what the UK Government estimates as desirable. The uptake of low carbon technologies for HGVs will come from the fuel savings that they deliver. Buyers can have the confidence that the solution provided by the model is insensitive in regards to MARR and carbon prices (unless these reach levels that affect negatively the national economy). This is not the case in regards to the costs of fuels and mileage.

5.5 MULTICRITERIA DECISION ANALYSIS FOR TECHNOLOGY SELECTION

This section explains the process involved for the generation of a ranking of preferred vehicle configurations based on the stated preferences of the industrial sponsor and the outcome of the performance of each strategy put forward by the metaheuristics model. Assuming current prices, Tables 78-80 represent the strategies to choose from under urban, regional and long-haul duties, respectively. The values found in these Tables are the outcomes of the metaheuristics model seen in the previous section. Strategy S0 has been excluded from the analytic hierarchy process (AHP) as the objective of this research is to reduce carbon emissions cost-efficiently and this does not happen in the do-nothing scenarios.

Table 78. Strategies to evaluate using AHP for urban vehicles.

	S0	S1	S2	S3	S4
	UB-BASE2	UB-UNLTD2	UB-GHG2	UB-RITM2	UB-RISL2
Net Present Cost (£)	250,895	226,318	252,666	229,675	243,408
GHG Emissions (t CO_2 eq.)	317	187	171	195	295
Risk Technology Maturity	10	4	4	6	7
Risk Safety & Limitations	6	4	3	4	6

Table 79. Strategies to evaluate using AHP for regional vehicles.

	S0	S1	S2	S3	S4
	RG-BASE2	RG-UNLTD2	RG-GHG2	RG-RITM2	RG-RISL2
Net Present Cost (£)	404,885	347,313	370,297	350,938	366,726
GHG Emissions (t CO_2 eq.)	564	295	271	303	481
Risk Technology Maturity	10	4	4	6	7
Risk Safety & Limitations	6	4	3	4	6

Table 80. Strategies to evaluate using AHP for long-haul vehicles.

	S0	S1	S2	S3	S4
	LH-BASE2	LH-UNLTD2	LH-GHG2	LH-RITM2	LH-RISL2
Net Present Cost (£)	441,658	383,693	403,641	385,943	394,271
GHG Emissions (t CO_2 eq.)	596	324	291	330	493
Risk Technology Maturity	10	4	4	6	7
Risk Safety & Limitations	6	4	3	4	6

The multicriteria model takes the values from Tables 78-80 and it produces a ranking of preferred strategies under each duty cycle based on the matrix of pair-wise comparisons between objectives provided by the industrial sponsor (Table 81). The pairwise comparisons are the outcome of internal discussions among Martin Brower's management board[25]. This Table reflects the importance of the selected goals for the industrial sponsor. The normalisation of the values yields Table 82 which is used to calculate the weight of each goal that appears in Table 83 (as described in Section 4.6). This Table shows that for Martin Brower UK Ltd., NPC is the least important objective (0.06), while GHG emissions is the most important one (0.482), followed by the preference for using technologies that are mature enough (0.312) and technologies that do not present new safety concerns or limitations (0.144). The pair-wise comparisons of criteria are consistent as the ratio between consistency index and random index is under 0.10 (Table 83).

Table 81. Scores of the pair-wise comparison of objective preferences.

Objectives	Net Present Cost (£)	GHG Emissions (t CO_2 eq.)	Risk Technology Maturity	Risk Safety & Limitations
Net Present Cost (£)	1	1/5	1/7	1/3
GHG Emissions (t CO_2 eq.)	5	1	3	3
Risk Technology Maturity	7	1/3	1	3
Risk Safety & Limitations	3	1/3	1/3	1

[25] The members that participated in the decision included the head of scheduling, the managing director, the finance director, and the engineering manager.

Table 82. Normalised scores of criteria preferences.

Objectives	Net Present Cost (£)	GHG Emissions (t CO_2 eq.)	Risk Technology Maturity	Risk Safety & Limitations
Net Present Cost (£)	0.063	0.107	0.032	0.045
GHG Emissions (t CO_2 eq.)	0.313	0.536	0.670	0.409
Risk Technology Maturity	0.438	0.179	0.223	0.409
Risk Safety & Limitations	0.188	0.179	0.074	0.136

Table 83. Weight calculated for each goal according to the industrial sponsor preferences stated in Table 81 and consistency index of criteria.

Net Present Cost (£) (w_1)	0.062	Aw_1^T	0.2508		CI	0.079
GHG Emissions (t CO_2eq.) (w_2)	0.482	Aw_2^T	2.1597		RI	0.9
Risk Technology Maturity (w_3)	0.312	Aw_3^T	1.3377		Ratio	0.087
Risk Safety & Limitations (w_4)	0.144	Aw_4^T	0.5942		≤0.10?	Yes
		Aw^T	4.2371		(It's consistent)	

The four strategies preselected (S1-S4) are scored following the AHP methodology (Section 4.6), according to their performance regarding each criteria. The intermediate calculations of the performance of each target under the urban duty are presented in Tables 84 to 91. The calculations related to regional and long-haul strategies appear in Appendices 18 and 19, respectively. As it can be appreciated in Table 85, 97 and 89 and following the methodology described in Section 4.6 (Page 180) all the pair-wise comparisons of the performance of each strategy according to each criera are consistent.

Table 84. Scoring of the strategies according to their costs.

Net Present Cost (£)	S1 (RG-UNLTD2)	S2 (RG-GHG2)	S3 (RG-RITM2)	S4 (RG-RISL2)	
S1 (UB-UNLTD2)	1	5	2	4	
S2 (UB-GHG2)	1/5	1	1/5	1/2	
S3 (UB-RITM2)	1/2	5	1	4	
S4 (UB-RISL2)	1/4	2	1/4	1	
	1.95	13.00	3.45	9.50	
					SCORE
S1 (UB-UNLTD2)	0.513	0.385	0.580	0.421	0.475
S2 (UB-GHG2)	0.103	0.077	0.058	0.053	0.073
S3 (UB-RITM2)	0.256	0.385	0.290	0.421	0.338
S4 (UB-RISL2)	0.128	0.154	0.072	0.105	0.115
	1.00	1.00	1.00	1.00	1.00

Table 85. Consistency index for the cost objective.

	AWT		
	n2=	4	
	AWT	Consistency Index	0.029586436
S1 (UB-UNLTD2)	1.9729	Random Index	0.9
S2 (UB-GHG2)	0.2925	Comparison	0.032873818
S3 (UB-RITM2)	1.3976		
S4 (UB-RISL2)	0.4631		
	4.0888	Under 0.10?	YES

Table 86. Scoring of the strategies according to their carbon emissions.

GHG Emissions (t CO_2 eq.)	S1 (RG-UNLTD2)	S2 (RG-GHG2)	S3 (RG-RITM2)	S4 (RG-RISL2)	
S1 (UB-UNLTD2)	1	1/2	2	4	
S2 (UB-GHG2)	2	1	2	5	
S3 (UB-RITM2)	1/2	1/2	1	4	
S4 (UB-RISL2)	1/4	1/5	1/4	1	
	3.75	2.20	5.25	14.00	
					SCORE
S1 (UB-UNLTD2)	0.267	0.227	0.381	0.286	0.290
S2 (UB-GHG2)	0.533	0.455	0.381	0.357	0.431
S3 (UB-RITM2)	0.133	0.227	0.190	0.286	0.209
S4 (UB-RISL2)	0.067	0.091	0.048	0.071	0.069
	1.00	1.00	1.00	1.00	1.00

Table 87. Consistency index for the carbon emissions objective.

	n2=	4	
	AWT	Consistency Index	0.029578835
S1 (UB-UNLTD2)	1.2009	Random Index	0.9
S2 (UB-GHG2)	1.776	Comparison	0.032865372
S3 (UB-RITM2)	0.8466		
S4 (UB-RISL2)	0.2803		
	4.0887	Under 0.10?	YES

Table 88. Scoring of the strategies according to their risk of technology maturity.

Risk Technology Maturity	S1 (RG-UNLTD2)	S2 (RG-GHG2)	S3 (RG-RITM2)	S4 (RG-RISL2)	
S1 (UB-UNLTD2)	1	1	1/4	1/5	
S2 (UB-GHG2)	1	1	1/4	1/5	
S3 (UB-RITM2)	4	4	1	1/3	
S4 (UB-RISL2)	5	5	3	1	
	10.00	10.00	5.67	1.65	
					SCORE
S1 (UB-UNLTD2)	0.091	0.091	0.056	0.115	0.088
S2 (UB-GHG2)	0.091	0.091	0.056	0.115	0.088
S3 (UB-RITM2)	0.364	0.364	0.222	0.192	0.285
S4 (UB-RISL2)	0.455	0.455	0.667	0.577	0.538
	1.00	1.00	1.00	1.00	1.00

Table 89. Consistency index for the risk of technology maturity objective.

	n2=	4	
	AWT	Consistency Index	0.032443138
S1 (UB-UNLTD2)	0.3554	Random Index	0.9
S2 (UB-GHG2)	0.3554	Comparison	0.036047931
S3 (UB-RITM2)	1.1704		
S4 (UB-RISL2)	2.2764		
	4.0973	Under 0.10?	YES

Table 90. Scoring of the strategies according to their risk of safety and limitations.

Risk Safety & Limitations	S1 (RG-UNLTD2)	S2 (RG-GHG2)	S3 (RG-RITM2)	S4 (RG-RISL2)	
S1 (UB-UNLTD2)	1	3	1	1/5	
S2 (UB-GHG2)	1/3	1	1/3	1/7	
S3 (UB-RITM2)	1	3	1	1/5	
S4 (UB-RISL2)	5	7	5	1	
	7.33	14.00	7.33	1.54	
					SCORE
S1 (UB-UNLTD2)	0.136	0.214	0.136	0.130	0.154
S2 (UB-GHG2)	0.045	0.071	0.045	0.093	0.064
S3 (UB-RITM2)	0.136	0.214	0.136	0.130	0.154
S4 (UB-RISL2)	0.682	0.500	0.682	0.648	0.628
	1.00	1.00	1.00	1.00	1.00

Table 91. Consistency index for the risk of technology safety and limitations.

	n2=	4	
	AWT	Consistency Index	0.02461734
S1 (UB-UNLTD2)	0.6251	Random Index	0.9
S2 (UB-GHG2)	0.2562	Comparison	0.0273526
S3 (UB-RITM2)	0.6251		
S4 (UB-RISL2)	2.6157		
	4.0739	Under 0.10?	YES

In Table 84, the pair-wise comparisons between strategies reflect the cost differences between them using a valuation similar to Table 92. Table 85 represents the evaluation in regards to GHG emissions savings using the rating that appears in Table 93. The results of these calculations yield the final scores that appear in Table 94-96 under each duty. The strategy that obtained the highest score in each type of duty has been highlighted in yellow. The meaning of the scores were explained in the methodology (Table 44, page 182).

Table 92. Score according to the cost savings performance between strategies.

Difference (£)	Score
0-500	1
501-10,000	2
10,001-20,000	3
20,001-30,000	5
30,001-40,000	7
40,001-50,000	9

Table 93. Score according to the GHG emissions savings performance between strategies.

Difference (t CO_2 eq.)	Score
0-5	1
6-50	2
51-100	3
101-150	4
151-200	5
201-250	6
251-300	7
300-350	8
350-400	9

Taking as an example the cost minimisation strategy (S1), the score for the UB-UNLTD2 scenario is the result of multiplying the score of the first goal (NPC) (Table 9484) by its weight (Table 83) plus the score of the second (GHG emissions) by its weight, and so on. The final score of 0.219 for S1 is the outcome of 0.475 x 0.062 + 0.290 x 0.482 + 0.088 x 0.346 + 0.144 x 0.13.

Table 94. Scores of each strategy based on the urban duty HGVs.

Raw Score	S1 (UB-UNLTD2)	S2 (UB-GHG2)	S3 (UB-RITM2)	S4 (UB-RISL2)
Net Present Cost (£)	0.475	0.073	0.338	0.115
GHG Emissions (t CO_2 eq.)	0.290	0.431	0.209	0.069
Risk Technology Maturity	0.088	0.088	0.285	0.538
Risk Safety & Limitations	0.154	0.064	0.154	0.628

Weighted Score	S1 (UB-UNLTD2)	S2 (UB-GHG2)	S3 (UB-RITM2)	S4 (UB-RISL2)
Net Present Cost (£)	0.029	0.004	0.021	0.007
GHG Emissions (t CO_2 eq.)	0.140	0.208	0.101	0.033
Risk Technology Maturity	0.028	0.028	0.089	0.168
Risk Safety & Limitations	0.022	0.009	0.022	0.091
Final Score	0.219	0.249	0.233	0.299

Table 95. Scores of each strategy based on the regional duty HGVs.

Raw Score	S1 (RG-UNLTD2)	S2 (RG-GHG2)	S3 (RG-RITM2)	S4 (RG-RISL2)
Net Present Cost (£)	0.481	0.085	0.322	0.113
GHG Emissions (t CO_2 eq.)	0.295	0.435	0.213	0.057
Risk Technology Maturity	0.095	0.095	0.232	0.578
Risk Safety & Limitations	0.154	0.064	0.154	0.628

Weighted Score	S1 (RG-UNLTD2)	S2 (RG-GHG2)	S3 (RG-RITM2)	S4 (RG-RISL2)
Net Present Cost (£)	0.030	0.005	0.020	0.007
GHG Emissions (t CO_2 eq.)	0.142	0.210	0.103	0.027
Risk Technology Maturity	0.030	0.030	0.072	0.180
Risk Safety & Limitations	0.022	0.009	0.022	0.091
Final Score	0.224	0.254	0.217	0.305

Table 96. Scores of each strategy based on the long-haul duty HGVs.

Raw Score	S1 (LH-UNLTD2)	S2 (LH-GHG2)	S3 (LH-RITM2)	S4 (LH-RISL2)
Net Present Cost (£)	0.476	0.081	0.288	0.154
GHG Emissions (t CO_2 eq.)	0.265	0.469	0.211	0.056
Risk Technology Maturity	0.095	0.095	0.232	0.578
Risk Safety & Limitations	0.154	0.064	0.154	0.628

Weighted Score	S1 (LH-UNLTD2)	S2 (LH-GHG2)	S3 (LH-RITM2)	S4 (LH-RISL2)
Net Present Cost (£)	0.029	0.005	0.018	0.010
GHG Emissions (t CO_2 eq.)	0.127	0.226	0.102	0.027
Risk Technology Maturity	0.030	0.030	0.072	0.180
Risk Safety & Limitations	0.022	0.009	0.022	0.091
Final Score	0.209	0.270	0.214	0.307

Under urban and long-haul cycles, S1 is the least preferred strategy and it also scores very low under regional duty. The reason for this is that despite being the most cost-efficient solution, NPC has very little weight in the final score; just 6%, as indicated in Table 83. As S1 is always riskier than S4, and risk is a such an important criteria for the industrial sponsor, S1 strategy consistently scores very low (between 0.209 and 0.224 depending on the type of duty).

S2 is always the second most preferred strategy. The reason for this is that this strategy minimises GHG emissions and this is the most important objective for the industrial sponsor (0.482). S2 is the worst performing strategy in regards to NPC (0.04-0.05); however, this has little negative impact on the final score as the NPC weight, as previously mentioned, is very small (0.06). The main challenge in regards to S2 is that the combination of technologies that it represents is the riskiest one (levels 4 for the risk of technology maturity and 6 for safety and limitations). As the industrial sponsor considers the combined technology risks as the most important objectives, and lower carbon technologies tend to be riskier, the final score of S2 is severely affected.

S3 yields very similar results to S1, with marginally higher costs and carbon emissions (Tables 94-96). This means that S3 scores are lower on both objectives and the same as S1 regarding the safety and limitation risks. However, S3 performs much better in regards to the risk of technology maturity (the most important criteria for the industrial sponsor). This leads to S3 scoring higher than S1 under urban and long-haul and roughly the same under regional duty. The final score of the S3 scenarios is between 0.214 and 0.233, which always excludes this strategy from the first two positions in the ranking.

S4 is always the dominant strategy for urban, regional and long-haul vehicles (Table 94-96). This strategy is based on minimising NPC considering technologies with a risk of technology safety and limitations above 6. The reason for S4 always performing better than other strategies is that by only allowing technologies with a risk of safety and limitations of level 6 or over, this yields a combination of technologies where the risk of technology maturity is at least 6. The aggregated score of both risks (0.456) is very similar to the weight of the carbon footprint criteria (0.482), as seen in Table 83 (Page 265), which helps S4 to score high.

HGVs specified with the technologies recommended under strategy S4 can save 22t, 83t and 103 t of GHG emissions while reducing NPC by £7,487, £38,159 and £47,387 under urban, regional and long-haul duties respectively (compared to their baseline scenarios). S4 is by no means the cheapest or most carbon avoiding solution; however, it still delivers savings on both accounts and the lowest risks. Considering the preferences stated by the industrial sponsor, S4 is the recommended strategy. At current energy prices, the optimal combination of LCT that vehicles should fit is the one that appears under the S4 scenarios UB-RISL2, RG-RISL2 and LH-RISL2 in Tables 67, 70 and 73 for urban, regional and long-haul HGVs correspondingly.

5.5.1 SENSITIVITY ANALYSIS OF WEIGHTS

To illustrate the impact that different corporative preferences have on the selection of the recommended vehicle specification, Table 97 represents the scores and ranking of the AHP for urban duty vehicles. The weights provided by the industrial sponsor have been substituted to value just one goal for each strategy; this means that the goal has a value of 1 (100%) and all the other criteria a value of 0. As expected, when just the NPC goal is considered, S1 is the strategy that obtains the highest score (0.475) and S2 is the least preferred (0.073), as it is the most expensive. When the only goal is minimising GHG emissions, S2 is the most preferred strategy with a score of 0.431 and S4 the least; when considering the risk of technology maturity, S3 is dominated by S4, as S4 over performs S3 in both risk dimensions. As expected, setting up safety and limitations risks as the only objective, results in S4 becoming the favourite strategy and as S2 has the highest risks, it becomes the least desirable.

Looking at the performance of each strategy regarding each target, S1 has the lowest score (0.088) when the only goal sought is minimising the risk posed from immature technologies (this means accepting combinations of low carbon technologies with a RITM level of 6 or over). S2 has the lowest score (0.064) when just the risk of technology safety and limitations is sought. S2 underperforms all the other strategies when considering individual goals (excluding GHG emissions). S3 does not lead under any of the four criteria. S4 dominates clearly any other strategy when either of both risks is the only goal sought. S4 presents the lowest score (0.069) when the target is reducing GHG emissions only, as it is clearly the strategy that saves less carbon.

Table 97. Scenario Analysis of selecting just one single criteria for the urban scenarios.

	Weighted Score	S1 (UB-UNLTD2)	S2 (UB-GHG2)	S3 (UB-RITM2)	S4 (UB-RISL2)
Net Present Cost (£) All the other criteria = 0	1	0.475 1st	0.073 Last	0.338	0.115
GHG Emissions (t CO_2 eq.) All the other criteria = 0	1	0.290	0.431 1st	0.209	0.069 Last
Risk Technology Maturity All the other criteria = 0	1	0.088 Last	0.088 Last	0.285	0.538 1st
Risk Safety & Limitations All the other criteria = 0	1	0.154	0.064 Last	0.154	0.628 1st

S3 minimises NPC including technologies with a level of technology maturity of 6 or over; however, as S4 includes more mature technologies, S3 is not the preferred option when only that objective is desired. S3 is the only strategy that is never chosen, regardless of the weights assigned to each objective. The score of S3 is maximum (0.338) when the NPC is the only objective sought but even then, this strategy is dominated by S1. S3 gets the lowest score (0.154) when the risk of technology safety and limitations is the only objective considered.

When all the objectives are equally important (each one weights 25%) the preferred strategy is S4 (Table 98). Therefore, S4 is not only the chosen strategy according to the priorities of the industrial sponsor, but also when all criteria are equally important.

An additional sensitivity analysis indicates that when the weights for the NPC, GHG, RITM and RISL criteria are 0.157, 0.483, 0.306 and 0.054, respectively, all four strategies are equally important (Table 99). Any other weighting produce a ranking where one or more strategies are clearly better than the rest. Ranking the strategies facilitate the discussions that may determine the optimal strategy (vehicle specification) that should be requested when procuring HGVs.

Table 98. Score and ranking of the AHP applied to equally important criteria (0.25) for an urban HGV.

	Weighted Score	S1 (UB-UNLTD2)	S2 (UB-GHG2)	S3 (UB-RITM2)	S4 (UB-RISL2)
All Objectives	0.25	0.252	0.164 Last	0.247	0.338 1st

Table 99. Indifference between strategies for urban HGVs.

Raw Score	S1 (UB-UNLTD2)	S2 (UB-GHG2)	S3 (UB-RITM2)	S4 (UB-RISL2)
Net Present Cost (£)	0.475	0.073	0.338	0.115
GHG Emissions (t CO_2 eq.)	0.290	0.431	0.209	0.069
Risk Technology Maturity	0.088	0.088	0.285	0.538
Risk Safety & Limitations	0.154	0.064	0.154	0.628

Weighted Score	S1 (UB-UNLTD2)	S2 (UB-GHG2)	S3 (UB-RITM2)	S4 (UB-RISL2)
Net Present Cost (£)	0.075	0.011	0.053	0.018
GHG Emissions (t CO_2 eq.)	0.140	0.208	0.101	0.033
Risk Technology Maturity	0.027	0.027	0.087	0.165
Risk Safety & Limitations	0.008	0.003	0.008	0.034
Final Score	0.250	0.250	0.250	0.250

KEY FINDINGS OF THE RESULTS

- The higher the risks accepted by the decision maker, the higher the cost savings and GHG emissions reductions. When the model excludes the technological risks (Strategy S1), urban HGVs can reduce fuel consumption by 30.7%, resulting on 9.8% lower NPCs and 40.9% fewer GHG emissions. Under regional duty, 35.8% fuel can be saved, which results in 14.2% lower NPC and a reduction of 47.7% in carbon emissions. Long-haul HGVs can reduce fuel consumption by 34% and NPC by 13.1% with 45.5% lower GHG emissions.
- The solution provided via AHP is highly insensitive towards MARR and carbon taxation. When carbon prices reach £144/t heat recovery technologies are added to the long-haul scenario. For prices up to £200/t, this does not happen for regional or urban HGVs. This suggests that taxating carbon in the logistics sector will not have any real impact on triggering the demand for low carbon technologies as companies will use these technologies anyway as they result in lower fuel costs. In contrast, the recommended solution is highly sensitive towards the weights given by the decision maker in the AHP. Changes on preferences result in a different ranking of choices.
- Considering the results of the AHP and the preferences of the multiple criteria determined by the industrial sponsor, strategy S4 is the one that meets the objectives of the organisation more closely. This strategy represents the combination of technologies that minimise costs with the lowest risks. As this alternative excludes technologies with higher technological risks, savings are more modest. Under S4, urban HGVs optimal combination of LCT reduced fuel consumption by 8.4%, which yields NPC savings of 3% and GHG emissions avoidances of 7%. Regional vehicles can reduce fuel consumption by 18.2%, which leads to 9.4% lower NPCs and 14.6% lower GHG emissions. Long-haul HGVs can reduce fuel consumption by 21.1% which lead to a NPC reduction of 10.7% and 17.1% lower carbon emissions. At current energy prices, the technologies that are included in S4 under all duties are spray reduction mudflaps, low rolling resistance tyres, automatic tyre pressure monitoring systems and lightweighting materials. Under urban duty, automated manual transmissions are added to the solution. Under regional and long-haul duty, aerodynamic trailers and predictive cruise control are recommended. Due to the limitations of refrigeration technologies, none of them are

included in the solution for the S4 scenarios. This results in NPC savings of £7,487, £38,159 and £47,387 and reductions of GHG emissions of 22t, 83t and 103t CO_2 eq. for urban, regional and long-haul vehicles, respectively, over the life span of the vehicle. This aggregates to total savings of 7,950 t CO_2 eq. and £3.5 million for the whole industrial sponsor's fleet over 5 years.

- **Conducting an analysis of TRU on their own (not as part of the metaheuristics model) indicate that 3 phase alternator refrigeration units are the most economic and lower carbon intensive of all the refrigeration technologies considered, with all scopes GHG savings of 52.5% and a cost reduction of 11.5% compared to conventional mechanical refrigeration systems. Using cryogenic air through a Dearman Engine seems a promising refrigeration technology as it can reduce carbon emissions by 46% with 1.5% lower costs than conventional systems.**

- **Waste from the FFSC can produce enough energy to power the whole logistics fleet of the industrial sponsor and generating a surplus that could be sold or used internally in combined heat and power stations. Fuel from waste can power the energy demands of between 20% to 68% of the diesel refuelled on the 20 major UK districts. Considering the UK as a whole, biofuel generated from the waste from quick service restaurants could cover between 4.4% and 5.5% of all the demand of UK fleets of HGVs refuelling on public refuelling stations.**

- **Several waste-to-fuel scenarios have been built. Scenario one suggests that 532 M km could be run with first generation B100 biodiesel from waste cooking oil and fat and 632 M km from biomethane from organic waste and paper. When the focus is producing second generation biodiesel (Scenario 2) the amount of km that could be run from waste cooking oil and fats decreases to 221 M km. When most of the waste fractions are anaerobically digested, there is potential to power biomethane trucks for 898 M km (Scenario 3).**

- **The well-to-wheel GHG emission factor of biodiesel produced from wasted cooking oil for the industrial sponsor chain is 13.6 g CO_2 eq. /MJ. This could be 10.2 g CO_2 eq. /MJ when producing second generation biodiesel despite that generating facilities are outside the UK. Biomethane emissions are higher at 26.4 g CO_2 eq. /MJ. This results in emission factors 84.7% and 88.5% lower than mineral diesel for 1^{st} and 2^{nd} generation biodiesel, and 61.9% lower than biomethane from municipal waste.**

- Conducting real world trials for ascertaining the fuel consumption reduction of low carbon technologies is not a very effective approach. The main reason is that obtaining statistically significant results is very difficult conducting a small number of trips as the error is often higher than the percentage of fuel savings that are being measured.
- Spray suppression mudflaps seem to save 1.5% under motorway driving; however, the results were statistically insignificant. Bearing in mind the challenges of conducting tests on roads, and the small sample of trips, it cannot be concluded that these devices yield any real benefits.
- Real world road tests are very expensive and risky. A two day trial costs £4,867 and there is no guarantee that human errors or climatological conditions will not invalidate the samples. Road live trials following SAE J1321 Type-II are unreliable as it is virtually impossible to conduct each trip under the exact same conditions, as weather and congestion levels cannot be controlled and an specific driving cycle is very difficult to reproduce with precision.
- Simulations are very effective to measure fuel savings from different technologies as the external factors that may distort the results can be avoided. This approach however requires the use of expensive and often too technical software that realistically may be beyond the reach of logistics firms. This, however presents a business opportunity for consulting firms that could measure the exact fuel savings of specific routes and vehicles for these logistics firms by using simulated low carbon technologies.
- Two approaches have beeb taken to calculate the optimal solutions. The non-heuristics approach was programmed with VBA to evaluate all the possible solutions and finding the optimal one. This approach takes several hours to yield one single scenario. In contrast, the metaheuristics approach takes minutes and this allows the running of many varying scenarios. This facilitates a faster analysis of sensibilities and it speeds up the inclusion of potential strategies in the multicriteria decision analysis.
- Computational fluid dynamics experiments of a rigid lorry suggest that aerodynamic improvements result in fuel savings of 6% under motorway driving and 4.2% under urban conditions.
- For two particular routes, a weight reduction of 500 kg reduced fuel consumption by 1.17% in 33 t articulated HGVs on motorway driving.

- **Reducing speed from 90 to 70 kph can save 10%-12.78% of fuel, depending on the route. This may lead to cost savings of 2.19-1.91% before counting the impact of this strategy on time windows. If reducing speed breaches service level agreements, this may cancel the any benefits as further vehicles may be needed to meet time windows.**
- **There is a large error when measuring fuel consumption from telematics units. A comparison of telematics readings with gravimetric measurements of the fuel tanks indicated that the telematics readings under measured real fuel consumption by an average of 5.47%. Besides, there is large variability from one trip to the next and among vehicles. Using ECU and telematics readings to conduct fuel consumption analyses should be avoided as these cannot be trusted.**
- **Uninstalling a driving assistance device from a control vehicle showed a fuel penalty of 1.39%; however, as the data was collected from the telematics unit (and this approach is quite unreliable) and there was no daily information of the tonnage carried by the vehicle and weather conditions (e.g. rain) it is not possible to ascertain that the worsening was undoubtedly a result of eliminating the driving assistance device.**
- **For carbon taxation becoming the main driver for low carbon technology selection, the cost of carbon (per tone), must be higher than the cost of 387.6 L of diesel.**

6. DISCUSSIONS, CONCLUSIONS AND RECOMMENDATIONS

Chapter Aims:

To discuss the findings and their implications for HGV fleets, vehicle manufacturers and policy makers.
To introduce concluding remarks.
To recommend areas for further research.

This chapter is structured in four main sections. In the first one, the results are discussed and their implications for the wider context assessed. The second section includes a comprehensive methodological discussion. In the third, low carbon policies are discussed and put forward to promote the uptake of innovative low carbon technologies. In the last section a range of research recommendations are suggested.

6.1 DISCUSSIONS AND CONCLUSIONS

6.1.1 LITERATURE REVIEW

The main aim of this research was helping decision makers to specify greener heavy duty vehicles. The fuel economy of rigid trucks (17-25t) and artics (over 33t) has been improving since the nineties (Figure 129), even with the implementation of successive Euro Emission Standards. However, in the literature review, it was stated that the threshold of the energy efficiency of diesel internal combustion engines is limited to 52-58% (Eckerle, 2007, Baker et al., 2009a). This research has developed a framework to help with the decision making process of selecting low carbon technologies. This framework consisted of four main blocks. In the first block an extensive literature review identified the relevant technologies, their strengths and weaknesses, costs, developmental stage and performance (fuel consumption reduction). The outcomes were used to map the technological landscape and to produce the information necessary to start to build the models. In the second block a series of empirical work was undertaken where simulations, trials and a waste-to-fuel audit produced results that were used in the metaheuristics model. In the third block a combinatorial metaheuristics tool was developed to find the optimal combinations of technologies according to several objective functions and constraints. In the fourth and last block, a qualitative model (analytic hierarchy process) was used to provide the final vehicle specification, according to the trade-offs revealed by the industrial sponsor and the scenarios built in the third stage.

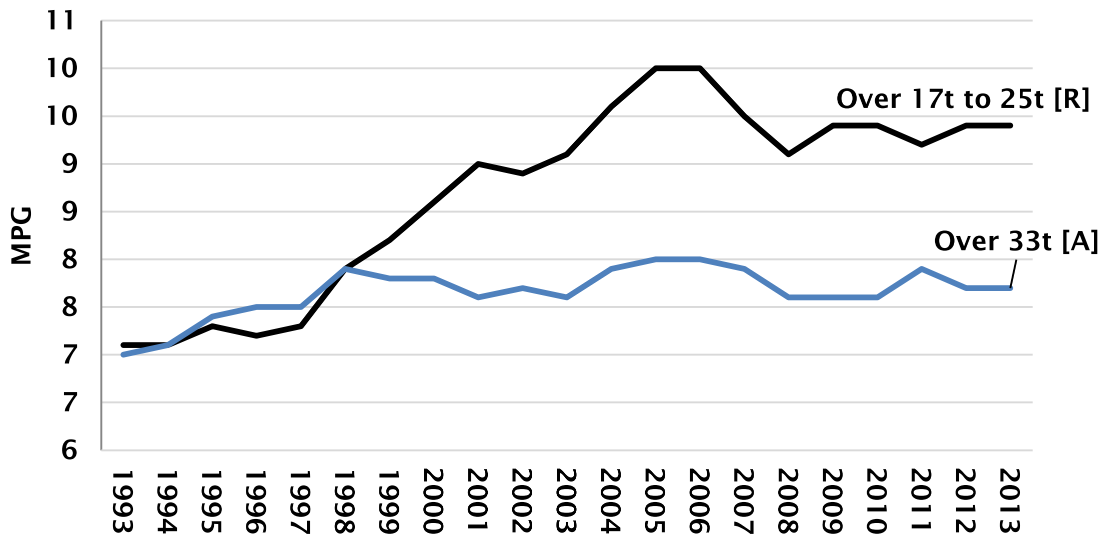


Figure 129. Fuel economy of British HGVs 1993-2013. Adapted from DfT (2015h).

A research gap was identified in the literature as no models were found that could automatize the selection of low carbon technologies for HGVs based on operational considerations and aiming to reduce carbon emissions cost efficiently. Reducing GHG emissions was found to be critical to mitigate the negative externalities of road haulage. The study of the literature also indicated that different studies conducted in the area of automotive energy efficient technologies are context dependent and their findings cannot be extrapolated to other geographically distant areas as the characteristics of vehicles and duty cycles vary. This results in different fuel consumption reductions even for the same technologies. When evaluating the different technologies over time, it was found that some of the ones that were in commercial stage in 2010 were later discontinued (e.g. pneumatic boosters, vacuum insulated panels) due to a lack of interest from the market. Other technologies that had been trialled on HGVs fleets, finally enter commercial stage (e.g. cryogenic refrigeration technologies), while other are still in research stage (e.g. Rankine cycles thermal recovery technologies, liquid air refrigeration). The literature also highlighted the broad range of existing waste-to-fuel pathways and the powertrain technologies that could benefit from these (e.g. biodiesel, biomethane) as well as their potential for decarbonising logistics.

Several simulation packages and methodologies were appraised in the literature review which led to the selection of Autodesk Flow (simulation of aerodynamic improvements) and IPG Truckmaker (speed limitation and lighting weight materials and strategies). Among the fuel consumption reduction standards reviewed, SAE J1321 was identified as the ideal for conducting live trials of low carbon technologies on HGVs due to its robustness and because is the standard used by most OEM companies when they want to report the fuel savings of their products. The literature review indicated that evolutionary metaheuristics was the best approach to solve the type of combinatorial problem defined in this research. Multicriteria decision analysis was identified as an appropriate method for evaluating qualitative objectives; a method used by H.M. Treasury (2013). c

6.1.2 SIMULATED EXPERIMENTS

The simulation with Autodesk Flow of a rigid CF65 lorry with aerodynamic improvements (cab fairings and cab collar) reduced drag coefficient from 0.60 to 0.46 which resulted in fuel savings of 6% at 90 km/h. At lower speed (36 km/h) the same technology was able to reduce fuel consumption less (4.2%). These results are consistent with Baker et al. (2009a). The addition of both technologies using the findings of Law et al. (2012), should add to reductions of 2.49% and 4.94% under low and high speeds, respectively. On the other hand, the results are slightly below the values reported by Platform for Aerodynamic Road Transport (2013) as shown in Table 8 (page 52).

The simulations with IPG Truckmaker of a semi-articulated trailer (4x2 axles 33 t) indicated that a weight reduction of 500 kg could yield fuel savings of 1.17%, a slightly lower value than the 2.2.% reported by Hill et al. (2011) easily explained by the fact that the driving cycles and gradient of the routes were different. Reducing 500kg of mass from new vehicles is possible by ordering lighter trailers (e.g. aluminium) or using lighter materials (e.g. composites) in the tractor unit for example. However, in vehicles already owned reducing mass is very difficult as only very minor changes can be made (e.g. such as using aluminium rims on the wheels or substituting steel rolling cages for plastic dollies and wrapping film, if possible). During the progression of this research, it was considered that perhaps loading the fuel tanks with just the amount of fuel needed would reduce vehicle weight in most operations which could potentially lead to fuel savings. For a particular route it was found that under normal conditions reducing the fuel loaded from 400L to 300L and 200L could reduce fuel consumption by 0.2% and 0.39% respectively (Table 51, Page 196). On a different simulated route, loading the fuel tank with just 100L of diesel saved 0.51% of combustible compared to a full tank. On the negative side, this strategy increased the risk of depleting the fuel tank before arriving to the depot. In that experiment, the trip costs decreased by £3.88; which according to the industrial sponsor was not enough to justify the

risk. And additional experiment was conducted to find out the impact of speed limiters on fuel consumption. Considering vehicles with full fuel tanks, reducing speed from 90km/h to 70 km/h could decrease fuel consumption by 12.78% while increasing travelling time by 12.76% for one of the routes and 10% and 12.32% in the other route. An analysis of transportation costs suggested that this could decrease transportation costs by 1.9%-2.2% (depending on the route) including labour costs (drivers) and excluding the impact of time windows. However, with the strict time windows that the industrial sponsor must meet, limiting the speed of the fleet could result in deploying further HGVs on the road which very likely could increase total costs and losing any benefits.

6.1.3 LIVE TRIAL

The industrial sponsor was starting to fit spray suppression mudflaps, a technology that according to the literature reduce fuel consumption by 1.5%-3.5% (Table 10, page 55). This presented an excellent opportunity to ascertain whether this savings could be also achieved by the industrial sponsor fleet. The results of the trial indicated that spray suppression mudflaps could save 1.5% fuel; however due to the large confidence interval (±4.9%) the results were statistically insignificant. This means that it cannot be concluded that mudflaps have any impact on fuel consumption. To achieve a confidence level of 95% in the t-Test 54 trips would be necessary per day of trial and vehicle. Conducting such trips under controlled conditions and following SAE J1321 preferably on test tracks to eliminate distorting factors is not feasible. This would also require the installation of very accurate fuel measurement devices as plugin and unplugging fuel tanks is too time consuming as to meet the criteria specified by the standard. In the metaheuristics model, the FCR attributed to this technology is 1.5% for long-haul duty vehicles, as this was the lower bound reported in the literature by Platform for Aerodynamic Road Transport (2013) and Vonk et al. (2013).

The analysis of the data revealed something truly surprising. The trial of spray suppression mud flaps revealed that the fuel consumption readings reported by the telematics system, under measured this value by an average of 5.47%; compared to the gravimetric measurement of fuel consumption undertaken on-site. There was a large variability from one trip to the next and from one vehicle to another (see Table 57, page 207). Telematics is often used by logistics operators to evaluate the fuel savings of different technologies and also to relate drivers' performance to pay (e.g. the industrial sponsor); however, it is highly recommended not to use telematics systems and ECUs to conduct such type of fuel consumption analyses as they are neither accurate nor reliable. The reason for this to happen could be attributed to the low reliability of on-board

measurenment devices but it could also be speculated that some manufacturers may be using algorithms to under report fuel consumption and giving the impression that their vehicles are more fuel efficient than the ones from their competition.

Using telematics data over 6 months (3 months before and 3 months after disabling a driving assistance device) showed an increase on fuel consumption of 1.39% for the vehicle without the technology. Here it is important to highlight that using telematics data is not a good approach to conduct any fuel saving experiment, for the reasons previously explained; however, considering that a trial for one single technology costs almost £5,000, telematics is the only option available for most fleet operators. This result was not representative as there were too many uncontrolled variables (e.g. there was not information of the loads of the vehicles, weather conditions along all the routes, driving styles).

6.1.4 WASTE-TO-FUEL OPPORTUNITIES AUDIT

Using a significant dataset of waste arisings from a major fast food chain operating in the UK, a detailed appraisal of the potential for using waste as feedstock to produce fuel for logistics fleets was undertaken. The results of the waste-to-fuel audit showed that UCO, fats, paper and cardboard, and wooden pallets can be used to generate biofuels while plastics can produce synthetic fuels. Mapping the supply chain, it was calculated that the carbon intensity of the UCO and fat to first generation biodiesel pathway was 13.6-13.4 g CO_2eq. /MJ and therefore it could save 84.7%-84.9% WTW GHG emissions respectively. Similarly, using the same feedstocks to produce second generation HVO would result in carbon intensities of 10.2 and 9.7 g CO_2eq. /MJ and therefore WTW GHG emissions savings of 88.5% and 85.1%, respectively, compared to mineral diesel. The carbon intensity of the biomethane pathway was 26.5 g CO_2eq. /MJ which resulted in carbon savings of 61.9% respect to natural gas and assuming that conventional diesel carbon intensity is 88.6 g CO_2eq. /MJ, a saving of 70%. Using wooden pallets waste presented the lowest carbon savings with 58.7% compared to conventional diesel, below the threshold required in the Renewable Energy Directive's sustainability criteria.

To evaluate the waste-to-fuel potential of the industrial sponsor supply chain, three scenarios were created. Under scenario 1 all the UCO and fat was used to produce FAME biodiesel. Scenario 2, assumed these wastes were used to produce HVO biodiesel, while under scenario 3 they were co-digested to produce biomethane. In all three scenarios, organic waste, paper and card produced biomethane; wasted wooden pallets produced bioethanol and wasted plastics produced synthetic diesel. Extrapolating the results to the 39,762 quick service restaurants (QSRs) that operate across Britain, the results indicated that waste from British QSRs could reduce the carbon emissions of logistics fleets by 68.5%, 63.9% and 59.5% for scenarios 1, 2 and 3 respectively (Table 61, page 219). It was found that waste could cover the energy needs of between 4.4% and 5.8% of all HGVs (depending on the scenario and year). This translated to around 14–17 million GJ of energy per year. Excluding non-biogenic feedstocks, the equivalent to 1,622 HGVs could be powered with second generation biodiesel B100 (scenario 2) or 3,891 with first generation B100 (scenario 1). As just 7% of first generation biofuel blend is allowed in the conventional fuel, this means that 55,585 HGVs could be powered by waste under scenario 1 (the one that used UCO and fat to produce FAME B100). Alternatively, conventional diesel can include up to 30% of second generation biodiesel, which means that under scenario 2 (the one that used UCO and fat to produce HVO B100) around 23,171 HGVs could receive the biodiesel fraction of their standard diesel from fuel from fuels producted from waste from British QSRs. Scenario 3 found that 1,943 biomethane trucks could be powered by digesting and co-digesting UCO and fat. Under all the scenarios, an additional 4.623 biomethane HGVs were expected to be powered from organic waste, paper and card; 73 with bioethanol from wooden pallets and 341 with synthetic diesel from wasted plastics. Other possible combinations were also possible such as dual fuel vehicles using biodiesel and biomethane but these were not explored in detail. It was identified an opportunity to produce synthetic diesel from plastics; however, carbon savings were unlikely as plastics come from oil. Risks were found in plastics, paper, cardboard and wood (pallets) waste-to-fuel pathways: using feedstocks that have not reached their end of life could trigger economic and environmental drawbacks, as the costs and GHG emissions of virgin materials are higher than the ones from recycled ones. Eliminating waste that could still be recycled, with the objective of producing fuels, will very likely drive prices of virigin feedstocks up. There are also health risks to consider when dealing with organic waste as any vehicle contamination could transfered to the food transported leading to potential to reputational damages.

As found out by Velazquez Abad et al. (2015), fuels from waste streams present a unique opportunity for certain supply chains to capture value while reducing emissions. It is not clear yet how the continuous improvements and zero waste strategies in food supply chains will affect the availability of the waste feedstock needed to produce biofuels. For these supply chains that can guarantee a stable production of feedstocks, the collection and commercialisation of waste could represent an additional stream of revenue. Bearing in mind the low margins in the sector (around 2-3%), this strategy may lead to a competitive advantage.

For example, 1 tonne of plastic film waste could be sold for £350 at letsrecycle.com (2014). This plastic could produce 750 L of synthetic diesel with a market value of more than £840 (assuming price of diesel £1.12/L as per Q1 2014), giving a margin of £490 to recover the processing costs and fuel tax (£0.65/l of fuel). As tax is around £0.52, processing costs must be around £0.13. It must be highlighted that the prices of waste plastic is related to the price of oil and therefore when the prices of oil go down, the prices of virgin plastics and recycled plastics do the same. Therefore, contemplating the possibility of collecting and processing the waste for the self-production of fuels is highly risky and the return on the investment may not materialise in the periods of time expected.

The reverse logistics of waste collections from QSRs managed by 3PLs show lower carbon emissions than those from dedicated waste fleets when these are done in otherwise empty back haul trips, as the emissions are attributed to the delivery of goods rather than the reverse logistics process. Under this assumption a small increase of fuel is assigned to the return trip due to the additional weight of the waste collected. Waste consolidation can be aggregated by 3PLs in their distribution centres. When biofuel processing plants are located nearby, carbon emissions and transportation costs become minimal. When this is not possible, dedicated fleets should locate their DCs in the optimal geographical locations. An analysis of the British districts where waste-from-fuel could cover a higher percentage of the refuelling demand of HGVs showed that there were 20 districts where the fuels could cover 20% of the demand. For example, it was found that the 7,313 QSRs located in Greater London could cover 24% of the refuelling of HGVs fleets that typically refuel in the area. Waste collection companies can benefit from placing their facilities in the geographical areas (clusters) shown in this research, where higher densities of QSRs are located (Figure 83, page 158).

The high capital expenditure of second generation biofuels processing facilities and the uncertainties surrounding energy policy have resulted in a lack of such facilities in many countries. This increases fuel costs but also WTW GHG emissions. It is reasonable to believe that logistics firms may soon start to compete with waste management companies for the control and management of of the waste resources.

As soon as all pre-Euro 6 fleets are renewed, the use of biodiesel will decrease and GHG emissions from road haulage will increase; there are however two options that may mitigate this. One possibility, is using the surplus of biodiesel in other areas (e.g. heating and power for warehouses). The second is using the fuel to power TRUs. Excluding biodiesel, from the pathways evaluated in this study, it seems that biomethane is the only realistic option for UK fleet operators as CNG vehicles deliver enough power and range for long haul duty cycles and the infrastructure for feedstock collection, fuel production and refuelling is well developed. Biomethane HGVs can meet Euro 6 emission standards, reduce GHG emissions and air quality pollutants. Biomethane can reduce GHG emissions by over 68% while reducing 35%, 17%, 50% and 70%, HC, CO, NO_x and PM_x respectively (Table 92). Other biofuels can also reduce CO_2 emissions but not necessarily air quality pollutants. Biodiesel from UCO (e.g. TOFA3a pathway) increases NO_x emissions by 8%, while decreasing CO, HC and PM_x emissions by 34%, 69% and 38% compared to mineral diesel HDVs. Surprisingly, virgin oil plant B100 increases the emissions of most pollutants by 50% (Table 92). This means that not all biofuels reduce GHG emissions and air pollution at the same time.

Table 100. Emission scaling factors for different biofuels relative to diesel for HDVs in regards to air quality pollutants (DERV=1). Adapted from: Defra (2011c).

Biofuel	HC	CO	NO_x	PM_x
FAME B100	0.31	0.66	1.08	0.62
Virgin Plant Oil B100	1.5	1.5	1.0	1.5
Biogas	0.65	0.83	0.5	0.3

6.1.5 QUANTITATIVE METAHEURISTICS MODEL

A total of 45 scenarios were evaluated with a bespoke metaheuristics model. This was the result of creating 3 types of duty x 5 strategies (sets of objective functions and constraints) x 3 energy prices assumptions. The scenarios were divided in three groups based on urban, regional and long-haul type of operations. Within each one of these groups, five subgroups were created. The first group included the do-nothing scenarios. The objective function of the second one was minimising net present costs, regardless of GHG emissions and risks (this was call S1). In the third, the objective function was minimising carbon emissions, regardless of costs or risks (this was called S2). In the fourth scenario, the objective function was minimising costs as long as the technologies selected were already in the market (this was called S3). In the fifth scenario, the same objective function was constrained to allow technologies that were as safe and at least as limited as or less than incumbent technologies (this was called S4). Within each one of these subgroups, 3 scenarios were created considering current fuel prices, and variations 20% over and under current prices. The outcome of the scenarios are presented in Table 93. In the table, the savings of scenarios

UNLTD1, GHG1, RITM1 and RISL1 are compared to BASE1, the ones ending in 2 with BASE2 and the ones ending in 3 with BASE3. Each scenario represents the aggregated savings for the whole fleet, assuming 39 urban lorries (DAF CF65), 78 regional (DAF CF85) and 6 long-haul semi-articulated HGVs (XF105).

Table 101. NPC, carbon savings, RITM and RISL for the whole fleet over 5 years.

Strategy	Scenario	Energy Prices	NPC Savings	GHG Savings (t CO_2 eq.)	RITM	RISL
S0	BASE1	-20%	£0	0	10	6
	BASE2	Fuel Price Medium	£0	0	10	6
	BASE3	20%	£0	0	10	6
S1	UNLTD1	-20%	£4,332,789	25,149	4	4
	UNLTD2	Fuel Price Medium	£5,796,909	27,684	4	4
	UNLTD3	20%	£7,470,429	20,796	4	4
S2	GHG1	-20%	£1,143,669	30,378	4	3
	GHG2	Fuel Price Medium	£2,903,424	30,378	4	3
	GHG3	20%	£4,663,290	30,378	4	3
S3	RITM1	-20%	£4,003,497	24,216	6	4
	RITM2	Fuel Price Medium	£5,369,736	26,712	6	4
	RITM3	20%	£6,728,226	26,676	6	4
S4	RISL1	-20%	£2,737,158	7,950	7	6
	RISL2	Fuel Price Medium	£3,552,717	7,950	7	6
	RISL3	20%	£4,373,964	8,262	7	6

Strategy S1 was the one that delivered the lowest costs and therefore the highest savings, as the risks associated to any particular technology did not constrained the solution. Under this strategy, a total of £5.8M and 27.6 Kt of CO_2 eq. could be saved compared to the do-nothing scenario over the 5 years in the life span of these vehicles when selecting the optimal vehicle specification (central energy prices forecast). Aggregating the scenarios that assumed energy prices 20% lower, costs and carbon savings were in the order of £4.3M and 25.1Kt of CO_2 eq., respectively. With 20% higher energy prices, the savings could reach almost £7.5M and GHG savings almost 21Kt. Under S2, the carbon savings were the highest at 30.3 Kt of CO_2 eq. The net present savings under this strategy were the lowest; £2.9 M with the central assumption of energy costs; £1.1M assuming 20% cheaper energy prices and £4.6 M with prices 20% more expensive. Under S3, the fleet decreased its NPC by almost £5.4M and carbon emissions by 26.7Kt over 5 years (central energy prices forecast). For energy prices 20% lower and 20% higher, savings were £4.0M and £6.7M respectively, with 24.2 Kt and 26.7Kt fewer GHG emissions. Compared to S1, this strategy was more expensive as fewer technologies could be selected as technologies had not reached commercial stage.

Under S4, the range of feasible technologies was much more reduced than with the other strategies. Under this strategy, technologies that were less safe or that presented more limitations than the incumbent technologies that they could replace were invalid. This resulted in the second lowest NPC savings (after S2) and the lowest GHG emissions savings of all strategies at £3.5m and 7.9Kt CO_2 eq. From a quantitative perspective, S4 is dominated by S3, as S3 presents higher NPC and carbon savings (Table 101). However, from a qualitative perspective, S4 is less risky, and this is one of the reasons that justifies the need for assessing the strategies with multicriteria decision analysis. Unless a method is followed, it is not intuitive that S4 represents the solution that meets MB goals best.

This research has demonstrated that carbon emissions of diesel HGVs can be halved cost efficiently by using the right combinations of vehicle, powertrain, fuel and refrigeration technologies. Considering the fleet as a whole and assuming the central forecast of energy prices, S1 can reduce GHG emissions by 46.2%, S2 by 50.7%, S3 by 44.6% and S4 by 13.27%. This suggests that diesel HGVs can still play a role in reducing the carbon emissions from road haulage, at least while the technical challenges related to battery electric and fuel cell hydrogen HGVs are overcome. The scenarios here presented have been compared with a baseline scenario where all vehicles use biodiesel B65, if the scenarios were compared with a baseline scenario where the vehicles use standard diesel (DERV), the carbon savings would be considerably higher, due to the fact that B100 has a carbon intensity 85-88% lower than mineral diesel depending on the pathway. Compared to S0, S1 can reduce NPC by 13.2%, S2 around 6.6%, S3 by 12.2% and S4 over 8%.

The optimal combinations of technologies under each duty appear in Tables 67, 70 and 73. There are a few generalisations that can be extracted from the results. Urban vehicles benefit from spray suppression mudflaps, lightweighting materials and automated manual transmissions, regardless of the scenario. This means that these technologies should be chosen from a quantitative perspective, regardless the objective function for prices ±20% from the central energy price projection. New generation single wide base tyres should also be selected unless the decision maker has concerns regarding the limitations of such tyres (as there is not a well-developed supply chain network for maintaining them and also some modifications in the lorries are required to fit the extra lateral width of these tyres). Except under S4, with medium energy prices or higher forecasts are assumed, three phase alternator refrigeration units should also be selected. Urban lorries should not be fitted with aerodynamic technologies as these are not worthwhile due to the fact that slow speed do not take the maximum advantage that aerodynamic improvements can provide; however if the objective is minimising carbon emissions regardless of costs (strategy S2), lorries should also fit this technology in addition to exhaust heat recovery technologies, pneumatic boosters, hybrid powertrains and vacuum insulated panels for the refrigerated trailer. Under S1 and S3, the hybrid powertrain is dominated by flywheels (kinetic energy recovery systems) as they present a better return on investment.

Regional semi-articulated trailers should typically be fitted with aerodynamic trailers, spray reduction mudflaps, automatic tyre pressure monitoring systems, lightweighting materials and predictive cruise control. Except for S4, where the risk of technology safety and limitation is a concern, new generation wide base tyres and controllable air compressors should also be chosen. When the objective is minimising GHG emissions, exhaust heat recovery technologies, AMT, pneumatic boosters, hybrid powertrain and vacuum insulated panels should also be selected. Similarly to urban lorries, hybridisation reduces carbon emissions more than flywheels however it is less cost efficient, and for this reason the latter is chosen in S1 and S3. As flywheels are considered to have a limited use on refrigerated HGVs, this technology is not selected under S4. Three phase alternator refrigeration units are recommended for S1, S2 and S3; however, under S1, when energy prices are assumed to be 20% higher, cryogenic air refrigeration units (based on the Dearman engine) represent better value for money. This is also the case for long-haul duty refrigerated vehicles. This means that LAIR refrigeration units are chosen when energy prices are high (by 20%) and the decision maker is not concerned by the fact that it is an immature technology with limitations in regards to the poor refilling infrastructure.

Long-haul semi-articulated trailers should be fitted with aerodynamic trailers, spray suppression mudflaps, lightweighting materials and predictive cruise control. Controllable air compressors should also be requested (except under S4) and low rolling resistance tyres (except under S2). Similarly to regional HGVs, when costs are irrelevant, GHG emissions are minimised (strategy S2) by specifying new generation single base tyres, exhaust heat recovery technologies, AMT, pneumatic boosters and hybrid powertrains. Under S1, the vehicle specification is the same for regional and long-haul vehicles. The main difference between regional and long-haul vehicles appears under strategy S3, where under regional duty, flywheels are not chosen when energy prices are assumed to be 20% higher, however AMT is.

Reducing carbon emissions from HGVs requires a holistic view where the life cycle analysis of technologies and fuels have to be considered together to produce an accurate calculation of the emissions from logistics operations. As

GHG emissions are a global issue, reporting all scope emissions is key to avoiding the transference of emissions to other elements in the supply chain and double counting.

Electric powertrains are currently limited to light duty vehicles (Baker et al., 2009a, Hill et al., 2011), urban buses (Arriva, 2014), hybrid urban duty lorries (Mercedes-Benz, 2013), shunting trucks (Terberg, 2014) and some utility trucks (Balqon, 2013). Once batteries can deliver the range and power needed by 18t and 33t HGVs, the real impact of electric trucks (e-trucks) on carbon emissions will depend on the carbon intensity of the national electricity grid mix. Electricity produced in countries with nuclear and renewable resources has a low carbon footprint; however, this is not the case in countries where fossil fuels are used to generate electricity. To deliver the power and range needed, regional and long-haul electric HGVs require the development of faster recharging systems, lighter and more energy intensive battery packs and/or the deployment of wireless induction recharging infrastructure on roads or unloading bays. E-Trucks (and fuel cell HGVs) do not appear as a feasible technology for the next 5-10 years in any of the technology maps reviewed in this research (Anandarajah et al., 2013, Automotive Council UK, 2013, NAIGT, 2009). E-trucks can also be powered by fuel cells; however, the technical challenges to develop a hydrogen economy are even greater than the ones found by battery electric trucks, as described in detail by Ball and Wietschel (2009) and Dodds and Demoullin (2013).

Transport refrigeration units can also benefit from using lower carbon intensive fuels as well as alternative powertrains (e.g. auxiliary alternator units) and cryogenic systems. There seems to be an interest in the market in developing lower carbon refrigerant gases, to respond to regulatory changes (F-Gases regulations). It has also been observed that in the last 5 years, some refrigeration technologies have reached a commercial stage (e.g. cryogenic LIN and CO_2 units from Linde Gases (2012) and Thermoking (2015)) and new ones are being developed (e.g. Dearman Engine developed by the Centre for Low Carbon Futures (2014)). The research has revealed that TRUs auxiliary alternator units have the greatest potential to reduce emissions. In the future, if the national grid is decarbonised, energy storage improved, and battery costs slashed, battery electric hybrid TRUs could minimise the emission of GHG from refrigerated transport; however, the cost of the only concept vehicle found (a 6x2 26t dairy rigid lorry developed by Volvo, Arla and Thermoking) were prohibitive (Transport Engineer, 2012). Cryogenic refrigeration still seems expensive; however, using liquid air has the potential to become a competitive technology if the prices of red diesel increase; as found under scenarios RG-UNLTD3 (Table 70, page 243) and LH-UNLTD3 (Table 73, page 251). In this area, there is scope for supply chain collaboration by sharing cryogenic infrastructure. Further development and testing of some refrigeration technologies is recommended to validate the results found in the literature.

6.1.6 MULTICRITERIA DECISION ANALYSIS

To reconcile qualitative and quantitative goals, a multicriteria decision analysis was performed. The urban, regional and long-haul scenarios were qualitatively evaluated through pair-wise comparisons. The industrial sponsor stated that from the four goals that they considered relevant when purchasing HGVs reducing GHG emissions was the most important (46.5%), followed by the risk of technology maturity (34.6%), risk of safety and limitations (13%) and surprisingly, costs were the less important criteria (6%). Applying an analytic hierarchy process (section 5.5, page 263), the results indicated that for all duty cycles, the combinations of technologies that fit better the preferences of the industrial sponsor correspond to the scenarios where risks are the lowest (strategies S4), followed by S2 (the strategy seeking the minimisation of GHG emissions). For urban and long-haul vehicles, S3 was the third choice, while under regional S3 was the last (almost at the same level as S1). The results make sense because cost was considered the least important criteria. Despite that S2 is the strategy that yielded the highest carbon savings, it is also the riskier one. As a result S2 scores very low in regards to the risks of technology maturity (RITM) and safety and limitation (RISL) objectives.

The technologies that are included in S4 under all duties are spray reduction mudflaps, low rolling resistance tyres, automatic tyre pressure monitoring systems and lightweighting materials. Under urban duty, automated manual transmissions are added to the solution and aerodynamic trailers and predictive cruise control under regional and long-haul duty. Due to the limitations of refrigeration technologies (e.g. not being able to work standing alone, not having a well-developed cryogenic gas refilling infrastructure), none of them were included in the solution. This results in NPC savings of £7,487, £38,159 and £47,387 and reductions of GHG emissions of 22t, 83t and 103t CO_2 eq. per urban, regional and long-haul respectively over their life span. The outcome of this process indicates that according to the central projection of energy prices, if the industrial sponsor follows this recommendation the fleet could save £3.5M over 5 years while saving 7,950 t CO_2 eq. (other scenarios under S4 appeared in Table 101, page 285). It can be concluded that risk perception is critical in the selection of low carbon technologies among logistic operators (in this case the industrial sponsor). This is consistent with the findings of Kay and Hill (2012) who

identified the lack of trust in technology provider's fuel economy claims, reliability risks perception and unknown vehicles residual values as the main general industry barriers for selecting low carbon technologies among fleet operators. As it can be seen in Figure 130, the potential net present savings for a fleet of similar size to the one of the industrial sponsor could change dramatically depending on the risk aversion of the decision maker (S1, S3 and S4) and objective function (S1,S3,S4 vs. S2) as represented by the strategies finally selected. Bridging these knowledge gaps (e.g. cost savings, reliability data) should be considered as a priority among policy makers, as it can led to substantial cost and emissions savings.

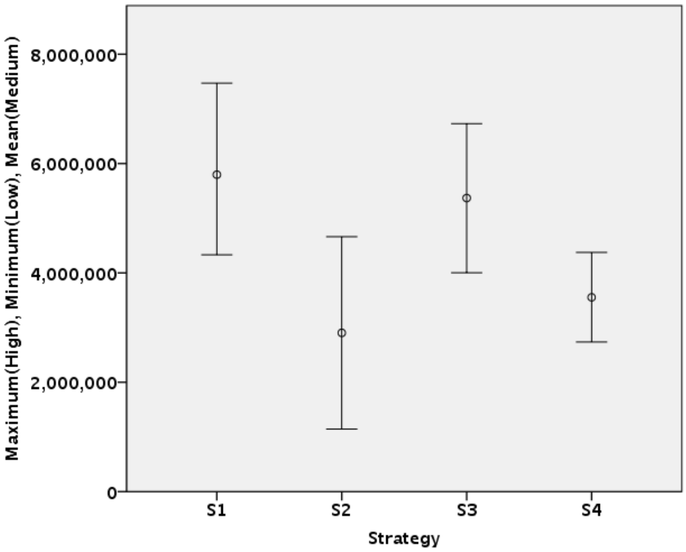


Figure 130. Savings (£) from each strategy according to low, medium and high energy costs projections.

6.2 METHODOLOGICAL DISCUSSION

The decision making framework developed in this research consisted of two main parts. In part one, the optimal combinations of low carbon technologies that meet a specific objective function were found based on different scenarios. In part two, based on multicriteria decision analysis, a preferred vehicle specification was chosen based on the goals stated by the decision maker. In part one, two contrasting approaches were developed. The first approach reviewed all possible combinations of LCTs through a bespoke VBA program. The second approach was based on a metaheuristics. While both approaches gave the same solution (which validated the heuristics model) the VBA one took almost three hours to run each single scenario. This means finding the optimal vehicle specification based on 25 technologies for each one of the three variations of fuel prices, for each one of the 4 goals required 12 runs for each duty cycle. In total this would require 108 hrs.; however, for each additional technology the calculation time doubled and if other

scenarios were produced (e.g. different MARR, different carbon emissions' prices) soon it become too time consuming to realistically execute the program with a desktop computer. The second approach, in contrast, took less than a minute to yield the optimal solution. This makes possible the production of different scenarios and sensitivity analyses fairly quickly. This also means that adding further technologies into the model increases the calculating time marginally. Unfortunately, the second approach uses a metaheuristics approach which means that despite that the runs gave the same results as the first approach; there is no guarantee that the algorithm will always yield the optimal solution. With heuristics approaches, there is no guarantee that the optimal solution is the best possible, as sometimes, the results represent a local optimum instead of a global one; however, the evolutionary approach combining scater search and tabu search improves the quality of the solution.

6.2.1 METAHEURISTICS MODEL

The heuristics model represents the state of the art on LCT for HGVs selection. Moreover, the results obey to specific driving cycles, vehicles and operating conditions. It is worthwhile to stress that it is not possible to produce a 100% exact result for this type of problem as just by changing the weight of the driver, fuel tanks loading or the weather conditions, the energy consumption of the vehicles change. Having said that, this framework represents the best approach to help decision makers to choose the optimal vehicle specification that meet their goals.

The model includes some synergies between technologies; however, not all the synergies have been simulated and modelled. The model considers the FCR of technologies in the 2015-2020 timeframe; however, it can deal with scenarios further into the future. It is more recommendable to run scenarios for the present time as there is less uncertainty regarding prices and the evolution of the fuel consumption reduction that a technology yields. Fuel prices are difficult to predict. The prices of innovative technologies depend on the cost of commodities (e.g. metals), currency exchanges rates and the amortisation of investments. Projecting the price of a particular technology 20 years into the future is unrealistic. If this is combined with the uncertainty of fuel prices, it seems a little bit superfluous to find out the best combinations of LCTs in the 2020 scenario or beyond (when the objective function is to minimise NPCs).

The application of the model has shown that using NPC instead of the payback period is a superior investment appraisal technique. In addition to the weaknesses discussed in the methodology chapter (e.g. time-value of money, returns beyond the payback period, and inclusion of rates of return), it has been found that when decision makers apply the payback period technique, they typically attribute a fuel saving to each technology individually, not noticing that the fuel saving of each one in combination with others is not linearly additive. For instance and taking as example a long-haul HGV, aerodynamic trailers improvements costing £3,000 can save around £4,333/year (payback 8.3 months), spray suppression mud flaps costing £172 can save around £664 /year (payback of 3.1 months) and lightweighting materials costing £1,486 can save £974/year (payback of 18.3 months). When all technologies are combined, the savings attributed to each one decreases to £4,174, £569 and £835 and as a result their payback periods increase to 8.6, 3.6 and 21.4 months respectively.

The issue of not considering the returns beyond the payback period is especially serious as the dimension of the savings is overseen. For example, a technology costing £100 saving £40 has a payback period of 2.5 years. Another technology costing £10,000 saving £3000 has a payback of 3.3 years. If the threshold to invest in technologies is 3 years, the first technology would be ordered while the second one would not. This would be a wrong decision. As the vehicle life is 5 years, the first technology would result in savings of £100 (over the remaining 2.5 years) while the second would result in savings of £5,000 (over the remaining 1.6 years).

The model considers a number of low carbon technologies that could be trialled now on HGVs. Other more futuristic technologies such as autonomous vehicles have not been included.; however, the National Research Council (2014) predicts that by 2030 these vehicles will reduce fuel consumption by 15-20% through more efficient driving patterns. Approaches that do not involve technologies that are fitted onto the vehicles have been excluded; however, their impact on fuel consumption can easily be added up to the results of the metaheuristics model. Examples of these include better axle alignment, keeping the vehicle properly maintained, training drivers on fuel efficient driving techniques, avoiding empty back hauling, improving loading factors, better routing and scheduling optimisation among other strategies. Longer and heavier HGVs were excluded as these were not suitable for the industrial sponsor.

The meheuristics model reports qualitative assessments of risk; however, the quantitative repercussions of fitting riskier technologies are excluded from the model. Higher levels of risk may lead to reliability issues and potentially more vehicles out of order. This may compromise time windows and the performance of logistics deliveries. The quantification of the impact of this potential outcome on NPC is beyond the objectives of this research. To conduct this type of study, it would be necessary to have historical data of technology reliability, which in the case of innovative technologies may not be available. Furthermore, suppliers may consider this information commercially sensitive and they may prefer not to release it.

6.2.2 TRIALING METHODOLOGY

Conducting real world trials for ascertaining the fuel consumption reduction of low carbon technologies is not a very effective approach. The main reason is that obtaining statistically significant results is very difficult conducting a small number of trips, as the confidence error is often higher than the percentage of fuel savings that are being measured. The conditions demanded in the SAE J1321 Type II methodology seem impossible to implement successfully on public roads. As explained in the methodology (section 4.3) and complemented in Appendix 9, this fuel consumption test procedure imposes very tight operational conditions. One major issue is that the maximum time between runs is 30 minutes. This was insufficient as uninstalling the fuel tanks to weigh them, take the tyre pressures and all the other readings from the ECU exceed this time. Additionally combining this with the statutory rests of the drivers (EU Working Time Directive) made this is even more challenging. Another of the requirements is that the difference between vehicles' travelling times must be less than 0.5% of the longest run in the warming trip and 0.25% in the next ones. This was very difficult to achieve on public roads for obvious reasons (e.g. congestion). Under test track conditions the likelihood to achieve the consistency required could improve; however, even if the vehicles have high precision flow meters, it would be necessary to count with very experienced drivers that can reproduce the driving cycles accurately and consistently between runs, and a team of at least 2/3 engineers to take the readings of the ECU, tyre air pressures and verify the validity of each trip (e.g. check test time constraints and weather conditions). Conducting trials on a dynamometer rig is not the solution either as the real driving conditions cannot be properly reproduced (e.g. gradient, turns, aerodynamics flows, etc.).

There are several tests that can be used to evaluate the efficiency of low carbon technologies. The ISO 28580 for instance is an accurate test for measuring tyres' rolling resistance; however, as each tyre manufacturer conducts these experiments independently, the machines (even when calibrated) can yield different results from one testing facility to another. This is common to all LCTs. A policy should be put forward for the creation of an independent body for the testing and validation of energy efficient technologies in the automotive sector. This body should test LCTs under different driving cycles and for each vehicle categories. This should provide greater transparency and it would make it easier for consumers to choose the most adequate technologies for them. The homologation of technologies is likely to be very expensive due to the amount of duty cycles and vehicle technologies; however, it would result in trustworthy values. Nowadays for example, tyre manufacturers advertise the energy band where their tyres fall into, but they do not give to their customers the exact rolling resistance coefficient of these. This goes against the best interest of the consumers, as having this exact figure would clearly indicate how much more efficient a tyre is, compared with another brand or model within the same energy band. Alternatively, developing simulation systems for vehicle type approval and technology fuel efficiency validation would be cheaper than trials, test bench or dynamometer tests. The outcome of these simulations could be used in the metaheuristic model to provide more tailored results. Attemps in this direction are being conducted by the EU via the VECTO program and in the USA with the development of the GEM simulation system.

In trials but also under regular operating conditions, there is a large error when measuring fuel consumption from ECU and telematics units (up to ±10% according to some vehicle and telematics manufacturers). Telematics data can support fuel consumption studies by providing GPS location of the vehicles (including the altitude as this is necessary to calculate and simulate roads' gradients). Statistically sound energy consumption studies should use a high precision flow meter; unfortunately, the cost of these is very expensive (over £1,000). The tonnage lifted by the vehicle is also a very useful data as this affects fuel consumption considerably; however, there are not many logistics operators who have a weighbridge on site. Using information from an ERP system as a proxy for weight transported is not accurate either.

6.2.3 SIMULATION METHODOLOGY

Simulations seem like a good approach for calculating the fuel savings achievable from specific technologies; however, this technique is probably beyond the technical capabilities of most logistics firms. This approach is better suited for vehicle and parts manufacturers, research centres and vehicle type approval bodies. Having a validated standardised simulation environment for testing technologies can reduce costs and improve the transparency and comparability of results under different driving cycles and vehicle categories. This in turn could decrease the perception of risk by enhancing the trust in vehicle and technology manufacturers and their fuel efficiency claims.

Three main types of simulations have been used in this research: simulations of individual technologies (e.g. aerodynamic fairings), simulations of whole vehicles (e.g. impact of weight reduction, speed limiters) and Montecarlo simulations for the sensitivity analyses. There are many software packages specialised in each type of simulation and their results do not always coincide. Calculating aerodynamic flows is computationally intensive and it is considered that wind tunnels are much more reliable; however, using these requires very expensive facilities. As it was reported, publicly funded whole vehicle simulation systems are under development in the USA (GEM) and the EU (Vecto). The literature indicated that GEM GHG emissions were 17% higher than the ones reported by VECTO. Improving these systems and making them accessible to the public would benefit the metaheuristics model developed in this research as it could be used to generate accurate inputs very economically. To use the values, the simulation developer should provide details of the technologies and components used in the vehicles, including fue consumption reductions, synergies with other subsystems and prices of the technologies, as these are fundamental parameters used in the metaheuristics model.

6.2.4 ANALYTIC HIERARCHY PROCESS

The metaheuristics model produces four solutions that optimise an objective based on a particular scenario. AHP uses pair-wise comparisons to score the four different solutions in each duty cycle, resulting in a ranking that best reflects the preferences of the decision maker. While in this case study the goals were related to net present costs, risks and carbon emissions, other organisations could choose different targets. Examples of these could include the impact of a particular technology on noise levels (e.g. TRUs PIEK noise standard), air quality, promotion of local employment, etc. At this point, the goals that may seem relevant to different organisations when ordering LCTs are unknown.

Ideally, to avoid cognitive bias, pair-wise comparisons should be the outcome of an internal discussion involving several people within an organisation. For example, an environmental manager may give more importance to GHG emissions than cost; a finance director may focus on reducing costs; a Health and Safety responsible may prioritise the risk of safety & limitations, an engineer may consider priority the risk of technology maturity, etc. The key point here is to understand that the results of the AHP are very sensitive towards the weights given and these will produce a very different ranking of choices depending on them.

6.3 POLICY RECOMMENDATIONS TO ENCOURAGE A GREATER LCT UPTAKE

This research set out to fill a knowledge gap by developing a framework where consumers can assess quantitatively the benefits of each particular technology according to the characteristics of their vehicles and operations and take a decision according to the objectives of their organisation. Given the large amount of LCTs, vehicle models and driving cycles, it is very difficult for companies to make rational investment decisions. Nowadays, there is little transparency regarding the testing standards and conditions under which each manufacturer reports the fuel savings of their technologies. There seems to be a need to produce global testing standards to facilitate the comparability of results between manufacturers of LCTs. Increasing transparency could eliminate one of the most notorious barriers regarding the adoption of more energy efficient technologies: the knowledge gap. Decision makers do not have independent fuel consumption information and methods to assess the investment in HGVs technologies systematically. This is of special interest to smaller companies, as they do not have the resources required to research all the technologies that may benefit them and conducting the trials to validate the claims of their suppliers

From a quantitative perspective, as shown in the results (section 5.4.4, page 260), if the Government would apply economic penalties associated with carbon emissions, these would have very little impact on the decision making process of LCT selection. The reason is that the main driver for technology selection is related to the fuel cost savings. Even in the case of long-haul HGVs emitting 595 t over 5 years, the potential penalty would be just a fraction of the total lifetime costs and it would be dominated by the cost savings, as the benefits from the fuel savings would be greater than just the benefits from lower carbon emissions taxation. As a reduction of fuel consumption is often aligned with a reduction of GHG emissions, companies drive for cost reduction results typically in lower carbon emissions. However, this is not the case when considering some refrigeration technologies, as some technologies use refrigerant gases with higher global warming potential than others. The cost of the technologies is also very important. More expensive technologies do not produce higher fuel savings (e.g. vacuum insulated panels cost £8,590 per year and they save just 5% of red diesel, while Hybrid TRUs save 11% and costs less than half). When combining LCTs there are diminishing returns; as getting a marginal improvement requires a considerable expense.

Policy measures are key to achieve a higher level of carbon reduction beyond economic considerations. In this line, the EU (see Appendix 3), UK (see

Appendix 4) and other countries around the globe are developing regulations, standards and support programs aiming to reduce GHG emissions. Examples of the impact of these on LCT development include the EU F-Gases regulations (European Commission, 2012b). These have steered the development of lower global warming potential (GWP) gases (e.g. R452, R744) that result in lower carbon transport refrigeration units. The modification of HGVs' weight and length regulations also focuses on reducing emissions of road haulage; the UK, for example, is conducting trials of longer combination vehicles DfT (2013a). Other areas where regulation is having a direct impact is related to fuel quality (e.g. Fuel Quality Directive) where the percentage of biofuel content on standard fuel blends is regulated.

However, it is in the USA where the topic of low carbon technologies for HGVs is being more regulated and more effort is being made to produce more transparent results in regards to the performance of LCTs. The Smartway program (Committee to Review the 21st Century Truck Partnership, 2015) for example offers consumers some degree of confidence in the performance delivered by certain energy efficient technologies, as all the homologated technologies included in the program must deliver a minimal FCR and follow a consistent testing methodology. This is fundamental to allow consumers to compare and contrast different options. Europe should follow the lead and include CO_2 mandatory average limits for HGVs in a new regulation or include some limits in the next Euro 7 emission standard.

One of the key factors that drive the selection of LCTs is fuel price. Forecasting fuel prices is very unreliable. For example, Brent crude oil prices declined by almost 60% in less than six months between the 20th of June of 2014 ($114.68/barrel) and the 13th of January of 2015 ($46.79/barrel). This decrease in fuel prices results in lower manufacturing and fuel costs which leads to lower capital and fleet operating expenditures. This negatively affects the intake of low carbon technologies as the fuel savings expected from these are much smaller and therefore their payback is longer. Policy actions are necessary to mitigate the impact of this volatility. There is consensus that climate change is a real issue and that oil reserves are dwindling, and therefore, there is a double reason to promote LCTs (environmental and geo-political), even in a temporary context of low oil prices like the one occurred in 2015. Considering this, regulations and economic policy instruments should promote the introduction of low carbon technologies. Examples of regulatory instruments include carbon quotas and compulsory carbon limits such as the ones promoted by fuel and vehicle efficiency standards such as the CAFE directives (Harrington and Krupnick, 2012) and the 'Phase 2 GHG

Emissions Standards and Fuel Efficient Standards for Medium –and Heavy-duty Engines and Vehicles' (US EPA et al., 2015) where fuel savings and GHG emissions of 20% and 24% by 2024 and 2027, respectively, will be compulsory. From this research it can be concluded that carbon pricing will not have too much impact in the selection of low carbon technologies (sections 5.4.4 and 0); there is though a trade-off. For carbon prices to change the optimal combination of low carbon technologies, these should exceed £200/t CO_2 eq. However, this is difficult to justify when the specific costs of the negative externalities associated with global warming are still unknown. High carbon taxation could severely affect the economic activity and competitiveness of nations. Other pricing policy instruments that could have a positive impact include increasing taxation of non-renewable fuels and refrigerant gases, as well as increase vehicle excise duty according to the emissions of the HGVs.

To promote research and development of innovative technologies, in the absence of a consumer market (e.g. due to a lack of infrastructure to service the technologies) research and innovation grants such as the Horizon 2020 EU calls create a nurturing environment. Fiscal policy instruments based on subsidisation, grants and discounted loans can also incentivise the uptake of greener HGVs fleets. Subsidisation of public refuelling infrastructure (e.g. biomethane / hydrogen / cryogenic gases), sustainable public logistic terminals (e.g. public-private partnerships) and creating mandatory green vehicle public procurement programs (e.g. post office fleets), can encourage further R+D efforts and create an initial demand that can lead to the development of a supply chain and the promotion of an energy efficient technologies' market.

Technology maturity is a critical barrier for the uptake of LCTs (section 6.1.6, page 289). Pneumatic boosters were trialled by 2009 and the literature suggested that this technology could reduce the fuel consumption of urban vehicles by 1.5% and regional and long-haul HGVs by 3.5% (Hill et al., 2011). Applying this assumption in the metaheuristics model, net present savings of around £5,000, £5,900 and £3,700 for urban, regional and long-haul vehicles over their life span were expected. This could represent savings over £675,000 over 5 years for the whole fleet. Because the technology cost was under £1,000 per vehicle, the cost could be quickly recovered. Unfortunately, according to the manufacturer (Knorr-Bremse AG, 2015) the technology was discontinued as there was no interest from the market. The reasons for this are unknown; however, Kay and Hill (2012) enumerates some key technology barriers to uptake of hybrid vehicles that may explain this (e.g. uncertainty over likely fuel cost savings, concern over residual values, reliability, payload reduction). The policy lesson is that Governments and manufacturers should work together to promote technologies that can really reduce carbon emissions cost-efficiently at least on the sectors of the economy where the range of solutions is rather limited. Examples of this include research hubs such as Hydrogen and Fuel Cell Research Hub (Stockford et al., 2015), the efforts from the UK Research Councils (e.g. EPSRC) and the Catapult centres (Catapult Programme, 2015). It would also project further transparency if an independent body would validate the savings delivered by innovative technologies, as this would reduce the risk perceived by the market.

Waste-to-fuel strategies present opportunities to reduce GHG emissions for the whole fast food supply chain, hedging against fuel price volatility and enhancing energy security. The role of policy makers is critical to establish a level playing field where some biofuels such as biomethane for transportation can compete with other uses. This is paramount when considering that the implementation of Euro 6 emission standards will make it more difficult to reduce GHG emissions of road haulage logistics fleets as engines cannot use biodiesel. As seen in Table 102, biomethane for transportation is clearly discriminated against, when it is used in transportation instead of in heating or electricity generation. This is very bad policy decision as biomethane is the only realistic alternative in the short term to substitute biodiesel/petrol HGVs, as it can deliver the performance and range needed and infrastructure can be deployed at a reasonable speed nationally. This is even more important when factoring in the air quality and climate change agendas. Assuming that diesel/biodiesel trucks air quality pollutants may be higher than expected due to the fact that vehicle official driving cycles are not representative of real driving conditions (Barlow et al., 2009), and assuming that newer Euro 6 engines cannot run with high concentration biodiesel, biomethane is one of the few fuel alternatives that can reduce air quality and GHG emissions. For this reason, if the negative discrimination of biofuels for transport is not correct, the only solution will be selling or using the biofuel in other elements of the supply chain (e.g. farms, factories) for heating, cooling and/or power generation where it is possible to take advantage of more favourable governmental incentives (e.g. feed-in-tariffs, renewable heating incentives) rather than the ones from renewable transport fuel obligations. This could also reduce the carbon emissions of the supply chain as a whole; however, the emissions from other components (e.g. production, storage) can be decreased more easily than GHG emissions from transport, as the former can rely on the percentage of renewables on the national grid.

Engine's manufacturers should also consider the potential for fuel production by British QSRs and realise that biodiesel can still play a huge role in the decarbonisation of the logistics sector and that more research and development should be carried out to overcome the technical challenges that Euro 6 brings and developing engines that can tolerate higher concentrations of biodiesel.

Table 102. UK Government support for biomethane in different sectors. Subsidies vary depending on plant size and year of installation. Adapted from: DfT (2014a).

Incentive	Heat	Electricity[26]		Transport[27]
	Renewable Heating (RHI)	Feed-in Tariffs	Renewables Obligation	Renewable Transport Fuel Obligation
£/MWh	£75 (<200kW)	£32.37-£53.06 (AD)	£0-£3.23 (landfill) £32.35 (AD)	£7.37-£26.47

At the same time, diesel and biodiesel as a fuel for transport seems to present challenges to many British and European local authorities trying to meet EU limits on air quality pollutants emissions. This research suggests that biomethane is a recommendable fuel for road freight as it supports both, air quality and GHG targets; however in the shorter term, while enough infrastructure is deployed, capital costs of procuring such vehicles go down and their engine reliability improves; biodiesel HGVs can still decrease GHG emissions considerably (depending on the risk seeking attitude of the buyers) cost-efficiently.

Lack of low carbon refuelling infrastructure is a common issue around the world; with exceptions in much localised areas where local governments have clearly supported specific technologies. For example in California and Japan, there is some hydrogen refuelling infrastructure(H2stations.org, 2015). BioDME research is being promoted in Sweden(BioDME, 2012). Electric recharging points are deployed at a large scale in the EU, being the Nederlands (Lebutsch and Weeda, 2011), France and Germany the countries with more recharging points (Chargemap.com, 2015). In the USA, where distances are larger and many HGVs stop overnight (on route) the deployment of electrified parking spaces is more common than in the EU. These vehicles use power from the grid and cooling and heating to avoid engine idling, reducing scope one emissions, for covering hotel loads (auxiliary equipment fitted on HGVs cabins such as heaters, air conditioners, TV, mobiles, air dryers, microwaves, etc.). Truck stop electrification providers include Shorepower, CabAire, IdleAir, AireDock and EnviroDock (Alternative Fuels Data Center, 2015).

[26] Assuming 35% efficiency from biomethane input to electricity output.
[27] Depending on the RTFC obtained from the different feedstocks and market values.

The lack of refuelling infrastructure and the low production of second generation biofuels are barriers for a higher market penetration of vehicles with lower carbon footprints. While the infrastructure for first generation biodiesel is fully developed, the production of second generation biodiesel is still marginal. The new EU waste policy proposal has set up an EU target for recycling 65% of municipal waste by 2030, with a legally binding target to reduce waste sent to landfill to 10%. This means that recycling will grow from the current 47% in the UK, 60% expected in the Nederlands by 2015 or the 50% in Sweden by 2018 (Climenhaga et al., 2013) until reaching the new EU goal. This means that biogas production will also increase and using green certificates, to buy biomethane from the national grid of natural gas instead of transporting it by road tankers, will decrease the carbon intensity this pathway. CNG refuelling stations are not cheap; Brightman et al. (2011) quoted £840,000 for a 10,000 kg/day station. Hydrogen refuelling infrastructure is extremely poor in the UK (basically a few pilot projects) as illustrated by H2stations.org (2015) and this is the case for most alternative fuels; with the exception of propane as illustrated by (US DoE, 2015b, Matvoz, 2015b) and advanced biofuels. The lack of infrastructure is perhaps one of the most important barriers for the success of non-conventional HGVs. Currently, there is no publicly available refuelling infrastructure for these fuels as there is no demand, and there is no demand because there is not enough infrastructure. In the initial stages of technology deployment, public infrastructure provision reduces the costs of ownership of the vehicles and favours sales. The same principle applies to cryogenic transport refrigeration units such as LAIR, LIN and CO_2. The amount of time that these vehicles can freeze cargo is limited and having refilling facilities on the major motorways could potentially extend the range of the vehicles. Bearing in mind that the UK government has set-up mandatory carbon reduction targets through successive carbon budgets, it makes sense that the government steps up and breaks this chicken and egg cycle by incentivising the deployment of alternative energy and cryogenic gases refilling infrastructure. Examples of this stimuli include financial support and other non-financial measures such as extended exploitation license periods. Alternatively, Lebutsch and Weeda (2011) suggests that providing an excise duty levy for a period of time can be considered as an indirect refuelling infrastructure cost gap and it can also bridge the cost gap between the incumbent and the new technology. Reducing the risks perceived by investors and customers is necessary to create a market. Some measures may result in missed revenue collected by the exchequer; however, one could argue that climate change's mitigation costs may be much lower than the costs derived from the negative effects of global warming (e.g. sea level rising, food and water crisis, extreme weather events, social unrest) and also as the IPCC (2014) found out much cheaper than the mitigation cost increases due to delayed action. However, economic related aspects are not the only barriers; there are as well technical challenges that need to be overcome (Ball and Wietschel, 2009, Dodds and Demoullin, 2013, Kay and Hill, 2012). Investment in research and development is critical to meet global warming targets.

6.3.1 HOW SHOULD SPENDING ON LOW CARBON INNOVATION BE PRIORITISED?

The outcome of the metaheuristics model for each scenario was a combination of low carbon technologies that optimised a specific objective function. Companies using similar types of vehicles and duty operations can extrapolate the findings (with caution) to help them to make their own procurement decisions. As explained in Table 66 (page 229), the scenarios were divided in five main area. The first one (S0) represented the do-nothing approach. The second group of scenarios (S1) minimised net present costs disregarding risks and reductions of carbon emissions; however, as there is a relationship between fuel costs and total costs, by minimising costs, often carbon emissions were also indirectly decreased. In the third scenario (S2), GHG emissions were also minimised, disregarding any risks and costs which in fact represented vehicles fitting all the feasible technologies that could reduce fuel consumption. The fourth scenario (S3) minimised costs allowing the selection of technologies that had been already trialled on fleets of HGVs. The fifth scenario (S4) minimised costs with technologies that were as safe and at least as little limited as incumbent technologies. The outcomes of such scenarios appeared in Table 101 (Page 285) where as it was stated that S1 was the group of scenarios with lowest costs, S2 the one with lowest emissions and higher risks, S3 was quite similar to S1 but with slightly smaller costs and carbon savings and S4 was the least risky solution. In all scenarios, the results indicated that there was still scope for reducing carbon emissions in diesel powered HGVs. By applying the qualitative multicriteria decision analysis the solution recommended for the industrial sponsor was S4; however according to the quantitative model this solution delivered £2.2M and £1.8M lower savings than S1 and S3, respectively and it underperformed all the other alternatives (excluding the do-nothing scenario) in regards to carbon savings with 19.7 kt, 22.4 kt and 18.8 kt higher emissions that S1, S2 and S3 respectively. By looking at the quantitative model, it seem obvious that S4 was the worse strategy; however, once qualitative factors were considered S4 was indeed the best. The reason is related to the aversion of risk from the industrial sponsor. Therefore promoting R+D, technology trials, helping LCT reach commercial stage and providing clear information regarding technology safety and developing supply chains and infrastructure to reduce technology limitations would allow the selection of technologies that could reduce costs and carbon emissions considerably. As part of these efforts, certifying the performance of energy efficient technologies by using realistic representative duty cycles could help to provide transparency regarding the reported FCR of each technology, a barrier also identified by Kay and Hill (2012). Independent programs for the promotion and diffusion of low carbon technologies could help decision makers choose the most cost-efficient alternatives; however, nowadays even companies using SAE J1321 Type II standard follow their chosen bespoke driving cycles. Higher standardisation and facilitating comparisons between technologies could benefit manufacturers that otherwise may end discontinuing technologies due to a lack of trust from the markets.

Due to the limitations of the thermal efficiency of diesel powertrains, much effort should be focus on decarbonising fuels. Increasing the energy yield of second generation biofuels and deploying refuelling infrastructure should be prioritised (as long as these biofuels also deliver reductions on air quality pollutant emissions). If electric powertrains and battery packs are developed for their use on long-haul HGVs, GHG emissions will not improve unless the national grid is decarbonised. For this reason, innovation on energy storage systems and the production of renewable power should be high in the policy agendas.

6.4 RECOMMENDATIONS FOR FUTURE RESEARCH

The framework developed in this research focuses on diesel HGVs and three main duty operations (urban, regional and long-haul). It is relatively easy to apply the mathematical models that make the framework for accommodating other vehicle categories and driving cycles. The metaheuristic model requires the update of the fuel consumption reduction (FCR) of each technology and their costs as well as the operating conditions of the vehicles. However, obtaining FCR values is complex as these require the development of trials or simulations. Undertaking trials for each technology is too expensive and impractical. Likewise, testing all the possible combinations is virtually impossible (as these are a function of 2^n, where ‘n’ represents the number of technologies). Simulating further HGVs and their technologies under different driving cycles is a time consuming task that seems better suited for large research organisations where cross-functional teams of engineers can work together to accurately reproduce different vehicles subsystems. Similarly, adapting the framework to another category of internal combustion LDVs and HDVs is fairly simple; however, obtaining the FCR for these, under their specific representative driving cycles requires supplementary analyses. This framework could be applied to light duty vehicles, urban buses and coaches, refuse trucks, military and off-road heavy duty vehicles with very minor changes on the models. Applying the methodology to rail seems feasible; however, substantial changes may be necessary as the technologies are different and the emission factors should be measured in ton CO_2 per passenger-km (the same applies to public transport HDVs or tonne-km in freight).

Adapting the metaheuristics model to accept other different fuel technologies and alternative powertrains such as biomethane, bioDME or battery electric (BEV) and fuel cell (FC) vehicles requires further research. Changes mainly affect powertrain technologies. The reasons are simple and include the different design of engines and transmissions. For example, the thermal efficiency of spark ignition and compression ignition engines is different and as a result, the energy that can be recovered from the exhaust may vary from one fuel to another (e.g. diesel vs. CNG). This may just require a different FCR value for a particular technology in the model. However, other alternative powertrains may require further changes. For example, fuel cells generate heat; however, this heat does not perform as an exhaust heat recovery system and therefore it does not improve engine's energy efficiency as there is an electric motor instead. The research will also need to consider that some powertrain technologies may not be compatible. Examples of this include heat recovery, electrical turbo compound and AMT with battery electric vehicles. With a battery electric powertrain (BEV), some alternative powertrain technologies included in the metaheuristics model such as electric and hydraulic hybrids become redundant. Unless breakthroughs on energy storage are developed, three phase alternator refrigeration units would not work with BEVs. Based on the methodology developed in this research, it is recommended to expand the current models including further vehicle types, technologies and duty cycles.

The multicriteria decision analysis model considers four goals. It is recommended to conduct a survey to ascertain the most sought objectives among different decision making organisations. The AHP was based on the sponsor organisation; however, other logistics firms may have different aims. It is very likely that these may differ to the ones determined by public policy makers or vehicle manufacturers. Finding this out, may result in the addition of other targets such as the impact on air quality pollution and noise from the low carbon technologies. The trade-offs between AQ and GHG emission agendas need to be considered when procuring environmentally friendly HGVs.

In the metaheuristics model it was assumed that the fuel consumption reduction of a combined number of technologies was the product of these; however it was recommended to assess the synergies of some combinations of technologies as their performance could be slightly different. For example, the aerodynamic effects of combining spray suppression mudflaps with undertray trailers and side skirts may require to assess them as packages according to the result of live trials. Similarly, the fuel savings of tyre pressure monitoring systems relates to conventional tyres; however, the synergistic impact when this technology is fitted on SWBT or low rolling resistance tyres was not specifically tested. Special attention may be paid to the synergies between technologies aiming to reduce AQ and those reducing GHG emissions. For example, active exhaust regeneration eliminates soot; however, it needs very high heat which increases fuel consumption and therefore GHG emissions. The synergies of some technologies may be simpler to model than others. For example, in this case, it may be sufficient with adding additional fuel consumption at specific intervals based on the number of expected regenerations during the life of the vehicle.

The impact of some technologies on noise levels is more evident in the case of TRUs as many of these are PIEK certified; however, researching other vehicle and powertrain technologies is also possible (e.g. tyres, turbo compound, and pneumatic boosters).

If further targets are added to the models, a further development could include the cost of the externalities of running HGVs. As the fuel consumption, mileage and technologies and refrigerant gases could be known, valuing the cost of air quality, GHG and noise emissions should be feasible.

HGV hire purchasing companies (e.g. vehicle manufacturers, leasing companies) do not benefit from the fuel savings that an optimal specified vehicle may yield. This results in a lack of incentive on their side to purchase more expensive vehicles fitted with LCTs as they may not be able to charge a higher rate to their customers. The only way for splitting the benefits for these companies is to increase rental quotas to their customers; however, this may prove difficult in a competitive environment were margins are so tight. Further complexity is added when considering that trailers can also be rented. Quantifying the fuel savings that the trailer technologies produce is difficult. Furthermore, as a trailer can be pulled by different tractors and the fuel savings are only enjoyed by the tractor owners, there is little motivation for trailer proprietors to invest in more fuel efficient trailers. It is necessary to research how to share the benefits between tractor and trailer owners when these are not owned by the same company. Financial leasing companies, on the other hand, can benefit from suggesting fitting LCTs in their HGVs as more expensive configurations lead to higher renenues and therefore profits for them. There is however a need to fully understand the risks associated to the technologies and maintenance costs. Leasing companies could use the framework here presented to advise their customers of the optimal vehicle specification and how this will reduce the net present total costs of ownership of their vehicles.

As the financial model is based on the leasing of a vehicle, end of life carbon emissions have not been included, as the leasing company recovers the vehicle after 5 years. Further research regarding the carbon emissions from vehicle manufacturing and disposal could enrich the model by providing a complete whole lifecycle carbon assessment. The US GREET model attempts to do something similar for cars. Further research is needed to quantify the energy needed to produce the vehicles and their parts, but also to recycle and dispose them.

A survey to ascertain how important is the perception of risk for the adoption of innovative technologies could provide interesting insights to the manufacturers of these energy efficient technologies. Velazquez Abad (2010) conducted a study regarding people's perception, attitude and awareness of hydrogen as a transportation fuel and found that there was little awareness of hydrogen and it was not perceived as risky. The knowledge gap of logistic firms regarding the risks of particular low carbon technologies is not well known.

The metaheuristics model considered qualitative risks related to technology maturity and the risk of safety and limitations. Quantifying economically the impact of those risks could add vital information for decision makers. It seems logical to think that innovative LCTs may present some reliability issues but the magnitude of this is unknown. Finding out the risk distribution functions that represent the reliability of each technology and combining these to forecast the likelihood of a vehicle breaking-out seems especially relevant to logistic firms, not so much for the cost of fixing repairs, but due to their impact on operations. It is common in the logistic industry to have on-time delivery targets embedded on service level agreements which may trigger penalties if the vehicles are out-of-order due to an innovative technology fails.

Further research is needed to find how minimising net present cost of HGVs could affect logistics costs and how this may impact modal shifts. One could argue that more fuel efficient fleets could improve brand image while reducing freight costs. Cheaper road haulage deliveries may shift demand from rail or short-sea trips to road. As road haulage becomes more competitive, higher demand should be expected, resulting on increased congestion levels. This may

increase travelling time for all road users. This may increase freight costs as drivers may spend longer hours working and further vehicles may also be needed to meet EU Working Time Directive Regulations and to meet time windows. This may increase GHG emissions, infrastructure wear and cause potentially, more road accidents. The relationship between greener road haulage demand and modal shift should be analysed using a complex systems analysis approach (e.g. agent based modelling).

In this research, it has been found that telematics fuel consumption data is very unreliable. It is not clear whether this is the outcome of the poor accuracy of the fuel measurement devices fitted on the vehicles tested or if this is related to the development of deficient ECU algorithms. One could argue that vehicle manufacturers under reporting fuel consumption could obtain a commercial profit by misleading customers and making them believe that the fuel consumption of their vehicles is better than it actually is. A market wide study should be conducted to verify that the data reported by telematics systems is in fact correct. This is also important as the pay of many drivers is related to their average fuel efficiency. Assessing the accuracy and variance of telematics systems could also send a clear message to logistics firms and policy makers that using telematics' fuel consumption for conducting serious statistical analysis is not a valid approach.

Little attention has been paid in the literature of energy efficient technologies for HGVs to refrigerated vehicles. Bearing in mind that refrigeration constitutes a significant percentage of the energy consumption of this sort of vehicles, future simulation systems such as GEM or VECTO should include them as a particular subset. This would entail a thorough research of the thermal needs of multi-temperature trailers in different geographical areas as well as the interactions of some of these technologies with powertrains. Linked to the study of the thermal differential between cargo freight and the ambient, a study of irradiance could also be used to revisit the topic of solar panels. With the deployment of smart grids, the improvements in solar panels efficiency and battery packs, solar panels installed on the roof of trailers could reduce the energy consumption of ancillary equipment, hotel loads and potentially provide cost efficient energy for chilling produce transportation. A survey of the number of hours that trailers spend on yards could also indicate the potential of using them in vehicle-to-grid systems to feed-in electricity to the grid providing an additional stream of revenue for logistics operators and/or trailers owners.

The calculation of the carbon emission factors of some fuels produced from waste and the quantification of the availability of these feedstocks was based on

the characterisation of the waste from a quick service restaurant chain and their distribution centres. A broader audit of further components of the upstream supply chain could show how much waste could be produced as a whole by each participant of the chain (from food producers and farmers to restaurants). Opportunities for waste minimisation may be revealed. It is necessary to evaluate a zero waste supply chain scenario to quantify how much fuel could be produced from waste in the future as this may affect the prices paid for these fuels and the emission factors of the different pathways. This study could also help the different organisations in the particular supply chain to develop a framework to share the benefits applying a shared approach to waste minimisation and the reuse of materials. For example, anaerobic digestion plants could be installed on an animal farm and the digestate could be used to enrich the soils where fields are cultivated. A logistics company may recover waste (e.g. paper, plastic, glass) for free but sell the this to a third party who may apply a discount when procuring virgin raw materials or fuels from other partners along the chain. How to manage all these logistics flows and how to share the rewards has not been fully explored. This research may also present further supply chain collaboration opportunities, including among other sharing refuelling infrastructure. Appendix 20 includes a potential framework to enhance collaboration to share refuelling infrastructure.

There is a need for the development of driving cycles that better represent the operations of urban, regional and long-haul freight delivery fleets. This is necessary not only to obtain more realistic vehicle fuel consumption and air quality emissions estimations during vehicle type approval tests but also to allow the reproduction of the conditions needed to simulate and homologate the fuel consumption reduction from LCTs. This would improve consistency and reliability of results.

The abundance of waste suitable to produce biofuels in the fast food supply chain and the incompatibility of Euro 6 engines with higher concentrations of biodiesel, presents an opportunity to use biodiesel on conventional transport refrigeration units. So far, some vehicle manufacturers allow the use of biodiesel on their machines but the service intervals of these decrease which results in higher operating costs. Researching materials that can perform well, working with biodiesel would reduce these operating costs. It is also recommended to conduct a survey to understand the current use of biodiesel in TRUs as there is no information available at all and the reasons for this alternative being so low. One would assume that as B100 for non-road use benefits from the same tax conditions as red diesel (mineral diesel has a fuel duty rate of 0.5795 £/l while the one of "Biodiesel for non-road use" is 0.1114 £/l) the reasons for not using

biodiesel might not be either financial or environmental. It is obvious that in terms of GHG emissions, scope 1 emissions from TRU could decrease by 99% by using B100[28].

The author acknowledges the limitation of the methodological approach for measuring the waste-to-fuels prospects. The quantitative analysis of 2,000 QSRs of a major food supply chain may not represent the waste profile of restaurants specialised in other types of take away foods. Future research could remediate this by surveying and conducting characterizations in other types of outlets.

[28] Emission factor (EF) for mineral diesel is 2.666 $kgCO_2eq./L$; EF of biodiesel B100 is 0.0195$kgCO_2eq./L$.

KEY MESSAGES FROM THE DISCUSSIONS, CONCLUSIONS AND RECOMMENDATIONS

- **The framework developed fills a research gap.**
- **The framework yields solutions that reduce costs and carbon emissions compared to the do-nothing scenario.**
- **Risks play a key role in the selection of the optimal vehicle specification by limiting the technologies that can be chosen and therefore not allowing the maximisation of cost and carbon emissions reductions.**
- **Over the lifetime of a vehicle, some technologies may reach maturity while others may be discontinued. The latter may affect vehicle reliability due to poorer maintenance alternatives.**
- **Discontinued technologies suffer from the knowledge gap and lack of trust from potential customers.**
- **The results from simulations and the live trial were consistent with the findings from the literature. Carbon emission factors were consistent with the literature; however, the amount of waste generated by the fast food supply chain was much higher than it had been reported in the literature.**
- **Some strategies such as reducing speed and filling the fuel tank with little fuel can save trip costs; however, when considering the whole organisation, the risks of breaching time windows may have the opposite effect.**
- **Live trials following SAE J1321 are too costly and rely on good weather. When conducted on public roads, congestion may invalidate whole runs.**
- **ECU/Telematics are very unreliable.**
- **Demonstrating the statistical significance of fuel savings from low carbon technologies requires a large number of trips under controlled conditions. This may be prohibitively expensive and probably only feasible by installing highly accurate flow meters.**
- **Biodiesel can deliver GHG emission targets by choosing lower carbon pathways.**
- **Lower fuel prices impact the demand of low carbon technologies.**
- **Waste management may lead to a competitive advantage (valuable resource).**
- **The demand for Euro VI HGVs will generate a surplus of biodiesel which will leave biomethane as the fuel with a realistic potential to reduce the GHG emissions of these fleets.**
- **Metaheuristics is a good approach for combinatorial optimisation (validated via VBA).**

- **Solutions are rather insensitive to carbon prices and MARR but very sensitive to fuels prices and mileage.**
- **Payback period is a flawed investment appraisal technique.**
- **AHP is accepted in the literature and it accepts interdependence (MAUT doesn't).**
- **There is much uncertainty regarding fuel prices, technology maturity and reliability.**
- **FCR from non technological approaches must be added to the findings of the quantitative model. E.g. axle alignment, keeping the vehicle properly maintained, training drivers on fuel efficient driving techniques, avoiding empty back hauling, improving loading factors, better routing and scheduling optimisation among other strategies.**

POLICY RECOMMENDATIONS

- **Bridge the knowledge gap. Regulate independent global testing standards to facilitate the comparability of results between manufacturers of LCTs (increasing transparency as a barrier for energy efficient technologies adoption).**
- **Include CO_2 mandatory average limits in the next Euro VII Emission Standard.**
- **Regulate a rising in the percentage of biofuels content in standard fuel blends (Fuel Quality Directive).**
- **Promote further research and development of innovative technologies (e.g. Horizon 2020).**
- **Implement fiscal policy instruments based on subsidisation, grants and discounted loans for the commercialisation of energy efficient vehicles.**
- **Enhance subsidisation of public refuelling infrastructure (e.g. biomethane / hydrogen / cryogenic gases). Extend exploitation licenses, implement an excise duty levy for the most efficient HGVs.**
- **Promote the deployment of sustainable public logistic terminals (e.g. public-private partnerships).**
- **Enforce mandatory green vehicle public procurement programs (e.g. post office fleets),**
- **Streamline energy policies to avoid the discrimination of some fuels in transport (e.g. biodiesel versus biomethane under FiT/RHI/RTFC).**
- **Enforce recycling of waste in industry to at least 65% by 2030. This could reduce waste and also enhance waste-to-fuel pathways.**

RECOMMENDATIONS FOR FURTHER RESEARCH

- **Apply the framework to light duty vehicles, urban buses and coaches, refuse trucks, military and off-road heavy duty vehicles, including further technologies and duty cycles.**
- **Conduct a survey to ascertain the most sought objectives among different decision making organisations.**
- **Assess the synergies of some combinations of technologies.**
- **Impact of some technologies on noise levels (PIEK certified).**
- **Could include the cost of the externalities of running HGVs.**
- **The knowledge gap of logistic firms regarding the risks of particular low carbon technologies. Quantifying economically the impact of those risks.**
- **Assessing lifecycle carbon emissions from vehicle manufacturing and disposal.**
- **The relationship between greener road haulage demand and modal shift should be analysed using a complex systems analysis approach (e.g. agent based modelling).**
- **Verify the correctness of telematics systems reported data.**
- **Demonstrate the effectiveness of driving assistance devices.**
- **Add multi-temperature TRUs to simulation systems such as GEM and VECTO.**
- **Investigate supply chain refuelling infrastructure collaboration opportunities.**
- **Investigate sharing of the benefits from more fuel efficient tractors and trailers between leasing companies, lessees, contractors, etc.**
- **Use of biodiesel on TRUs.**
- **Surveying and conducting characterizations in other types of QSR with a different waste profile.**

APPENDICES

APPENDIX 1 – INTERVIEWS WITH RELEVANT ORGANISATIONS

Table 103. Interviews with vehicle, trailers and parts manufacturers, fuel producers, waste and logistics companies and other relevant organisations in the area of energy efficient technologies.

Name of the Company	Position	Sector	Topic Discussed	Dates
Aerodyne	Sales & Marketing Manager	Aerodynamic devices manufacturer	Benefits, challenges, costs, safety of aerodynamic fairings	2013
Spraydown	Engineering Manager	Aerodynamic devices manufacturer	Benefits, challenges, costs, safety of spray suppression mudflaps	2013, 2015
AVL	Business Manager	Automotive engineering	Simulation of vehicles, SOFCs	2014, 2015
Hard Staff	Vehicle Applications Manager	Automotive engineering	Performance dual fuel engines	2014
Millbrook	Head of Sales	Automotive engineering	Costing and challenges of trialling low carbon technologies	2015
Ricardo	Chief Engineer	Automotive engineering	Discussion regarding alternative powertrains	2011, 2014
GKN	New business development manager	Automotive engineering (Flywheels)	Request for Information / Quotations	2015
Knorr-Bremse AG	Sales / Technical	Automotive engineering (PBS)	Request for information / quotation pneumatic booster system	2012, 2015
Cenex	Senior Technical Specialist	Consultancy	Analysis of statistically representative driving cycles. Outcome of biomethane trial.	2014
E4 Tech	Manager	Consultancy	Well-to-Wheel lifecycle GHG emissions analysis	2012
Joulevert	Head	Consultancy	Techno-economics of biomethane fleets and infrastructure	2011, 2013
Mint Green Sustainability	Trends analyst	Consultancy	Projects regarding biomethane fleets	2011, 2013
ENN	Business development manager	Energy	Deployment NG infrastructure	2013

Name of the Company	Position	Sector	Topic Discussed	Dates
Gas Alliance Solutions	CEO	Energy	Deployment NG infrastructure	2014
GasRec	Engineering Manager	Energy	Deployment NG infrastructure	2013
Shell	General Manager	Fuels	Roadmaps alternative fuels strategy	2012
Linde CryoPlants Ltd	Engineering Manager	Gases manufacturing	Cryogenic transport refrigeration gas infrastructure	2012
Kevothermal	Sales Manager	Insulation manufacturing	Request for information / quotation vacuum insulated panels (refrigeration)	2013, 2015
Southampton City Council	Principal public planner	Local authority	Alternative fuels refuelling infrastructure deployment roadmap. Flywheels low carbon technology trial plan.	2014
Saica	Area Manager	Paper Manufacturing	Combined Heat and Power fed by waste biogas from paper production process	2013
DPS Logix	Head of business development	Routing and schedulling software	Training	2011
Paragon Software Systems	Major Account Manager	Routing and schedulling software	Nexus routing and scheduling software and carbon emissions	2011-2012
IPG	UK Sales Manager	Simulation software	Technical traning simulation software (Truckmaker)	2010-2015
NREL	Senior Research Engineer	Simulation software	Analysis of statistically representative driving cycles (DRIVE Tool)	2012, 2013
Spectrum	Engineering Manager	Telematics	Reliability telematics systems	2014, 2015
Mix Telematics	DLD Support Manager	Telematics	Telematics protocols / SOAP	2012-2015
Eddie Stobart	General manager - Compliance	Third party logistics distribution	Outcome / challenges of low carbon technology trials	2012
Gist	Consulting Services Manager	Third party logistics distribution	Outcome / challenges of low carbon technology trials	2013

Name of the Company	Position	Sector	Topic Discussed	Dates
Howard Tenens	Estates Manager	Third party logistics distribution	Outcome / challenges of biomethane trucks ' trials and their infrastructure	2014
Martin Brower Ltd.	General manager	Third party logistics distribution	Outcome / challenges of low carbon technology trials	2013
Martin Brower Ltd.	Head of Schedulling	Third party logistics distribution	Technical challenges	2010-2015
Martin Brower Ltd.	Transportation Manager	Third party logistics distribution	Outcome / challenges of low carbon technology trials	2014
NFT	Technical director	Third party logistics distribution	Outcome / challenges of low carbon technology trials	2014
NFT	Fleet Engineer	Third party logistics distribution	Outcome / challenges of low carbon technology trials	2015
UPS	Automotive	Third party logistics distribution	Outcome / challenges of electric trucks ' trials and their infrastructure	2012
Cartwright	Sales	Trailer manufacturer	Discussion regarding multi-temperature refrigerated double decker trailers	2013
Gray & Adams	Sales	Trailer manufacturer	Discussion regarding multi-temperature refrigerated double decker trailers	2013
MarshallWeb	Key Account Manager	Transport Refrigeration Units Installations	Request for Information / Quotations Cryogenic CO2 TRU	2012, 2015
BOC	Senior pplications engineer	Transport Refrigeration Units Manufacturing	Cryogenic transport refrigeration units	2013, 2015
Frigoblock	Area Sales Manager	Transport Refrigeration Units Manufacturing	Request for Information / Quotations 3 phase alternator refrigerator	2013, 2015
The Dearman Company	Chief Executive	Transport Refrigeration Units Manufacturing	Request for Information / Quotations cryogenic air refrigerator	2015
Thermoking	UK Sales Manager	Transport Refrigeration Units Manufacturing	Request for Information / Quotations conventional TRU	2013, 2015
Continental	Sales	Tyre manufacturer / Automatic inflation systems	Request for Information / Quotations	2015

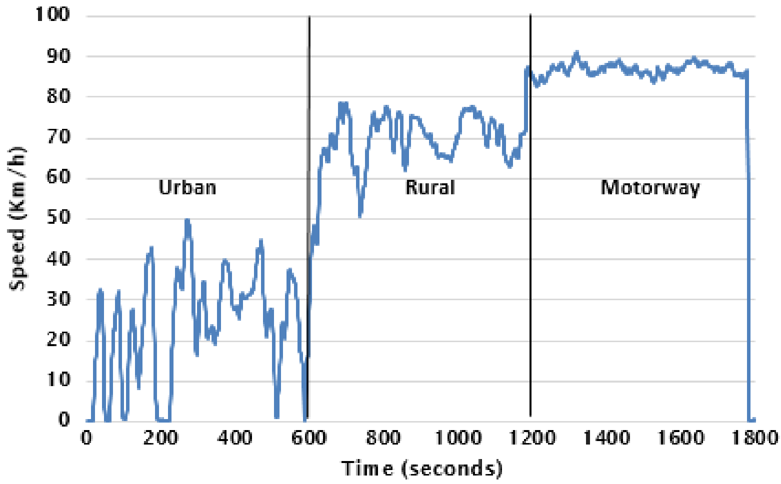
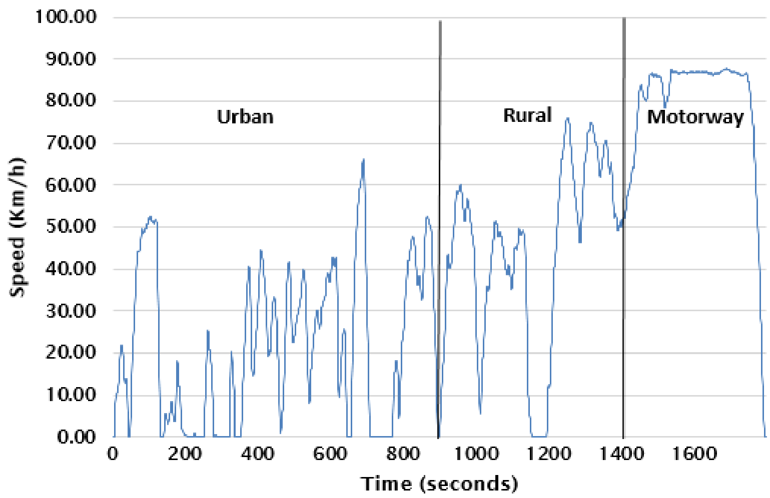
Name of the Company	Position	Sector	Topic Discussed	Dates
Iveco	Product manager	Vehicle manufacturing	Euro VI and biofuels (biomethane), technology roadmaps	2012, 2014
Man Trucks & Bus Ltd	Applications engineer	Vehicle manufacturing	Euro VI and biofuels (biodiesel), technology roadmaps	2013
Mercedes-Benz	Sales engineering manager	Vehicle manufacturing	Euro VI and biofuels (biodiesel), technology roadmaps	2013, 2014
Paccar / DAF	Sales director	Vehicle manufacturing	Euro VI and biofuels (biodiesel), technology roadmaps	2013
Scania	Sales Manager	Vehicle manufacturing	Euro VI and biofuels (biodiesel), technology roadmaps	2013
Terberg	Sales Manager	Vehicle manufacturing	Request for Information / Quotations electric trucks	2014
Vision Motor Corporation	Executive Vice President of Operations	Vehicle manufacturing	Hydrogen fuel cell heavy goods vehicles and infrastructure	2012
Volvo Trucks	Legislation and Environmental	Vehicle manufacturing	Euro VI and biofuels (DME), technology roadmaps	2013
HTC Reading	Service Manager	Vehicle service	Logistical challenges trials and technical characteristics vehicles	2014, 2015
Olleco	National Business Development director	Waste Management	Challenges regarding waste collections fractions (wasted cooking oil) and biofuel plants	2012, 2013

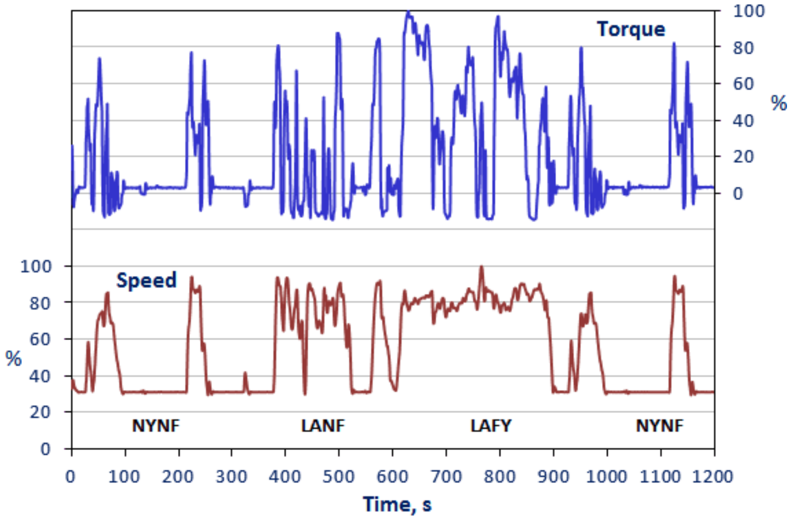
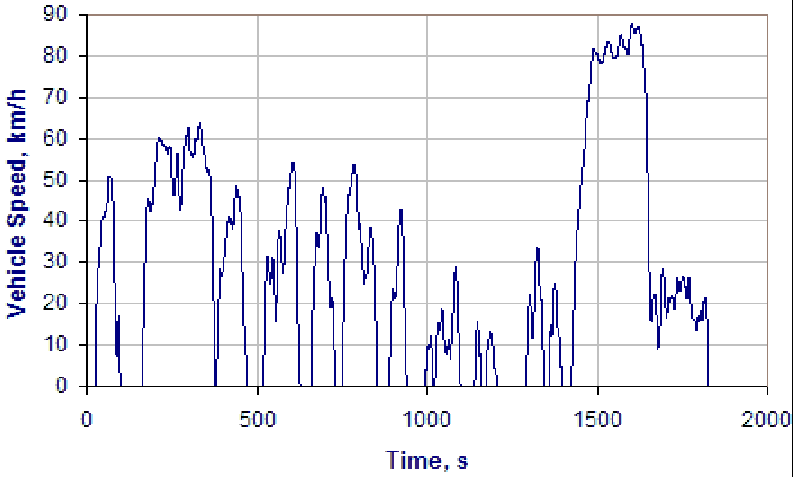
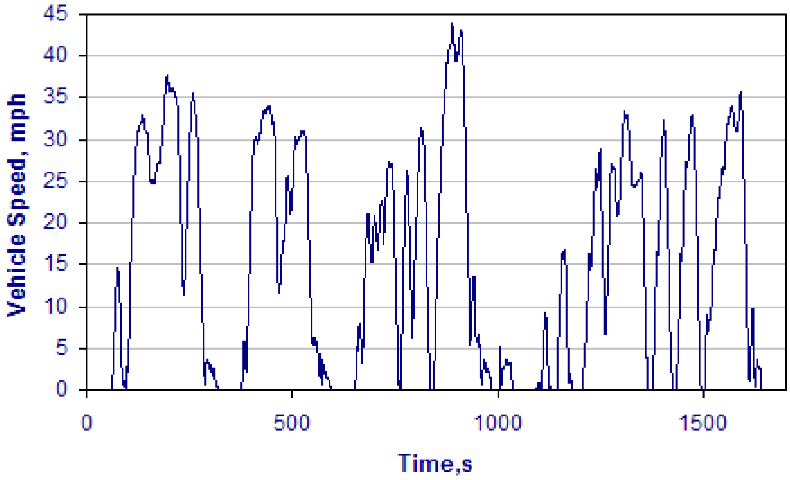
APPENDIX 2 – ILLUSTRATION OF SOME STANDARD DRIVING CYCLES

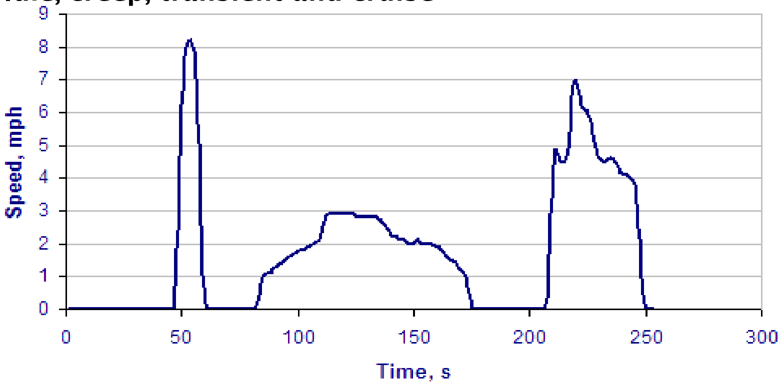
Table 104. Some drive cycles for testing on chassis dynamometer. Source:Ahlvik (2008).

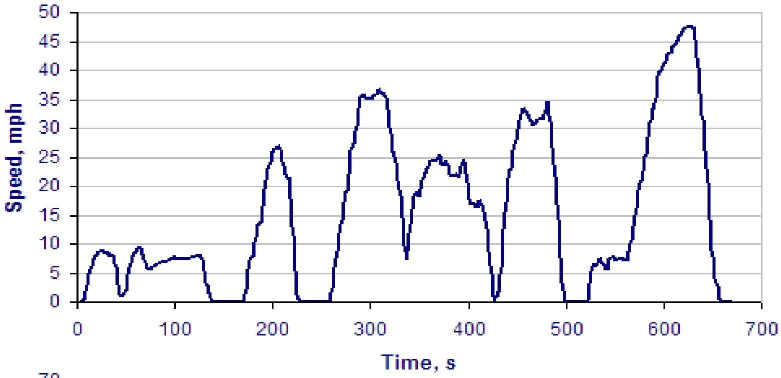
Driving Cycle	Driving distance (km)	Max speed (km/h)	Average speed (km/h)	Duration (s)	Description
Braunschweig city driving cycle	10,9	58,2	22,9	1740	A transient driving cycle for chassis dynamometer simulating urban bus driving with frequent stops.
European Transient Cycle (ETC), simulated on chassis dyn., FIGE	29,5	Urban: 50	Rural: 72 Motorway: 88	1800	Engine dynamometer test originating from vehicle loggings. The three different parts of the cycle includes urban, rural and motorway driving.
Central Business District (CBD)	3,22	32,2	20,2	560	This driving cycle represents a so-called sawtooth driving pattern, composed of repetitions with idle, acceleration, cruise and deceleration modes.
World Harmonised Vehicle Cycle (WHVC), whole test cycle	20,074			1800	The chassis dynamometer version of the proposed World Harmonised Duty Cycle (WHDC) for testing of heavy-duty engines.
WHVC urban	5,322	66,2	21,3	900	Urban part of the WHVC
WHVC rural	5,827	75,9	43,6	481	Rural part of the WHVC.
WHVC motorway	8,926	87,8	76,7	419	Motorway part of the WHVC. This cycle starts at a certain speed (not from stand still)
WHVC rural and motorway	14,752	87,8	59,0	900	Rural and motorway part of the WHVC.
WHVC selection	11,992	87,8	70,8	610	From of the WHVC test cycle, part of the rural and the whole motorway part were chosen.

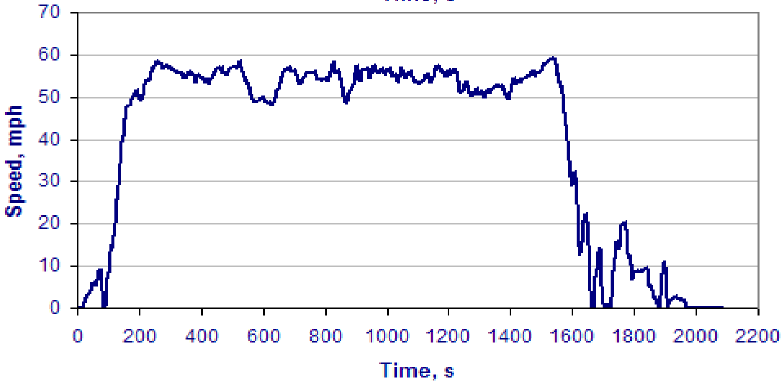
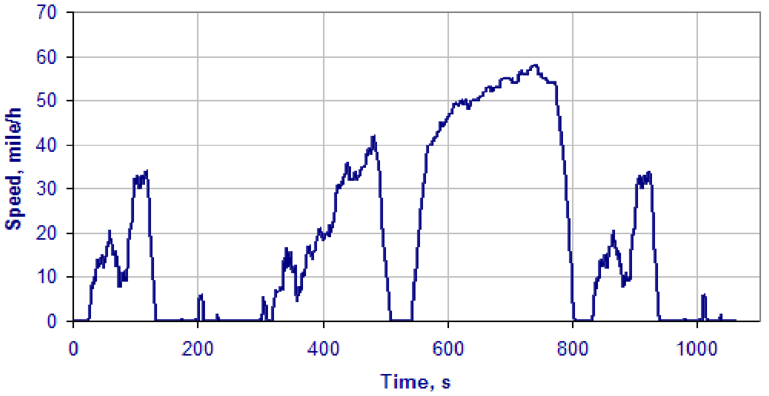
Ilustration of transient driving cycles for heavy duty vehicles. Except ETC and WHVC, the source of the other illustrations is Ecopoint (2013).

Name	Area	Shape
ETC (FIGE) (Regulatory for Euro V HDVs)	EU	 Urban: maximum speed of 50 km/h, frequent starts, stops, and idling. Rural driving average speed 72 km/h. Motorway average speed of about 88 km/h.
WHVC Similar to WHTC but used for research purposes		

FTP Transient (Regulatory)	**USA**	
JE-05 (Regulatory)	**Japan**	 **Average speed 26.94 km/h** **Maximum speed 88 km/h**
CSC	**USA**	**Suburban**  **Average speed 22.8** **Max speed 70.26**

<table>
<tr>
<td>HHDDT</td>
<td>USA</td>
<td>Idle, creep, transient and cruise





</td>
</tr>
<tr>
<td>HD-UDDS</td>
<td>USA</td>
<td>Urban


Average speed: 18.86 mi/h = 30.4 km/h
Maximum speed: 58 mi/h = 93.3 km/h</td>
</tr>
</table>

APPENDIX 3 – RELEVANT EU DIRECTIVES / REGULATIONS AND POLICIES RELATIVE TO GHG EMISSIONS FROM HGVs

Table 105. EU Level Policies that have been considered when evaluating technologies to build the mathematical model. Adapted from European Commission (2013c).

Energy Efficiency	
Labelling of tyres regulations	Regulation (EC) No 1222/2009
Energy Efficiency Directive	Directive 2012/27/EU

Power generation and energy markets	
Directive on the promotion of the use of energy from renewable sources ("RES Directive")	Directive 2009/28 EC

(Cross-sectorial) Climate policies	
EU ETS directive	Directive 2003/87/EC as amended by Directive 2004/101/EC, Directive 2008/101/EC and Directive 2009/29/EC and implementing Decisions, in particular 2010/384/EU, 2010/634/EU, 2011/389/EU (cap), 2011/278/EU, 2011/638/EU (benchmarking and carbon leakage)
GHG Effort Sharing Decision	Decision 406/2009/EC
F-gas Regulation	Regulation (EC) No 842/2006

Transport related policies	
Fuel Quality Directive	Directive 2009/30/EC
Regulation Euro VI for heavy duty vehicles	Regulation (EC) No 595/2009
Eurovignette Directive on road infrastructure charging	Directive 2011/76/EU
Directive on the Promotion of Clean and Energy Efficient Road Transport Vehicles (in public procurement)	Directive 2009/33/EC
End of Life Vehicles Directive	Directive 2000/53/EC
Mobile Air Conditioning in motor vehicles	Directive 2006/40/EC
Directive concerning social legislation relating to road transport activities	Directive 2009/5/EC

Environment and other related policies	
Landfill Directive	Directive 99/31/EC
EU Urban Wastewater Treatment Directive	Directive 91/271/EEC
Waste Framework Directive	Directive 2008/98/EC
Industrial emissions	Directive 2010/75/EU
Directive on national emissions' ceilings for certain pollutants	Directive 2001/81/EC
Substances that deplete the ozone layer	Relevant EU legislation implementing the Montreal protocol e.g. Regulation (EC) No 1005/2009 as amended by Commission Regulation (EU) 744/2010

APPENDIX 4 – RELEVANT UK LOW CARBON INITIATIVES

Table 106. UK bodies and research centres focused on reducing GHG emissions of HGVs.

Bodies / Main research centres	Details
DfT-Office for Low Emission Vehicles (OLEV)	OLEV was established specifically to position the UK as a world leader in the development, demonstration, manufacture and use of ultra-low carbon automotive technology.
Innovate UK (previously known as Technology Strategy Board)	Innovate UK is the new name for the Technology Strategy Board, a UK "innovation agency, accelerating economic growth" that funds, supports and connects "innovative businesses through a unique mix of people and programmes to accelerate sustainable economic growth". This body aim is to "Provide a single-point web resource area for all information about LCVIP competitions recent, current, and future. Provide online areas for organisations to network and consortia-build in preparation for their competition applications. Provide a discussion forum and interact with peers including being notified when peers have left requests for competition partners". The government's programme of research and development for low carbon vehicle technologies is delivered through the Technology Strategy Board's low carbon vehicles innovation platform (LCVIP). "The Transport Systems Catapult" has been established by Innovate UK to support innovation and integration of transport and its systems.
Energy Technologies Institute LLP (ETI)	"ETI delivers innovation from strategic planning to technology demonstration." Its aims are "Undertaking a systems integration approach to the future of vehicle design & vessel concepts • Developing and then demonstrating component technologies • Applying technologies to demonstration vehicles & vessels that are at least 30% more efficient"
The Centre for Sustainable Road Freight (CSRF)	"The focus of the Centre is to achieve deep reductions in CO_2 emissions from the road freight sector by combining highly-focussed vehicle engineering with systematic improvements to freight distribution".

Table 107. UK programs targeting low carbon technologies.

Programs
2015: £20 million low carbon vehicle R&D competition through "IDP 12: Seeding tomorrow's vehicle technologies today."
2015: "Developing advanced lightweight vehicles" up to £20m in "collaborative research & development projects to significantly reduce the mass of road-going vehicles".
2015: "Spearheading future electric vehicle battery production"up to £10 million in a single consortium to develop a pilot line to understand how to produce high-voltage electric vehicle batteries at a rate that can later be scaled up for commercial production.
2015: "APC4: Driving UK capability and economic impact through low carbon propulsion technologies"Investment of up to £60m in collaborative research and development funding to support the development of low carbon, low emission automotive propulsion technologies.
2015: £4 million to support the early deployment of publically accessible gas refuelling points for heavy goods vehicles (HGVs) across the UK.
2014: Low Carbon Vehicle Procurement Programme (LCVPP) The Low carbon vehicle public procurement programme, which ran from 2008 to 2014, was an example of innovation oriented procurement. It provided grant support to stimulate innovation, low carbon vehicle technology development and vehicle uptake by public sector fleets.
2013: "Plugged in Places"£30m infrastructure support, offering match funding to 3 to 6 locations in the UK to support an electric charging network. £8.8m has been allocated to the first round winners who are the North East, London and Milton Keynes.
2012: "Low carbon truck and refuelling infrastructure demonstration trial evaluation": £11.3 million funding to encourage and assist UK road haulage operators to buy and use low carbon heavy goods vehicles and supporting infrastructure.
2012: "Longer semi-trailer trial evaluation". The 10 year trial is expected to save 3000 tonnes of GHG emissions from up to 1,800 HGVs.
2009: Ultra Low Carbon Vehicle Demonstration Programme (ULCV) £25m for consortia to deliver low carbon vehicles to consumers across eight locations in the UK. Consortia bids bring together car manufacturers, power companies, Regional Development Agencies, councils and academic institutions.
2009: Fuel Cells and Hydrogen Demonstration Programme £7.2m for capital funding for a Fuel Cells and Hydrogen Demonstration programme.

APPENDIX 5 – GWP REFRIGERANT GASES

Table 108. GWP of different refrigerant gases and blends. Source: Ashford et al. (2006), Defra/DECC (2012) and Forster and G. Raga (2007).

Industrial Designation or Common Name (years)	Global Warming Potential for Given Time Horizon
	SAR‡ (100-yr)
CO_2	1
Methane	21[29]
Nitrous oxide	310
Substances controlled by the Montreal Protocol	
HCFC-22	1,500
HCFC-123	90
Hydrofluorocarbons	
HFC-23	11,700
HFC-32	650
HFC-125	2,800
HFC-134a	1,300
R-290	3.3
R-404A	3,260
R409A	444
R-502	4,657
R-503	4,692
R-507	3,300
R-507A	3,300
R-508A	10,175
R-508B	10,350
R-509A	3,920
R600A = Isobutane	0.001
R1234yf	4
R1234ze	6
Liquid Air (LAIR)	0
Liquid Nitrogen (LIN)	0

[29] The latest IPCC assumes that his value is 25.

APPENDIX 6 – DATA COLLECTION FLOWS

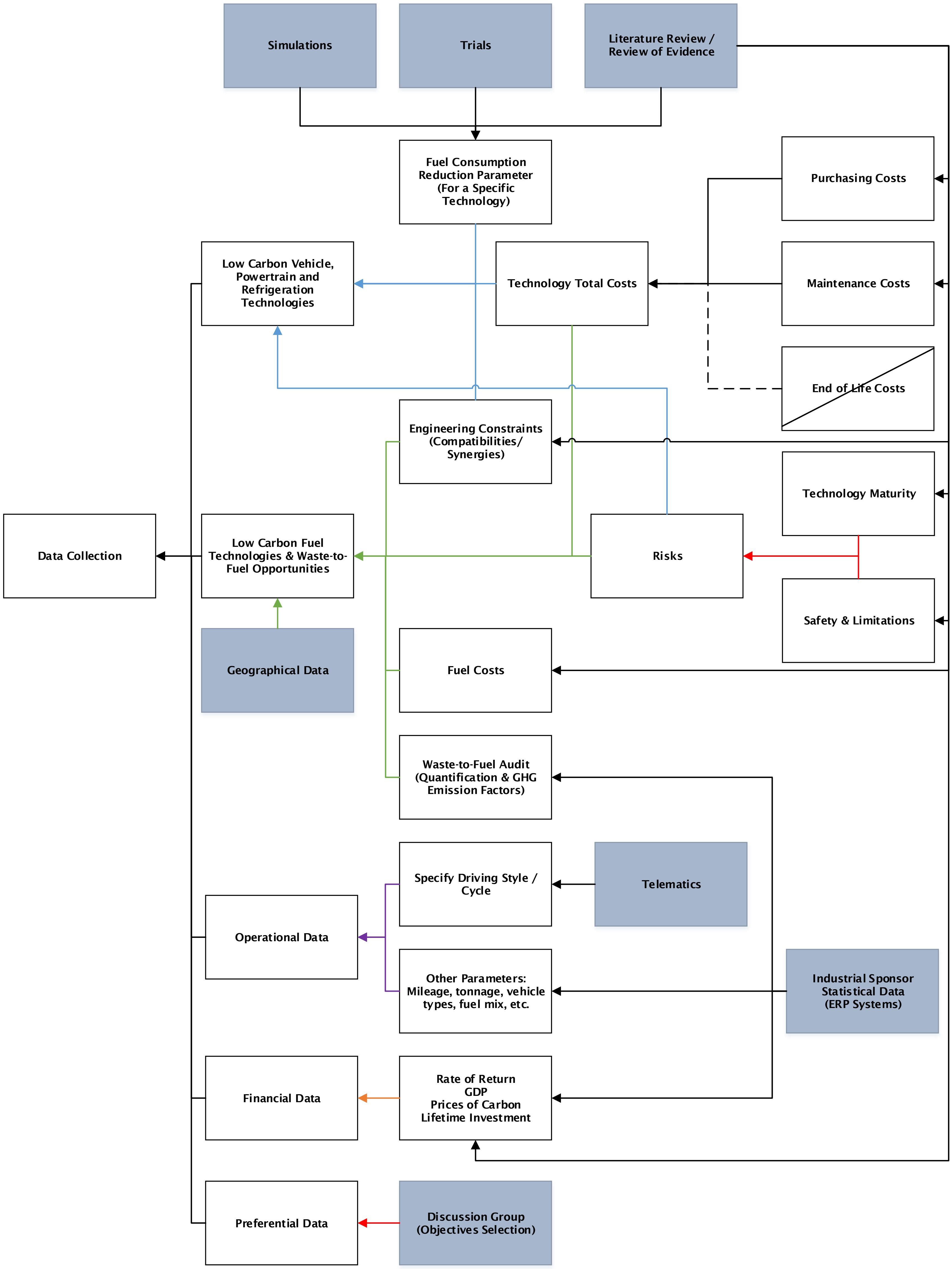
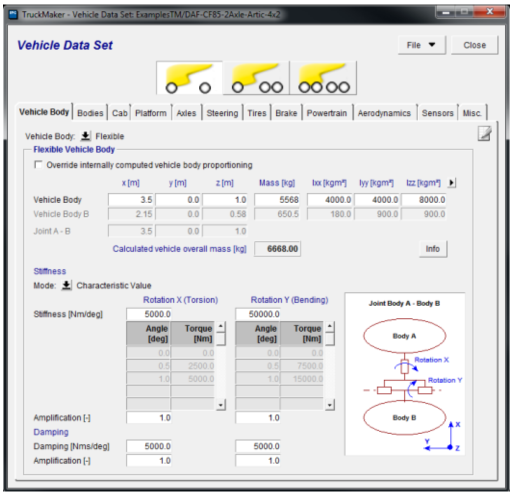
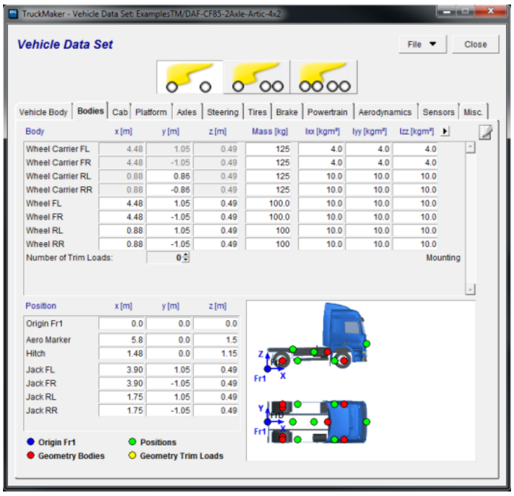


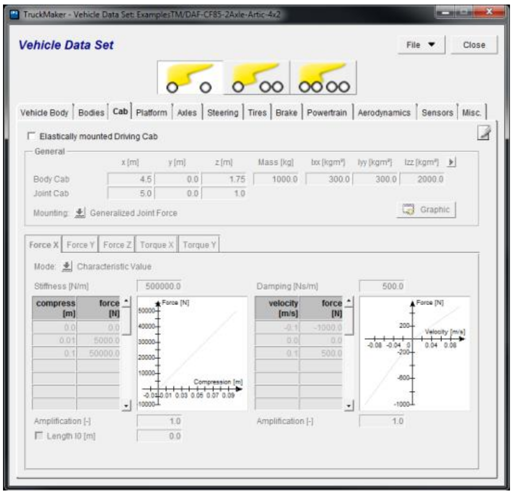
Figure 131. Data flows for data collection.

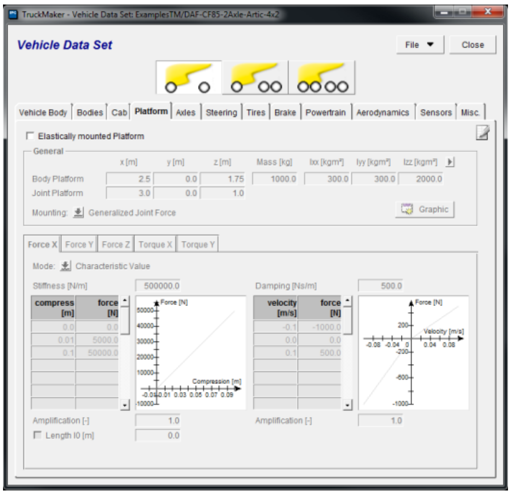
APPENDIX 7 – PARAMETERS SIMULATED VEHICLE

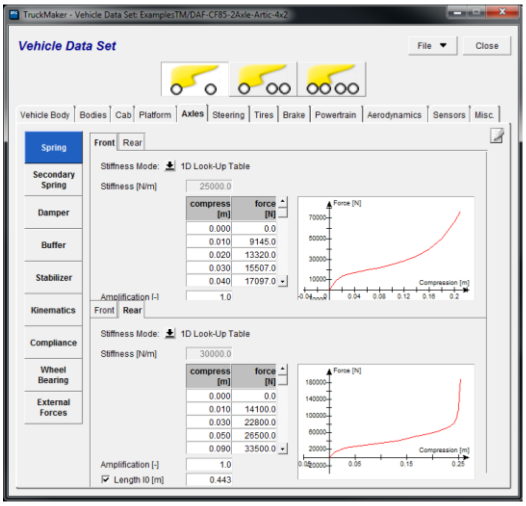
TRACTOR UNIT

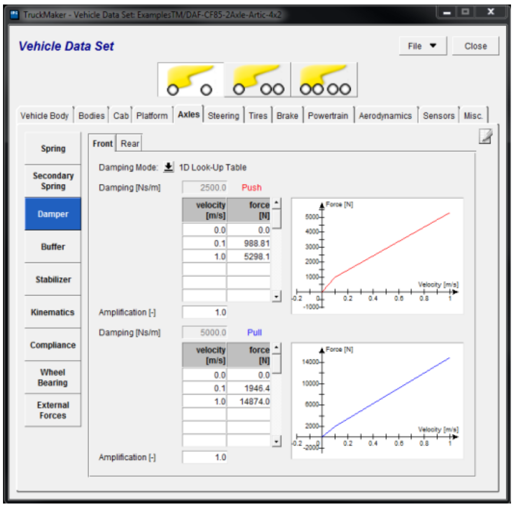


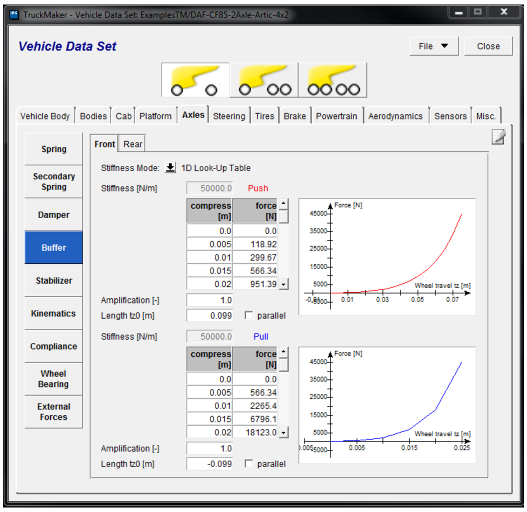


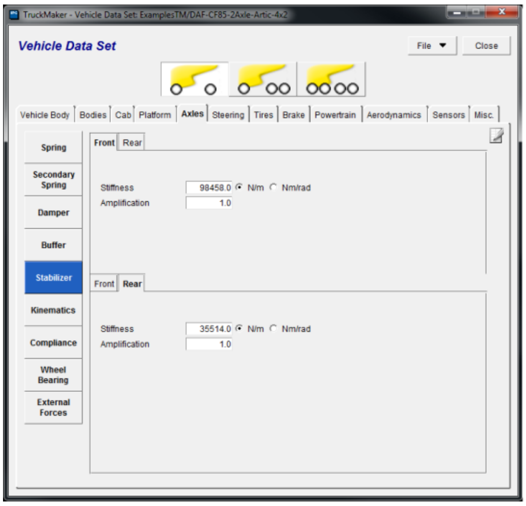


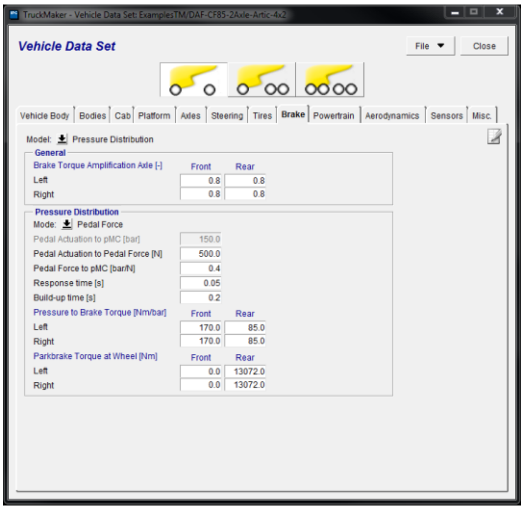


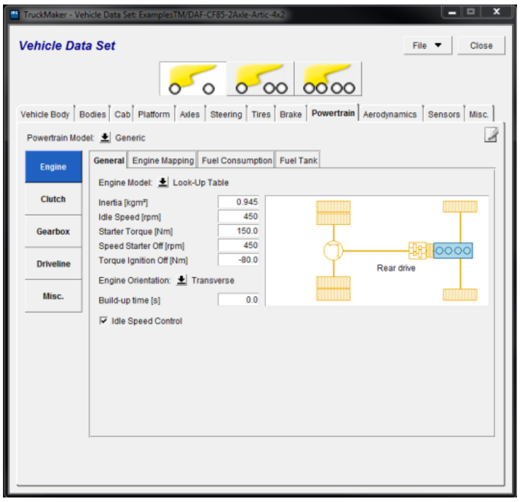


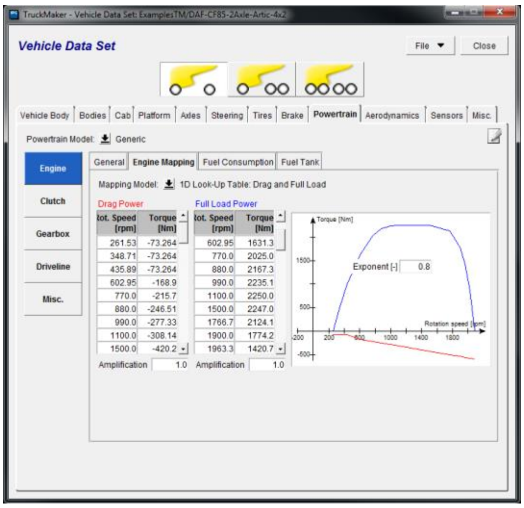


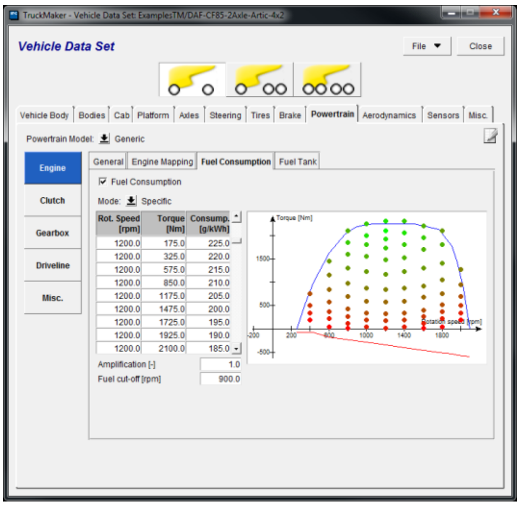

TruckMaker - Vehicle Data Set: ExamplesTM/DAF-CF85-2Axle-Artic-4x2
Vehicle Data Set
File
Close
Vehicle Body
Bodies
Cab
Platform
Axles
Steering
Tires
Brake
Powertrain
Aerodynamics
Sensors
Misc.
Spring
Secondary Spring
Damper
Buffer
Stabilizer
Kinematics
Compliance
Wheel Bearing
External Forces
Front
Rear
Stiffness Mode: 1D Look-Up Table
Stiffness [N/m]
Push
Pull
Amplification [-]
Length tz0 [m]
parallel

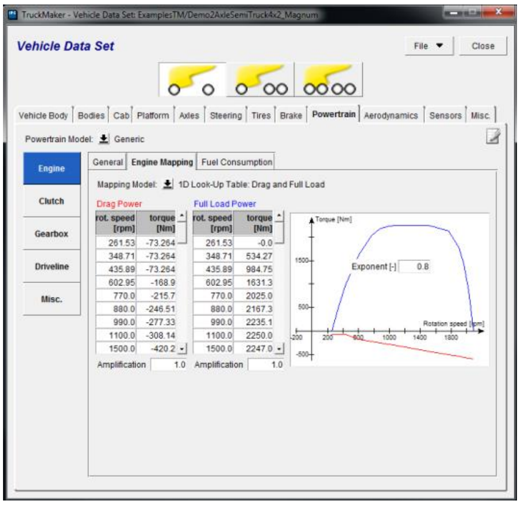

TruckMaker - Vehicle Data Set: ExamplesTM/DAF-CF85-2Axle-Artic-4x2
Vehicle Data Set
File
Close
Spring
Secondary Spring
Damper
Buffer
Stabilizer
Kinematics
Compliance
Wheel Bearing
External Forces
Front
Rear
Stiffness
Amplification
N/m
Nm/rad

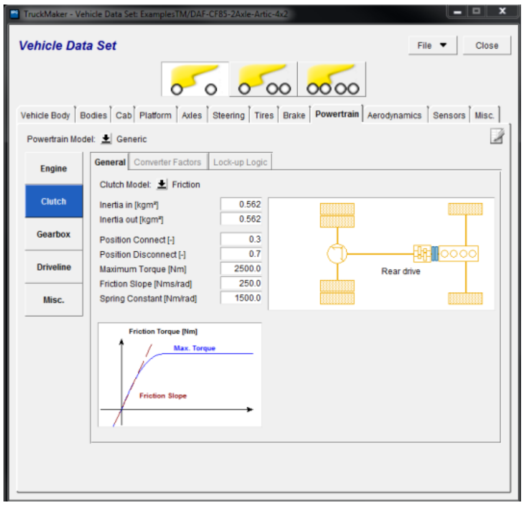

TruckMaker - Vehicle Data Set: ExamplesTM/DAF-CF85-2Axle-Artic-4x2
Vehicle Data Set
File
Close
Model: Pressure Distribution
General
Brake Torque Amplification Axle [-]
Front
Rear
Left
Right
Pressure Distribution
Mode: Pedal Force
Pedal Actuation to pMC [bar]
Pedal Actuation to Pedal Force [N]
Pedal Force to pMC [bar/N]
Response time [s]
Build-up time [s]
Pressure to Brake Torque [Nm/bar]
Parkbrake Torque at Wheel [Nm]

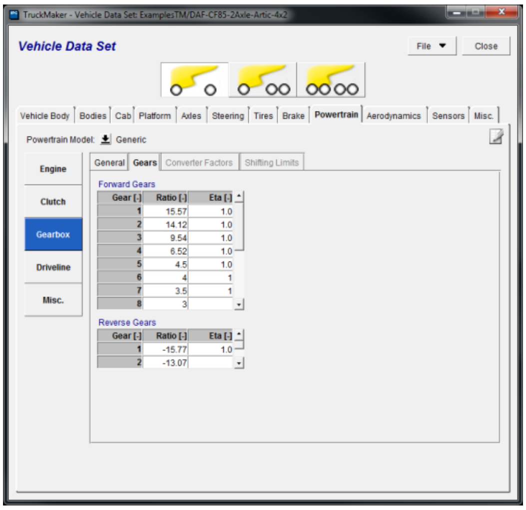

TruckMaker - Vehicle Data Set: ExamplesTM/DAF-CF85-2Axle-Artic-4x2
Vehicle Data Set
File
Close
Powertrain Model: Generic
Engine
Clutch
Gearbox
Driveline
Misc.
General
Engine Mapping
Fuel Consumption
Fuel Tank
Engine Model: Look-Up Table
Inertia [kgm²]
Idle Speed [rpm]
Starter Torque [Nm]
Speed Starter Off [rpm]
Torque Ignition Off [Nm]
Engine Orientation: Transverse
Build-up time [s]
Idle Speed Control
Rear drive

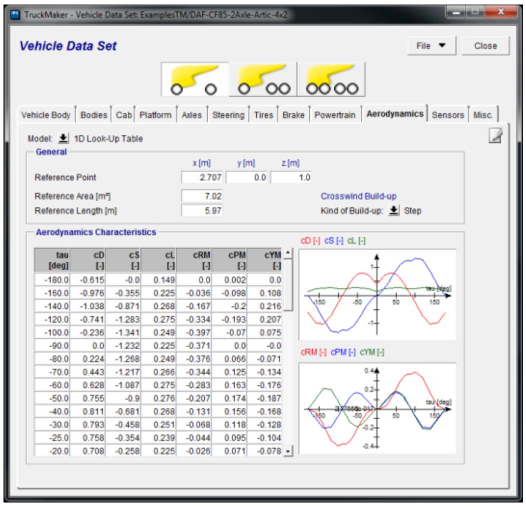

TruckMaker - Vehicle Data Set: ExamplesTM/DAF-CF85-2Axle-Artic-4x2
Vehicle Data Set
File
Close
Powertrain Model: Generic
Engine
Clutch
Gearbox
Driveline
Misc.
General
Engine Mapping
Fuel Consumption
Fuel Tank
Mapping Model: 1D Look-Up Table: Drag and Full Load
Drag Power
Full Load Power
Amplification
Exponent [-]


TruckMaker - Vehicle Data Set: ExamplesTM/DAF-CF85-2Axle-Artic-4x2
Vehicle Data Set
File
Close
Powertrain Model: Generic
Engine
Clutch
Gearbox
Driveline
Misc.
General
Engine Mapping
Fuel Consumption
Fuel Tank
Fuel Consumption
Mode: Specific
Amplification [-]
Fuel cut-off [rpm]

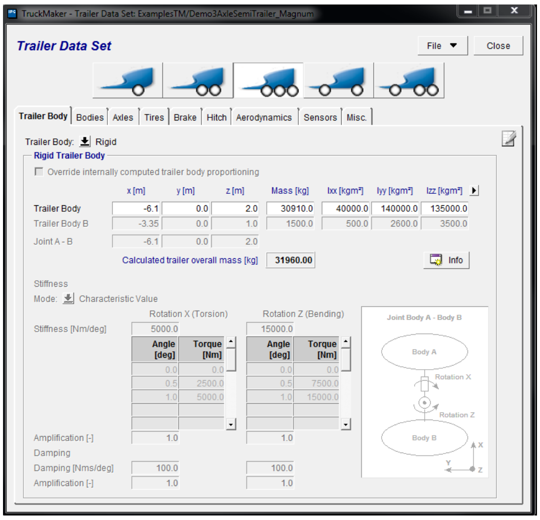

Vehicle Data Set
File
Close
Vehicle Body
Bodies
Cab
Platform
Axles
Steering
Tires
Brake
Powertrain
Aerodynamics
Sensors
Misc.
Powertrain Model: Generic
Engine
Clutch
Gearbox
Driveline
Misc.
General
Engine Mapping
Fuel Consumption
Mapping Model: 1D Look-Up Table: Drag and Full Load
Drag Power
Full Load Power
Amplification

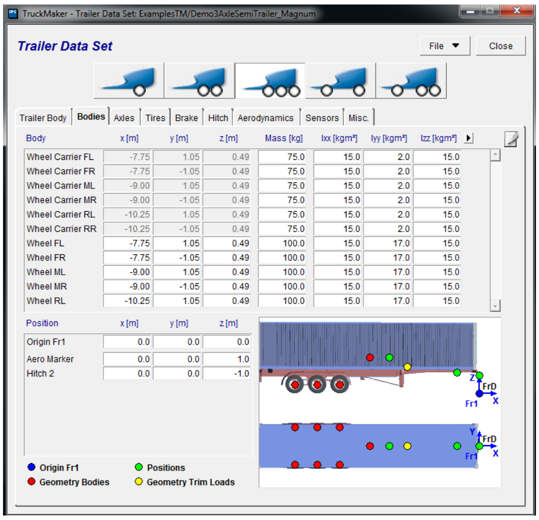

Vehicle Data Set
File
Close
Powertrain Model: Generic
Engine
Clutch
Gearbox
Driveline
Misc.
General
Converter Factors
Lock-up Logic
Clutch Model: Friction
Position Connect [-]
Position Disconnect [-]
Maximum Torque [Nm]
Friction Slope [Nms/rad]
Spring Constant [Nm/rad]
Rear drive
Friction Torque [Nm]
Max. Torque
Friction Slope

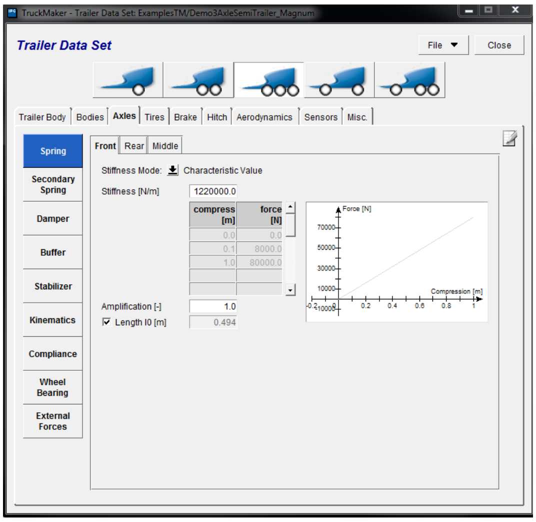

Vehicle Data Set
File
Close
Powertrain Model: Generic
Engine
Clutch
Gearbox
Driveline
Misc.
General
Gears
Converter Factors
Shifting Limits
Forward Gears
Reverse Gears

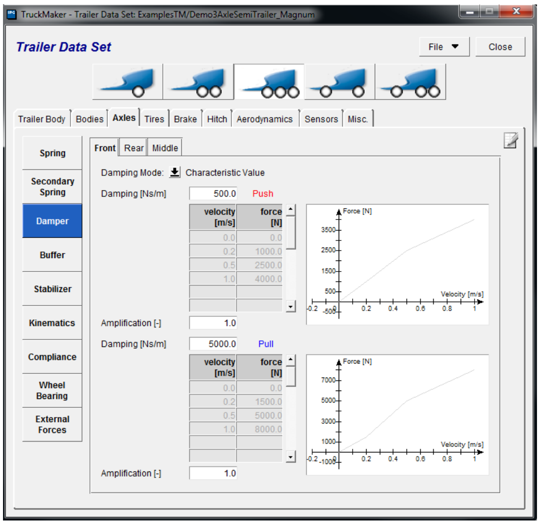

Vehicle Data Set
File
Close
Model: 1D Look-Up Table
General
Reference Point
Reference Area [m²]
Reference Length [m]
Crosswind Build-up
Kind of Build-up: Step
Aerodynamics Characteristics

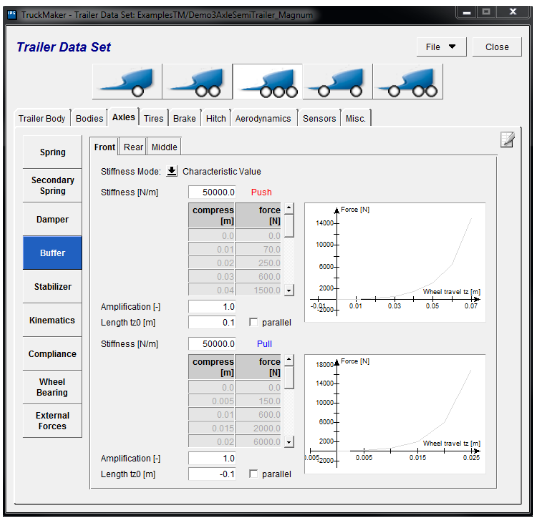
TRAILER UNIT

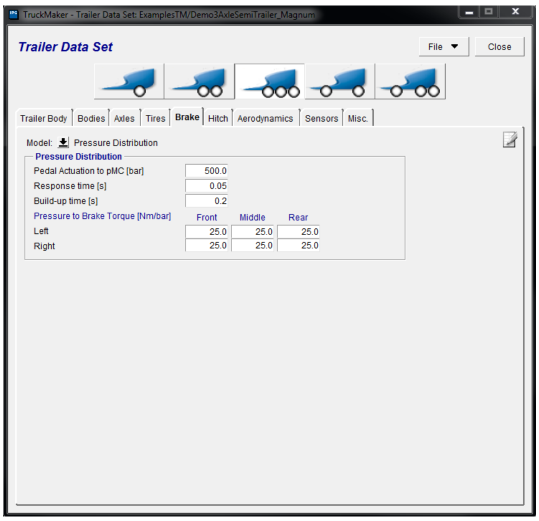


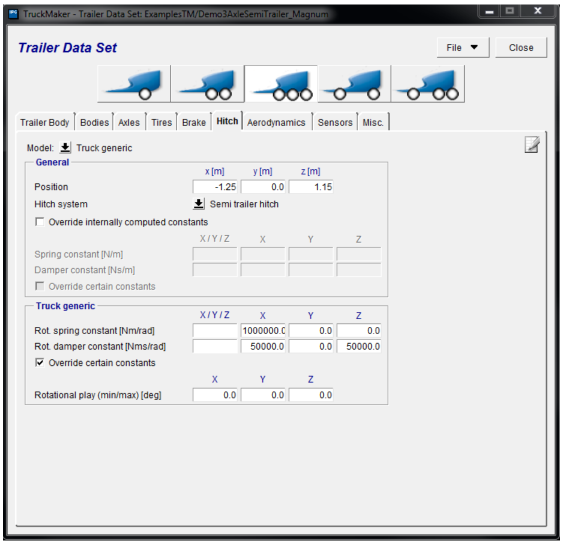


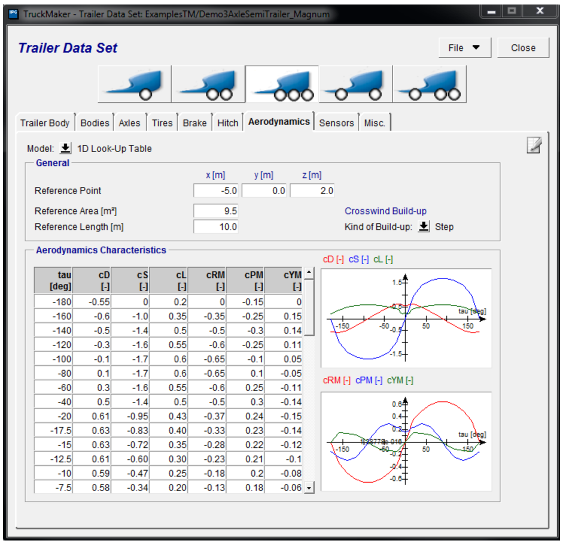









TruckMaker - Trailer Data Set: ExamplesTM/Demo3AxleSemiTrailer_Magnum
Trailer Data Set
File
Close
Trailer Body
Bodies
Axles
Tires
Brake
Hitch
Aerodynamics
Sensors
Misc.
Model: Truck generic
General
x [m] y [m] z [m]
Position -1.25 0.0 1.15
Hitch system Semi trailer hitch
Override internally computed constants
X / Y / Z X Y Z
Spring constant [N/m]
Damper constant [Ns/m]
Override certain constants
Truck generic
X / Y / Z X Y Z
Rot. spring constant [Nm/rad] 1000000.0 0.0 0.0
Rot. damper constant [Nms/rad] 50000.0 0.0 50000.0
Override certain constants
X Y Z
Rotational play (min/max) [deg] 0.0 0.0 0.0


TruckMaker - Trailer Data Set: ExamplesTM/Demo3AxleSemiTrailer_Magnum
Trailer Data Set
File
Close
Trailer Body
Bodies
Axles
Tires
Brake
Hitch
Aerodynamics
Sensors
Misc.
Model: 1D Look-Up Table
General
x [m] y [m] z [m]
Reference Point -5.0 0.0 2.0
Reference Area [m²] 9.5
Reference Length [m] 10.0
Crosswind Build-up
Kind of Build-up: Step
Aerodynamics Characteristics
tau [deg] cD [-] cS [-] cL [-] cRM [-] cPM [-] cYM [-]
-180 -0.55 0 0.2 0 -0.15 0
-160 -0.6 -1.0 0.35 -0.35 -0.25 0.15
-140 -0.5 -1.4 0.5 -0.5 -0.3 0.14
-120 -0.3 -1.6 0.55 -0.6 -0.25 0.11
-100 -0.1 -1.7 0.6 -0.65 -0.1 0.05
-80 0.1 -1.7 0.6 -0.65 0.1 -0.05
-60 0.3 -1.6 0.55 -0.6 0.25 -0.11
-40 0.5 -1.4 0.5 -0.5 0.3 -0.14
-20 0.61 -0.95 0.43 -0.37 0.24 -0.15
-17.5 0.63 -0.83 0.40 -0.33 0.23 -0.14
-15 0.63 -0.72 0.35 -0.28 0.22 -0.12
-12.5 0.61 -0.60 0.30 -0.23 0.21 -0.1
-10 0.59 -0.47 0.25 -0.18 0.2 -0.08
-7.5 0.58 -0.34 0.20 -0.13 0.18 -0.06
cD [-] cS [-] cL [-]
1.5
0.5
-0.5
-1.5
-150
-50
50
150
tau [deg]
cRM [-] cPM [-] cYM [-]
0.6
0.4
0.2
-0.2
-0.4
-0.6
-150
-50
50
150
tau [deg]

APPENDIX 8 – STATISTICAL ANALYSIS DRIVING CYCLE

Table 109. Statistical analysis of driving cycles of a limited sample of the fleet trips.

Cycle Statistics	Original	Representative Compressed Original	Difference from Original	Percent Difference from Original
absolute time duration (hrs.)	0.5	0.5	0	0
speed data time duration (hrs.)	0.5	0.5	0	0
non-recorded time (hrs.)	0	0	0	
data vs. absolute time ratio	1	1	0	0
maximum driving speed (mph)	56.6	56.4642	-0.1357	-0.2397
total average speed over cycle (mph)	36.6493	36.6550	0.0056	0.0153
average driving speed (speed > 0, mph)	36.6493	38.6746	2.0252	5.5261
variance of speed (mph)	318.1969	318.4793	0.2823	0.0887
standard deviation of speed (mph)	17.8380	17.8459	0.0079	0.0443
zero speed time (s)	0	94	94	65535
0+ - 5 mph time (s)	128	33	-95	-74.2187
5+ - 10 mph time (s)	51	51	0	0
10+ - 15 mph time (s)	122	124	2	1.6393
15+ - 20 mph time (s)	158	156	-2	-1.2658
20+ - 25 mph time (s)	115	114	-1	-0.8695
25+ - 30 mph time (s)	58	60	2	3.4482
30+ - 35 mph time (s)	24	24	0	0
35+ - 40 mph time (s)	62	58	-4	-6.4516
40+ - 45 mph time (s)	270	272	2	0.7407
45+ - 50 mph time (s)	217	219	2	0.9216
50+ - 55 mph time (s)	529	527	-2	-0.3780
55+ - 60 mph time (s)	66	68	2	3.0303
60+ - 65 mph time (s)	0	0	0	
65+ - 70 mph time (s)	0	0	0	
70+ - 75 mph time (s)	0	0	0	
75+ mph time (s)	0	0	0	
zero speed time (%)	0	5.2222	5.2222	65535
0+ - 5 mph time (%)	7.1111	1.8333	-5.2777	-74.2187
5+ - 10 mph time (%)	2.8333	2.8333	0	0
10+ - 15 mph time (%)	6.7777	6.8888	0.1111	1.6393
15+ - 20 mph time (%)	8.7777	8.6666	-0.1111	-1.2658
20+ - 25 mph time (%)	6.3888	6.3333	-0.0555	-0.8695
25+ - 30 mph time (%)	3.2222	3.3333	0.1111	3.4482
30+ - 35 mph time (%)	1.3333	1.3333	0	0
35+ - 40 mph time (%)	3.4444	3.2222	-0.2222	-6.4516
40+ - 45 mph time (%)	15	15.1111	0.1111	0.7407
45+ - 50 mph time (%)	12.0555	12.1666	0.1111	0.9216

Cycle Statistics	Original	Representative Compressed Original	Difference from Original	Percent Difference from Original
absolute time duration (hrs.)	0.5	0.5	0	0
speed data time duration (hrs.)	0.5	0.5	0	0
non-recorded time (hrs.)	0	0	0	
data vs. absolute time ratio	1	1	0	0
maximum driving speed (mph)	56.6	56.4642	-0.1357	-0.2397
total average speed over cycle (mph)	36.6493	36.6550	0.0056	0.0153
average driving speed (speed > 0, mph)	36.6493	38.6746	2.0252	5.5261
variance of speed (mph)	318.1969	318.4793	0.2823	0.0887
standard deviation of speed (mph)	17.8380	17.8459	0.0079	0.0443
zero speed time (s)	0	94	94	65535
0+ - 5 mph time (s)	128	33	-95	-74.2187
5+ - 10 mph time (s)	51	51	0	0
10+ - 15 mph time (s)	122	124	2	1.6393
15+ - 20 mph time (s)	158	156	-2	-1.2658
20+ - 25 mph time (s)	115	114	-1	-0.8695
25+ - 30 mph time (s)	58	60	2	3.4482
30+ - 35 mph time (s)	24	24	0	0
35+ - 40 mph time (s)	62	58	-4	-6.4516
40+ - 45 mph time (s)	270	272	2	0.7407
45+ - 50 mph time (s)	217	219	2	0.9216
50+ - 55 mph time (s)	529	527	-2	-0.3780
55+ - 60 mph time (s)	66	68	2	3.0303
60+ - 65 mph time (s)	0	0	0	
65+ - 70 mph time (s)	0	0	0	
70+ - 75 mph time (s)	0	0	0	
75+ mph time (s)	0	0	0	
zero speed time (%)	0	5.2222	5.2222	65535
0+ - 5 mph time (%)	7.1111	1.8333	-5.2777	-74.2187
5+ - 10 mph time (%)	2.8333	2.8333	0	0
10+ - 15 mph time (%)	6.7777	6.8888	0.1111	1.6393
15+ - 20 mph time (%)	8.7777	8.6666	-0.1111	-1.2658
20+ - 25 mph time (%)	6.3888	6.3333	-0.0555	-0.8695
25+ - 30 mph time (%)	3.2222	3.3333	0.1111	3.4482
30+ - 35 mph time (%)	1.3333	1.3333	0	0
35+ - 40 mph time (%)	3.4444	3.2222	-0.2222	-6.4516
40+ - 45 mph time (%)	15	15.1111	0.1111	0.7407
45+ - 50 mph time (%)	12.0555	12.1666	0.1111	0.9216
50+ - 55 mph time (%)	29.3888	29.2777	-0.1111	-0.3780
55+ - 60 mph time (%)	3.6666	3.777	0.111	3.0303
60+ - 65 mph time (%)	0	0	0	
65+ - 70 mph time (%)	0	0	0	
70+ - 75 mph time (%)	0	0	0	
75+ mph time (%)	0	0	0	

Cycle Statistics	Original	Representative Compressed Original	Difference from Original	Percent Difference from Original
total percentage	100	100	0	0
0+ - 5 mph distance traveled (miles)	0.0355	0.0280	-0.0074	-21.0300
5+ - 10 mph distance traveled (miles)	0.1086	0.1098	0.0012	1.1256
10+ - 15 mph distance traveled (miles)	0.4401	0.4491	0.0090	2.0557
15+ - 20 mph distance traveled (miles)	0.7834	0.7734	-0.0100	-1.2776
20+ - 25 mph distance traveled (miles)	0.7134	0.7056	-0.0078	-1.0931
25+ - 30 mph distance traveled (miles)	0.4371	0.4515	0.0144	3.2894
30+ - 35 mph distance traveled (miles)	0.2140	0.2144	0.0004	0.1882
35+ - 40 mph distance traveled (miles)	0.6631	0.6209	-0.0421	-6.3525
40+ - 45 mph distance traveled (miles)	3.1831	3.2044	0.0213	0.6695
45+ - 50 mph distance traveled (miles)	2.8240	2.8484	0.0243	0.8626
50+ - 55 mph distance traveled (miles)	7.9057	7.8747	-0.0309	-0.3917
55+ - 60 mph distance traveled (miles)	1.0161	1.0466	0.0305	3.0020
60+ - 65 mph distance traveled (miles)	0	0	0	
65+ - 70 mph distance traveled (miles)	0	0	0	
70+ - 75 mph distance traveled (miles)	0	0	0	
total distance traveled (miles)	18.324	18.3275	0.0028	0.0156
0+ - 5 mph distance (%)	0.1937	0.1529	-0.0407	-21.0423
5+ - 10 mph distance (%)	0.5929	0.5995	0.0066	1.1098
10+ - 15 mph distance (%)	2.4017	2.4507	0.0489	2.0397
15+ - 20 mph distance (%)	4.2754	4.2201	-0.0552	-1.2930
20+ - 25 mph distance (%)	3.8934	3.8502	-0.04316	-1.1086
25+ - 30 mph distance (%)	2.3856	2.4636	0.0781	3.2732
30+ - 35 mph distance (%)	1.1681	1.1701	0.0020	0.1726
35+ - 40 mph distance (%)	3.6186	3.3882	-0.2304	-6.36719
40+ - 45 mph distance (%)	17.3710	17.4846	0.1136	0.6538
45+ - 50 mph distance (%)	15.4113	15.5419	0.1305	0.8468
50+ - 55 mph distance (%)	43.1428	42.967	-0.1757	-0.4072
55+ - 60 mph distance (%)	5.5450	5.7106	0.1655	2.9859
60+ - 65 mph distance (%)	0	0	0	

Cycle Statistics	Original	Representative Compressed Original	Difference from Original	Percent Difference from Original
65+ - 70 mph distance (%)	0	0	0	
70+ - 75 mph distance (%)	0	0	0	
75+ mph distance (%)	0	0	0	
total distance traveled (%)	100	100	-1.98952E-13	-1.98952E-13
maximum acceleration (ft./s/s)	12.6133	4.5563	-8.0569	-63.8766
maximum deceleration (ft./s/s)	-13.2000	-12.5576	0.6424	-4.8666
average acceleration (ft./s/s)	0.6773	0.5383	-0.1390	-20.5282
average deceleration (ft./s/s)	-0.7738	-0.6022	0.1715	-22.1722
time spent accelerating (s)	794	904	110	13.8539
time spent decelerating (s)	695	808	113	16.2589
percent of time spent accelerating (%)	44.1111	50.2222	6.1111	13.853
percent of time spent decelerating (%)	38.6111	44.8889	6.2777	16.2589
total number of acceleration events	215	93	-122	-56.744
total number of deceleration events	220	93	-127	-57.7272
number of acceleration events per mile	11.732	5.0743	-6.6584	-56.7509
number of deceleration events per mile	12.0056	5.0743	-6.9313	-57.7338
average time duration per acceleration event	2.6930	8.7204	6.0274	223.8156
average time duration per deceleration event	2.1590	7.6881	5.5291	256.0837
total number of stops	0	5	5	65535
number of stops 0+ - 30 seconds	0	4	4	65535
number of stops 30+ - 60 seconds	0	1	1	65535
number of stops 60+ seconds	0	0	0	
number of stops per mile	0	0.3273	0.32737	65535
number of stops 0+ - 30 seconds per mile	0	0.2182	0.21825	65535
number of stops 30+ - 60 seconds per mile	0	0.0545	0.05456	65535
number of stops 60+ seconds per mile	0	0	0	
average stop duration (s)	0	11.8	11.8	65535
maximum stop duration (s)	0	34	34	65535
minimum stop duration (s)	0	2	2	65535

Cycle Statistics	Original	Representative Compressed Original	Difference from Original	Percent Difference from Original
variance of stops (s)	0	138.56	138.56	65535
standard deviation of stops (s)	0	11.7711	11.7711	65535
maximum kinetic power density demand (W/kg)	85.4176	30.8458	-54.5717	-63.8881
total kinetic power demand (W/kg)	2030.0940	1684.4511	-345.6428	-17.0259
average kinetic power demand (W/kg)	2.5567	1.8633	-0.6934	-27.1223
variance of kinetic power demand (W/kg)	5.0630	2.2674	-2.7956	-55.2157
standard deviation of kinetic power demanded (W/kg)	2.2501	1.5058	-0.7443	-33.0789
maximum kinetic power density regen (W/kg)	-88.8509	-61.0701	27.7807	-31.2667
total kinetic power regen (W/kg)	-2030.0940	-1684.4511	345.6428	-17.0259
average kinetic power regen (W/kg)	-2.9209	-2.0847	0.8362	-28.6299
variance of kinetic power regen (W/kg)	11.0643	8.1241	-2.9402	-26.573
standard deviation of kinetic power regen (W/kg)	3.3263	2.8502	-0.4760	-14.3108
maximum aerodynamic power density demand (W/rho/CD/FA)	8078.0646	8032.6501	-45.414	-0.5621
total aerodynamic power demand (W/rho/CD/FA)	6467623.238	6469802.19	2178.9516	0.0336
average aerodynamic power demand (W/rho/CD/FA)	3595.1213	3779.0900	183.9687	5.1171
variance of aerodynamic power demand (W/rho/CD/FA)	8123081.8	7456268.223	-666813.5769	-8.2088
standard deviation of aerodynamic power demanded (W/rho/CD/FA)	2850.1020	2730.6168	-119.4852	-4.1923
maximum rolling power density demand (W/kg/RRC0)	247.91321	247.4478	-0.4654	-0.18772
total rolling power demand (W/kg/RRC0)	289204.4598	289249.6773	45.2175	0.01563
average rolling power demand (W/kg/RRC0)	160.7584	168.9542	8.1957	5.0982
variance of rolling power demand (W/kg/RRC0)	6098.1488	4791.0267	-1307.1221	-21.4347
standard deviation of rolling power demanded (W/kg/RRC0)	78.0906	69.2172	-8.8734	-11.3629
maximum kinetic energy density (J/kg)	320.1073	318.5740	-1.5332	-0.4789

Cycle Statistics	Original	Representative Compressed Original	Difference from Original	Percent Difference from Original
average kinetic energy density (J/kg)	166.0085	166.0778	0.0693	0.0417
cumulative kinetic energy density change (J/kg)	-3.37508E-14	1.33227E-15	3.5083E-14	-103.9473
maximum aerodynamic energy density (J/kg/rho/Cd/FA)	8099.5045	8041.3816	-58.1228	-0.7176
average aerodynamic energy density (J/kg/rho/Cd/FA)	3593.4779	3594.5875	1.1095	0.0308
cumulative aerodynamic energy density change (J/kg/rho/Cd/FA)	-1.56319E-13	-5.5955E-14	1.00364E-13	-64.2045
maximum rolling resistance energy density (J/kg/RRC0)	248.1324	247.5374	-0.5949	-0.2397
average rolling resistance energy density (J/kg/RRC0)	160.6696	160.6942	0.0246	0.0153
cumulative rolling resistance energy density change (J/kg/RRC0)	1.42109E-14	0	-1.42109E-14	-100
characteristic acceleration (m/s/s)	0.06883	0.0571	-0.0117	-17.03892589
characteristic deceleration (m/s/s)	-0.06883	-0.0571	0.0117	-17.0389
aerodynamic speed (m/s)	20.9433	20.9451	0.0018	0.0090
kinetic intensity (1/km)	0.1569	0.1301	-0.0267	-17.0538
characteristic acceleration (ft./s/s)	0.2258	0.187	-0.0384	-17.0389
characteristic deceleration (ft./s/s)	-0.2258	-0.1873662	0.0384	-17.0389
aerodynamic speed (ft./s)	68.7116	68.7178	0.0062	0.0090
kinetic intensity (1/mile)	0.2525	0.2095	-0.0430	-17.0538

APPENDIX 9 – LIVE TRIAL DETAILS GIVEN TO THE INDUSTRIAL SPONSOR

Conditions, requirements and other relevant information of the low carbon trial that will be conducted on the agreed date. This trial follows the SAE1321 Type II protocol for measuring fuel consumption reductions from energy efficient technologies installed on heavy goods vehicles.

LOCATION

The trial will be conducted with two of Basingstoke's DC heavy goods vehicles. Please provide at your earliest convenience the number plates of such vehicles; this is of critical importance to proceed with the work required for the trial as the trials must be undertaken with the same vehicles on both trial days.

COSTS

The cost of fuel, equipment (GPS, flow meters, weather station, etc.) and their installation will be fully covered by the University of Southampton budget. MB will cover the labour costs of the drivers and other MB staff involved in the trial and it will provide two identical heavy goods vehicles to conduct the trial for two whole days.

VEHICLES

Identical vehicles are defined as having the same; external surface contours (preferably the same make, model and year), tyres and wheels (preferably the same type, condition, mileage and same tyre model per tyre position) aerodynamic configuration, power-train, and are in the same operational and physical condition. This includes same load and cargo weight distribution. If the odometer on both vehicles is greater than 30,000 miles (48,300 km) they can be compared; otherwise, if the odometer difference is between 10k and 30k, the difference between odometers must be within 10k miles of each other.

DEVICES TO INSTALL

A serial logging device will be fitted in the vehicle to record telematics data. This device will be purchased and installated by the University of Southampton researcher.

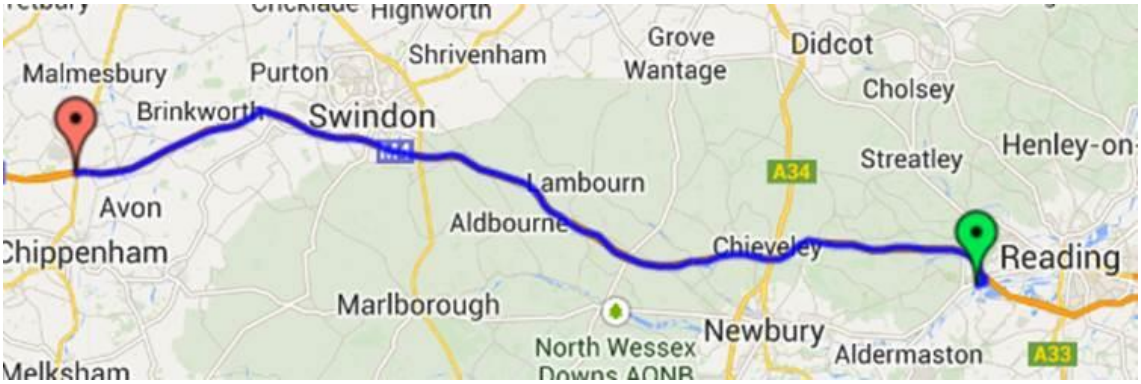
STAFF

Drivers will be trained to participate in the trial. Drivers should be sufficiently skilled so that test results are not affected by the driver's technique during the test period. All drivers shall be interviewed after each run and their comments noted. Drivers shall remain with their vehicles for the complete test. MB's Fleet Engineer in Basingstoke will be the interliassion in regards to staff matters.

RUNS

The experiment comprises two phases. The first phase (calibration) will consist of three "calibration runs" of 101 miles each, with 2 vehicles running simultaneously and at a distance of no less than 800 feet (243.8 m) to minimize traffic interference between both vehicles. Day one will consist of tree round trips per vehicle between Theale and Stanton St Quintin (Chippenham). The second trial (test trial) will consist of tree "test runs" of 101 miles each with the same 2 vehicles running simultaneously over the same baseline segment; however, one vehicle will include the "Spraydown" mud flaps that are being tested. In each run, the driving cycle of both vehicles must be the same and therefore the difference in time between both vehicles to complete each run must be less than 0.5% of the longest run time. The runs will be conducted with no rain.

The total distance covered will be the sum of the 3 calibration runs x 101 miles + 3 test runs x 101 miles = 606 miles x 2 vehicles = 1,212 miles (1,950 km).



The Control and Test Vehicles must be fuelled from the same dispenser (fuel source) during the entire test to insure consistent fuel grade and quality. Before starting the trips on each phase, both vehicles have to circulate for 1 hour to warm up. Before starting the trial, the vehicles will depart from Basingstoke DC to the workshop in Theale and from there to the vehicle weighting facility.

Parameter readings will be taken at the warm-up stage, between runs and at the end of the test day. These parameters include: Oil pressure and leaks; Brake air system leaks; coolant temperature and leaks, exhaust gas temperature; engine air filter restriction, electrical load, tyre pressures; brake dragging (i.e. temperature); exhaust smoke; observed ability to maintain selected test speed; transmission or differential leaks; intake manifold pressure (turbocharger boost) and other intake system losses; number and duration of DPF regeneration events. After the treatment condition, the state of DPF loading and regeneration state, drivers should note the dash displays that indicate or broadcast the regeneration state or a DPF illuminated before keying off after warm up; Check/investigate all vehicle diagnostic caution and warning signals/alarms and resolve all vehicle operational concerns prior to proceeding with the test. Some of the parameters will be compared with the results of telematics data as discussed with the telematics service provider (Mix Telematics).

The maximum time between runs is 30 minutes. If the 30 minutes window is exceeded, the vehicles must be put through a warm up process. Other operational details will be instructed to the drivers. Examples of these include: Cold tyre pressure measured and inflated to vehicle or tyre manufacturer standard within a tolerance of ±1 psi (6895 Pa); Prior to the initial Run all vehicles must be checked for mechanical malfunction that would affect test results.

The difference in time for the Control and Test vehicles to complete the first Run in the Baseline Segment shall be less than 0.5% of the longest Run time for the vehicles. For example, if the Control Vehicle takes 1 h to complete the first run and the Test Vehicle(s) require less time to complete their first run the Test Vehicle(s) must have completed their first run within 18 s of the Control Vehicle Run time. Time for each vehicle to complete all subsequent Runs in the Baseline Segment must be within ±0.25% of the time for that specific vehicle to complete its first Run in the Baseline Segment.

Fuel consumption will be statistically analysed to ascertain that the fuel consumption reduction achieved by the low carbon technology being tested is statistically significant.

APPENDIX 10 – DATA COLLECTED FOR REAL WORLD TRIAL (FOLLOWING SAE J1321)

Table 110. Form D0 Reporting.

Test facility name and location and test date and time	HTC, RG7 4AG to SN15, 30/09/2014 – 25/11/2014
Test track drawing and dimensions	168.2 km
Test track weather data collection sites location and dimensions	Theale, Chippenham
Vehicle (truck and trailer) manufacturer, model, and year	DAF CF85.410/2013 Euro V.
Vehicle (truck and trailer) dimensions (length, width, height)	TRACTOR 5.75 x 2.49x3.51 TRAILER Gray&Adams
Engine manufacturer, model and EPA level	Paccar 410 Hp (300 kW)
Photographs of each vehicle (truck and trailer) configurations	Done
Photographs of each vehicle at test site	Done
Description and dimensions of vehicle modifications under investigation	30/09/2014 Calibration Day, no modifications. 25/11/2014 Spraydown Spray Suppression Mudflaps
Photographs of vehicle modifications under investigation	Done
Time history plot of all weather conditions during test	Done
Test duty cycle description	Bespoke Motorway

Table 111. Form D1-Part 1-Tractor Units Description.

Vehicle Unit Number	Control Vehicle - LOXXXXX	Test Vehicle - LKXXXXX
Vehicle Make / Model	DAF / CF85 410	DAF / CF85 410
Year	2013	2013
Number of Axles	FT 4x2	FT 4x2
Number of Driving Axles	1	1
Engine Make / Model	Paccar 410 MX-13 300 /410 hp	Paccar 410 MX-13 300
Engine Build Year	2013	2013
Emission Label Info	Euro V	Euro V
Governed Speed (rpm)	1000	1000
@ no load (high idle)	2,000	2,000
Rated Power, (bhp)	300	300
Peak Torque (lb-ft)	1,500	1,500
Peak Torque Speed (rpm)	1,900	1,900
Transmission Make/Model	ZF/AS Tronic 12 Speed	ZF/AS-Tronic 12 Speed
Geared for mph (km/h)	90	90
Differential Ratio	2.8	2.8
Steer Tyre Type/Make/Model	Good Year RHD II / 295/80R22.5	Good Year RHD II / 295/80R22.5
Steer Pressure (cold) psi (kPa)	90	90
Drive Tyre Type/Make/Model	Good Year RHD II / 295/80R22.5	Good Year RHD II / 295/80R22.5
Drive Tyre Pressure (cold) psi (kPa)	100	100
5th Wheel Setting (distance fulcrum is ahead or behind bogie centreline) in (mm)	1,250	1,250

Table 112. Form D1-Part 2-Trailer Description.

Vehicle Unit Number	Control Vehicle - FT189 (LOxxxxx)	Test Vehicle - FT193 (LKxxxxx)
Vehicle Make / Model	Gray & Adams	Gray & Adams
Registration Year	2013	2013
S/N	F4.12.0262711	F4.12.0262715
Type	Refrigerated Box	Refrigerated Box
Length (mm)	14,020	14,020
Width (mm)	2,600	2,600
Type Door	Back + DROLANDIA LIFT	Back + DROLANDIA LIFT
Number of Trailer Axles/Type	2	2
Truck Trailer Gap	Yes	Yes
Aerodynamic Gap	Yes	Yes
Gross Vehicle Weight (kg)	31,000	31,000
Tyre Type/Make/Model	Encore 385/65R22.5/ETE2	Encore 385/65R22.5/ETE2
Total Weight Tractor + Trailer without driver (kg)	18,680	18,920
Comment		UCO tank is Full (+240kg)

Table 113. Form D1-Part 3-Devices, Components or Systems that are incorporated into Control and Test Vehicle Specification.

List of Components	No	Yes	Type	Comments
Radiator Shutters (on-off or modulating)	X			
Engine Cooling Fan Sys (describe below - A)		X	Electron C	
Aerodynamic Device (Fairings)		X		Side Cab
Aerodynamic Device (Spraydown Mudflap)	X			
Other Mudflaps		X		25/09/2014 Frontal spray suppression flaps in front trailer wheel + normal rear flaps (both vehicles). 30/11/2014 Test vehicle had Spraydown Mudflaps in tractor and trailer.
Engine Oil		X	10/40	
Transmission Lube		X	75/80	
Differential Lube		X	80/90	
Fuel Heater		X		Under fuel tank
Oil Cooler		X	Water Cooled	Built on the engine
Tag Axle	X			
Air Lift Axle	X			
Low Back Pressure Exhaust System	X			

Table 114. Form D2 – Instrumentation.

Description	Features	Part number	Serial number
"Davie" ECU Console	Reading ECU Codes	VCI-560	132105
Vehicle scale	Weight (Precision x kg)	CSG LP510	AE10081833
Tyre Pressure Measuring tool	Measure tyre pressure in psi	-	-
Data logger	County Scales Limited LBW Industrial Floor Scale. 550kg-50g	S.10	14-00340 14-00341
Weather Station	Temp, humidity, wind, rain	Davis Vantage Vue 6250	MH140807027

Table 115. Form D4-Part 1-Vehicles & Component Check.

Task	Check ed	Acce pt	Comments
Each engine speed control set to manufacturer's recommendation or the operator's standard	V	V	90 km/h
New air cleaner element and new fuel filters	V	V	Last service 27/8/2014
Each vehicle shall be clean and free of damage or missing body parts	V	V	Windows closed
Confirm cab windows for all vehicles are closed. If windows are open the openings shall be the same in each vehicle for the entire test.	V	V	Air Conditioner ON
Accessory load for each vehicle as consistent as possible (for example, defroster off, blower speed at the same setting, and lights on)	V	V	Air Conditioner ON
Trailer axle alignment checked and proper	V	V	
Truck/tractor alignment checked and proper	V	V	
Each vehicle properly lubricated prior to test			
All fluid levels should be checked and be at prescribed levels	V	V	Water issue in control vehicle on 25/09/2014
Temperature controlled fan drives shall be set to the same operating mode throughout the test	V	V	
Cold tyre pressures measured and inflated to vehicle or tyre manufacturer standard within a tolerance of ±1 psi (6895 Pa).	V	V	120F/100R/1 10Trailer
A stall check made on vehicles equipped with automatic transmissions and torque converters	N/A	N/A	
Exhaust system free of mechanical and operational defects (e.g. leaks)	V	V	
Proper brake adjustment	V	V	
All emission after treatment components must be in proper working condition.	V	V	

Table 116. Form D4-Part 2-Vehicles check warm-up (25/09/2014).

Tasks	Checked	Accept	Control Vehicle	Test Vehicle
Oil pressure and leaks (bar)	V	V	2.6	2.7
Brake air system leaks	V	V		
Coolant temperature and leaks	V	V	72	
Exhaust gas temperature (°C)	V	V	92/104	90/108
Engine air filter restriction				
Electrical load	V	V		
Tyre pressures (Front=F, Rear=R, Trailer=T)	V	V	120F/100R/110Trailer	120F/100R/110Trailer
Exhaust smoke	V	V		
Observed ability to maintain selected test speed	V	V		
Transmission or differential leaks	V	V		
Intake manifold pressure (turbocharger boost) and other intake system losses (bar)	V	V	1.02	1.02
Check/investigate all vehicle diagnostic caution and warning signals/alarms and resolve all vehicle operational concerns prior to proceeding with the test	V	V		

Table 117. Form D4-Part 2-Vehicles check warm-up (30/11/2014).

Tasks	Checked	Accept	Control Vehicle	Test Vehicle
Oil pressure and leaks (bar)	V	V	2.2	2.6
Brake air system leaks	V	V		
Coolant temperature and leaks (˚C)	V	V	76	66
Exhaust gas temperature (˚C)	V	V	83/85	64/78
Electrical load	V	V		
Tyre pressures (Front=F, Rear=R, Trailer=T)	V	V	120F/100R/110 Trailer	120F/100R/110 Trailer
Exhaust smoke	V	V		
Observed ability to maintain selected test speed	V	V		
Transmission or differential leaks	V	V		
Intake manifold pressure (turbocharger boost) and other intake system losses (bar)	V	V	1.02	1.03
Check/investigate all vehicle diagnostic caution and warning signals/alarms and resolve all vehicle operational concerns prior to proceeding with the test	V	V		

Table 118. Form D4-Part 3-Vehicles check run 1-run 2 (25/09/2014).

Tasks	Checked	Accept	Control Vehicle	Test Vehicle
Oil pressure and leaks (bar)	V	V	2.2	2.6
Brake air system leaks	V	V		
Coolant temperature and leaks	V	V	82.7	72
Exhaust gas temperature (°C)	V	V	106/161	125/197
Electrical load	V	V		
Tyre pressures (Front=F, Rear=R, Trailer=T)	V	V	124F/103R	124F/103 R
Brake dragging (i.e. temperature)				
Exhaust smoke	V	V		
Observed ability to maintain selected test speed	V	V		
Transmission or differential leaks	V	V		
Intake manifold pressure (turbocharger boost) and other intake system losses (bar)	V	V	1.02	1.03
Check/investigate all vehicle diagnostic caution and warning signals/alarms and resolve all vehicle operational concerns prior to proceeding with the test	V	V		

Table 119. Form D4-Part 3-Vehicles check run 1-run 2 (30/11/2014).

Tasks	Checked	Accept	Control Vehicle	Test Vehicle
Oil pressure and leaks	V	V	2.1	2.6
Brake air system leaks	V	V		
Coolant temperature and leaks	V	V	82.7	72
Exhaust gas temperature	V	V	106/161	125/197
Electrical load	V	V		
Tyre pressures (Front=F, Rear=R, Trailer=T)	V	V	124F/103R	124F/102 R
Brake dragging (i.e. temperature)				
Exhaust smoke	V	V		
Observed ability to maintain selected test speed	V	V		
Transmission or differential leaks	V	V		
Intake manifold pressure (turbocharger boost) and other intake system losses	V	V	1.02	1.03
Check/investigate all vehicle diagnostic caution and warning signals/alarms and resolve all vehicle operational concerns prior to proceeding with the test	V	V		

Table 120. Form D4-Part 3-Vehicles check run 2-run 3 (25/09/2014).

Tasks	Checked	Accept	Control Vehicle	Test Vehicle
Oil pressure and leaks	V	V	2.1	2.1
Brake air system leaks	V	V		
Coolant temperature and leaks	V	V	84.7	82.4
Exhaust gas temperature	V	V	108/150	125/187
Electrical load	V	V		
Tyre pressures (Front=F, Rear=R, Trailer=T)	V	V	123F/103R / 110 Trailer	124F/102R / 112 Trailer
Brake dragging (i.e. temperature)				
Exhaust smoke	V	V		
Observed ability to maintain selected test speed	V	V		
Transmission or differential leaks	V	V		
Intake manifold pressure (turbocharger boost) and other intake system losses	V	V	1.02	1.02
Check/investigate all vehicle diagnostic caution and warning signals/alarms and resolve all vehicle operational concerns prior to proceeding with the test	V	V		

Table 121. Form D4-Part 3-Vehicles check run 2-run 3 (30/11/2014).

Tasks	Checked	Accept	Control Vehicle	Test Vehicle
Oil pressure and leaks	V	V	2.4	2.1 bar
Brake air system leaks	V	V		
Coolant temperature and leaks	V	V	78	82.4
Exhaust gas temperature	V	V	83/106	99/138
Electrical load	V	V		
Tyre pressures (Front=F, Rear=R, Trailer=T)	V	V	122F/100R	124F/102 R
Brake dragging (i.e. temperature)				
Exhaust smoke	V	V		
Observed ability to maintain selected test speed	V	V		
Transmission or differential leaks	V	V		
Intake manifold pressure (turbocharger boost) and other intake system losses	V	V	1.02 bar	1.02bar
Check/investigate all vehicle diagnostic caution and warning signals/alarms and resolve all vehicle operational concerns prior to proceeding with the test	V	V		

Table 122. Form D4-Part 4-Vehicles check End of Day (25/09/2014).

Tasks	Checked	Accept	Control Vehicle	Test Vehicle
Oil pressure and leaks	V	V	2.1	2.1 bar
Brake air system leaks	V	V		
Coolant temperature and leaks	V	V	85.6	85.4
Exhaust gas temperature	V	V	108/150	113/148
Electrical load	V	V		
Tyre pressures(Front=F, Rear=R, Trailer=T)	V	V	124F/100R/ 120 Trailer	120F/100R/ 115 Trailer
Exhaust smoke	V	V		
Observed ability to maintain selected test speed	V	V		
Transmission or differential leaks	V	V		
Intake manifold pressure (turbocharger boost) and other intake system losses	V	V	1.02 bar	1.02bar
Check/investigate all vehicle diagnostic caution and warning signals/alarms and resolve all vehicle operational concerns prior to proceeding with the test	V	V		

Table 123. Form D4-Part 4-Vehicles check End of Day (30/11/2014).

Tasks	Checked	Accept	Control Vehicle	Test Vehicle
Oil pressure and leaks	V	V	2.4	2.2 bar
Brake air system leaks	V	V		
Coolant temperature and leaks	V	V	73.5	78.4
Exhaust gas temperature	V	V	85/104	94/125
Electrical load	V	V		
Tyre pressures (Front=F, Rear=R, Trailer=T)	V	V	122F/100R/ 110 Trailer	120F/100R/ 120 Trailer
Exhaust smoke	V	V		
Observed ability to maintain selected test speed	V	V		
Transmission or differential leaks	V	V		
Intake manifold pressure (turbocharger boost) and other intake system losses	V	V	1.01 bar	1.02bar
Check/investigate all vehicle diagnostic caution and warning signals/alarms and resolve all vehicle operational concerns prior to proceeding with the test	V	V		

APPENDIX 11 – UK CARBON CALCULATOR ASSUMPTIONS

UCO TO FAME B100

Module: Fuel chain Liquid (UCO Collections)

Plant was in operation on 23 Jan 2008		1
Soil Carbon Accumulation		3
Type of GHG data		Actual data for entire fuel chain

Module: Feedstock transport (Reverse Logistics UCO (Backhauling))

Distance transported	km	35
Energy intensity of transport	MJ(Fuel)/t-km	1.01
Module efficiency	Tonnes(output)/Tonnes(input)	1
Transport mode		Truck for dry product

Transports fuel, row 1

	MJ(Fuel)/Tonnes	4.35
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.0876388888888889
Type of fuel used		Diesel

Module: Depot (Storage UCO (Barrels))

Amount of electricity used	MJ(Electricity)/Tonnes(output)	0
Country of origin		United Kingdom

Module: Depot (Storage UCO (Barrels))

Amount of electricity used	MJ(Electricity)/Tonnes(output)	0
Country of origin		United Kingdom

Module: Feedstock transport (Transportation UCO (Road))

Distance transported	km	240
Module efficiency	Tonnes(output)/Tonnes(input)	1
Transport mode		Truck for dry product

Transports fuel, row 1

	MJ(Fuel)/Tonnes	224.64
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.0876388888888889
Type of fuel used		Diesel

Module: Biofuel plant or oilseed crush / mill (Refining UCO)

Conversion country of origin		United Kingdom

co-products, row 0

co-products is empty

Fuels per biofuel, row 1

	MJ(fuel)/Tonnes(output)	328.8889
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.0679836944444445
Type of fuel used		Natural gas (EU mix quality)

Fuels per biofuel, row 2

	MJ(fuel)/Tonnes(output)	5.92
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.128245138888889
Type of fuel used		Electricity (EU MV)

Module: Biofuel plant or oilseed crush / mill (Trans-Esterification (FAME))

Amount of electricity used	MJ(Electricity)/Tonnes(output)	151.38
Conversion country of origin		United Kingdom
Electricity emissions factor	kg(CO2e)/MJ(electricity)	0.128

Fuels per biofuel, row 0

Fuels per biofuel is empty

Module: Liquid fuel transport (Transportation Biodiesel (Road))

Distance transported	km	240

Transports fuel, row 1

	MJ(Fuel)/Tonnes	241.92
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.0876388888888889
Type of fuel used		Diesel

Module: Depot (Storage Biodiesel (DC))

Amount of electricity used	MJ(Electricity)/Tonnes(output)	31.3
Country of origin		United Kingdom

Module: Fuel handling (Refuelling Point (DC))

Country of origin		United Kingdom

UCO TO HVO B100

Module: Fuel chain Liquid (UCO Collections)

Biofuel production process		Natural gas as process fuel in CHP plant
Fuel chain default carbon intensity	grams(CO2e)/MJ	32
Plant was in operation on 23 Jan 2008		1
Soil Carbon Accumulation		3
Type of GHG data		Actual data for entire fuel chain

Module: Feedstock transport (Reverse Logistics UCO (Backhauling))

Distance transported	km	35
Energy intensity of transport	MJ(Fuel)/t-km	1.01
Module efficiency	Tonnes(output)/Tonnes(input)	1
Transport mode		Truck for dry product

Transports fuel, row 1

	MJ(Fuel)/Tonnes	4.35
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.0876388888888889
Type of fuel used		Diesel

Module: Depot (Storage UCO (Barrels in DC))

Amount of electricity used	MJ(Electricity)/Tonnes(output)	0
Country of origin		United Kingdom

Module: Feedstock transport (Transportation UCO (Road))

Distance transported	km	267
Module efficiency	Tonnes(output)/Tonnes(input)	1
Transport mode		Truck for dry product

Transports fuel, row 1

	MJ(Fuel)/Tonnes	249.912
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.0876388888888889
Type of fuel used		Diesel

Module: Feedstock transport (Transportation UCO (Sea))
Felixstowe to Rotterdam

Distance transported	nautical mile	134
Module efficiency	Tonnes(output)/Tonnes(input)	1
Transport mode		Ocean bulk carrier (Fuel oil)

Transports fuel, row 1

	MJ(Fuel)/Tonnes	50.52204144
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.0872
Type of fuel used		Heavy fuel oil for maritime transport

Module: Feedstock transport (Transportation UCO (Road))

Distance transported	km	25
Module efficiency	Tonnes(output)/Tonnes(input)	1
Transport country of origin		Netherlands
Transport mode		Truck for dry product

Transports fuel, row 1

	MJ(Fuel)/Tonnes	23.4
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.0876388888888889
Type of fuel used		Diesel

Module: Biofuel plant or oilseed crush / mill (Refining UCO)

Amount of electricity used	MJ(Electricity)/Tonnes(output)	330.86
Conversion country of origin		Netherlands
Plant yield	Tonnes(output)/Tonnes(input)	0.405
Product produced by this module		Used cooking oil

Chemicals, row 1

Chemical emissions factor	kg(CO2e)/kg(chemical)	3.63254724
Description		
Rate of chemical usage	kg(chemical)/Tonnes(output)	2.47
Type of chemical used		n-hexane

co-products, row 0

co-products is empty

Fuels per biofuel, row 1

	MJ(fuel)/Tonnes(output)	1591.22
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.0679836944444445
Type of fuel used		Natural gas (EU mix quality)

Module: Liquid fuel transport (Transportation Diesel (Road))

Distance transported	km	25
Module efficiency	Tonnes(output)/Tonnes(input)	0.999
Transport mode		Truck for liquids

Transports fuel, row 1

	MJ(Fuel)/Tonnes	25.2
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.0876388888888889
Type of fuel used		Diesel

Module: Liquid fuel transport (Transportation Biodiesel (Sea))

Distance transported	nautical mile	134
Module efficiency	Tonnes(output)/Tonnes(input)	0.999

Transports fuel, row 1

	MJ(Fuel)/Tonnes	50.52204144
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.0872
Type of fuel used		Heavy fuel oil for maritime transport

Module: Biofuel plant or oilseed crush / mill (Hydrogenation Vegetable Oil (HVO))

All data reported in this module are actual data		0
Conversion country of origin		Netherlands
Electricity emissions factor	kg(CO2e)/MJ(electricity)	0.128
Plant yield	Tonnes(output)/Tonnes(input)	0.791

Chemicals, row 0

Chemicals is empty

co-products, row 1

Coproduct Market Value	value/kg(coproduct)	0
Coproduct name		Electricity
Coproduct use		Electricity from grid (EU-MV)
Coproduct yield	Tonnes(coproduct)/Tonnes(output)	66.24
Credit or debit for coproduct use	kg(CO2e)/Tonnes(coproduct)	-0.12824513889
Description		
Energy Content	MJ/kg(coproduct)	0

co-products, row 2

Coproduct Market Value	value/kg(coproduct)	0
Coproduct name		Steam
Coproduct use		Steam from natural gas boiler
Coproduct yield	Tonnes(coproduct)/Tonnes(output)	350
Credit or debit for coproduct use	kg(CO2e)/Tonnes(coproduct)	-0.078502896605
Description		
Energy Content	MJ/kg(coproduct)	0

Fuels per biofuel, row 1

	MJ(fuel)/Tonnes(output)	3770
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.0878713333333333
Type of fuel used		Hydrogen

Module: Liquid fuel transport (Transportation Biodiesel (Road))

Distance transported	km	267
Module efficiency	Tonnes(output)/Tonnes(input)	0.999
Transport country of origin		United Kingdom
Transport mode		Truck for liquids

Transports fuel, row 1

	MJ(Fuel)/Tonnes	269.136
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.0876388888888889
Type of fuel used		Diesel

Module: Depot (Storage Biodiesel (DC))

Amount of electricity used	MJ(Electricity)/Tonnes(output)	31.3
Country of origin		United Kingdom

Module: Fuel handling (Refuelling Point (DC))

Amount of electricity used	MJ(Electricity)/Tonnes(output)	149.6
Country of origin		United Kingdom

Module: Fuel chain Liquid (Waste Wood (Pallets))
BTL
Lignocellulosic to Ethanol

Plant was in operation on 23 Jan 2008		1
Soil Carbon Accumulation		3
Type of GHG data		Actual data for entire fuel chain

Module: Feedstock transport (Reverse Logistics Pallets (Backhauling))

Distance transported	km	35
Energy intensity of transport	MJ(Fuel)/t-km	1.01
Module efficiency	Tonnes(output)/Tonnes(input)	1
Transport mode		Truck for dry product

Transports fuel, row 1

	MJ(Fuel)/Tonnes	4.35
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.0876388888888889
Type of fuel used		Diesel

Module: Depot (Storage Wood (Pallets in DC))

Amount of electricity used	MJ(Electricity)/Tonnes(output)	0
Country of origin		United Kingdom

Module: Feedstock transport (Transportation Pallets (Road))

Distance transported	km	141
Module efficiency	Tonnes(output)/Tonnes(input)	0.999
Transport mode		Truck for dry product

Transports fuel, row 1

	MJ(Fuel)/Tonnes	131.976
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.0876388888888889
Type of fuel used		Diesel

Module: Biofuel plant or oilseed crush / mill (Crush Wood)

Conversion country of origin		United Kingdom

Module: Feedstock transport (Transportation Wood (Road))

Distance transported	km	179
Module efficiency	Tonnes(output)/Tonnes(input)	0.999
Transport mode		Truck for dry product

Transports fuel, row 1

	MJ(Fuel)/Tonnes	167.544
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.0876388888888889
Type of fuel used		Diesel

Module: Feedstock transport (Transportation Wood (Sea))
From Felixstowe to Port of Havneholmen

Distance transported	nautical mile	644
Module efficiency	Tonnes(output)/Tonnes(input)	1
Transport mode		Ocean bulk carrier (Fuel oil)

Transports fuel, row 1

	MJ(Fuel)/Tonnes	242.80742304
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.0872
Type of fuel used		Heavy fuel oil for maritime transport

Module: Feedstock transport (Transportation Wood (Road))
Port of Havneholmen to
Borregaard, Hjalmar Wessels vei 10, 1721 Sarpsborg, Norge

Distance transported	km	18
Module efficiency	Tonnes(output)/Tonnes(input)	1
Transport country of origin		Norway
Transport mode		Truck for dry product

Transports fuel, row 1

	MJ(Fuel)/Tonnes	16.848
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.0876388888888889
Type of fuel used		Diesel

Module: Liquid fuel transport (Transportation Diesel (Road))
Borregaard, Hjalmar Wessels vei 10, 1721 Sarpsborg, Norge
Port of Havneholmen

Distance transported	km	18
Module efficiency	Tonnes(output)/Tonnes(input)	0.999
Transport mode		Truck for liquids

Transports fuel, row 1

	MJ(Fuel)/Tonnes	18.144
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.0876388888888889
Type of fuel used		Diesel

Module: Liquid fuel transport (Transportation Biodiesel (Sea))
Port of Havneholmen
Felixstowe

Distance transported	nautical mile	644
Module efficiency	Tonnes(output)/Tonnes(input)	0.999

Transports fuel, row 1

	MJ(Fuel)/Tonnes	242.80742304
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.0872
Type of fuel used		Heavy fuel oil for maritime transport

Module: Liquid fuel transport (Transportation Biodiesel (Road))
Lutts (LU6 2PN) to each DC

Distance transported	km	141
Module efficiency	Tonnes(output)/Tonnes(input)	0.999
Transport country of origin		United Kingdom
Transport mode		Truck for liquids

Transports fuel, row 1

	MJ(Fuel)/Tonnes	142.128
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.0876388888888889
Type of fuel used		Diesel

Module: Biofuel plant or oilseed crush / mill (BioEthanol)

Conversion country of origin		Norway
Electricity emissions factor	kg(CO2e)/MJ(electricity)	0.128
Plant yield	Tonnes(output)/Tonnes(input)	0.166
Product produced by this module		Bioethanol

Chemicals, row 1

Chemical emissions factor	kg(CO2e)/kg(chemical)	1.0314898
Description		
Rate of chemical usage	kg(chemical)/Tonnes(output)	38.19
Type of chemical used		Lime

Chemicals, row 2

Chemical emissions factor	kg(CO2e)/kg(chemical)	0.2088337
Description		
Rate of chemical usage	kg(chemical)/Tonnes(output)	94.97
Type of chemical used		Sulphuric acid

Chemicals, row 3

Chemical emissions factor	kg(CO2e)/kg(chemical)	2.6765336
Description		
Rate of chemical usage	kg(chemical)/Tonnes(output)	65.89
Type of chemical used		Ammonia

Chemicals, row 4

Chemical emissions factor	kg(CO2e)/kg(chemical)	0.828571428571428
Description		
Rate of chemical usage	kg(chemical)/Tonnes(output)	18.76
Type of chemical used		Ammonium sulphate

co-products, row 1

Coproduct Market Value	value/kg(coproduct)	0
Coproduct name		Electricity
Coproduct use		
Coproduct yield	Tonnes(coproduct)/Tonnes(output)	9.9
Credit or debit for coproduct use	kg(CO2e)/Tonnes(coproduct)	-1
Description		
Energy Content	MJ/kg(coproduct)	0

Fuels per biofuel, row 1

	MJ(fuel)/Tonnes(output)	957.16
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.0876388888888889
Type of fuel used		Diesel

Module: Depot (Storage Biodiesel (DC))

Amount of electricity used	MJ(Electricity)/Tonnes(output)	22.5
Country of origin		United Kingdom

Module: Fuel handling (Refuelling)

Amount of electricity used	MJ(Electricity)/Tonnes(output)	91.1
Country of origin		United Kingdom

FOOD WASTE TO BIOMETHANE

Module: Fuel chain Gas (Food Waste Collections)
Food Waste from QSRs and DCs
Closest AD Plant to DC

Plant was in operation on 23 Jan 2008		1
Soil Carbon Accumulation		3
Type of GHG data		Actual data for entire fuel chain

Module: Feedstock transport (Reverse Logistics Food Waste (Backhauling))

Distance transported	km	35
Energy intensity of transport	MJ(Fuel)/t-km	1.01
Module efficiency	Tonnes(output)/Tonnes(input)	1
Transport mode		Truck for dry product

Transports fuel, row 1

	MJ(Fuel)/Tonnes	4.35
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.0876388888888889
Type of fuel used		Diesel

Module: Depot (Storage Food Waste)

Country of origin		United Kingdom

Distance transported	km	34
Module efficiency	Tonnes(output)/Tonnes(input)	1
Transport mode		Truck for dry product

Transports fuel, row 1

	MJ(Fuel)/Tonnes	31.824
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.0876388888888889
Type of fuel used		Diesel

Module: Biomethane plant (Anaerobic Digestion)

Conversion country of origin		United Kingdom

Fuels per biofuel, row 1

	MJ(fuel)/Tonnes(output)	6631.955
Description		
Fuel emissions factor	kg(CO2e)/MJ	0
Type of fuel used		Biogas from same production unit

Fuels per biofuel, row 2

	MJ(fuel)/Tonnes(output)	6631.955
Description		
Fuel emissions factor	kg(CO2e)/MJ	0.00106709350406829
Type of fuel used		CH4 and N2O emissions from biogas CHP plant

Module: Biomethane plant (CH4 Upgrade)

Conversion country of origin		United Kingdom

Module: Gaseous fuel transport (Injet into the Grid)

Distance transported	km	149

Module: Fuel handling (Refueling)

Country of origin		United Kingdom

APPENDIX 12 – VBA CODE MATRIX FEASIBLE COMBINATION

```
Sub EvaluateAll()
' Keyboard Shortcut: Ctrl+Shift+E
   Dim UsedArray(25) As Integer       ' Table that represents that a technology has
been evaluated
   Sheets("Model").Select              ' Select Sheet Model
   xRow = 9
   Cells(1, 59).Value = "Processing Data"
   Cells(1, 58).Value = Time
   Application.ScreenUpdating = False
   For xBH = 0 To 1
    For xBI = 0 To 1
     If xBH + xBI < 2 Then
      For xBJ = 0 To 1
       If xBH + xBJ < 2 Then
        For xBK = 0 To 1
         For xBL = 0 To 1
          If xBK + xBL < 2 Then
           For xBM = 0 To 1
            For xBN = 0 To 1
             If xBM + xBN < 2 Then
              For xBO = 0 To 1
               If xBM + xBN + xBO < 2 Then
                For xBP = 0 To 1
                 If xBM + xBN + xBO + xBP < 2 Then
                  For xBQ = 0 To 1
                   If xBP + xBQ < 2 Then
                    For xBR = 0 To 1
                     If xBQ + xBR < 2 Then
                      For xBS = 0 To 1
                       If xBQ + xBR + xBS < 2 Then
                        For xBT = 0 To 1
                         If xBQ + xBR + xBS + xBT < 2 Then
                          For xBU = 0 To 1
                           If xBQ + xBR + xBS + xBT + xBU < 2 Then
                            For xBV = 0 To 1
                             If xBS + xBT + xBU + xBV < 2 Then
                              For xBW = 0 To 1
                               For xBX = 0 To 1
                                For xBY = 0 To 1
                                 For xBZ = 0 To 1
                                  For xCA = 0 To 1
                                   For xCB = 0 To 1
                                    For xCC = 0 To 1
                                     For xCD = 0 To 1
                                      For xCE = 0 To 1
                                       For xCF = 0 To 1
                                        'VALID COMBINATION
                                       Cells(xRow, 60).Value = xBH
                                       Cells(xRow, 61).Value = xBI
                                       Cells(xRow, 62).Value = xBJ
                                       Cells(xRow, 63).Value = xBK
                                       Cells(xRow, 64).Value = xBL
                                       Cells(xRow, 65).Value = xBM
                                       Cells(xRow, 66).Value = xBN
                                       Cells(xRow, 67).Value = xBO
```

```
                                             Cells(xRow, 68).Value = xBP
                                             Cells(xRow, 69).Value = xBQ
                                             Cells(xRow, 70).Value = xBR
                                             Cells(xRow, 71).Value = xBS
                                             Cells(xRow, 72).Value = xBT
                                             Cells(xRow, 73).Value = xBU
                                             Cells(xRow, 74).Value = xBV
                                             Cells(xRow, 75).Value = xBW
                                             Cells(xRow, 76).Value = xBX
                                             Cells(xRow, 77).Value = xBY
                                             Cells(xRow, 78).Value = xBZ
                                             Cells(xRow, 79).Value = xCA
                                             Cells(xRow, 80).Value = xCB
                                             Cells(xRow, 81).Value = xCC
                                             Cells(xRow, 82).Value = xCD
                                             Cells(xRow, 83).Value = xCE
                                             Cells(xRow, 84).Value = xCF
                                              xRow = xRow + 1
                                             Next 'xCF
                                            Next 'xCE
                                           Next 'xCD
                                          Next 'xCC
                                         Next 'xCB
                                        Next 'xCA
                                       Next 'xBZ
                                      Next 'xBY
                                     Next 'xBX
                                    Next 'xBW
                                   End If
                                  Next 'xBV
                                 End If
                                Next 'xBU
                               End If
                              Next 'xBT
                             End If
                            Next 'xBS
                           End If
                          Next 'xBR
                         End If
                        Next 'xBQ
                       End If
                      Next 'xBP
                     End If
                    Next 'xBO
                   End If
                  Next 'xBN
                 Next 'xBM
                End If
               Next 'xBL
              Next 'xBK
             End If
            Next 'xBJ
           End If
          Next 'xBI
    Next 'xBH
    Cells(1, 59).Value = "Done"
    Cells(2, 58).Value = Time
    Application.ScreenUpdating = True
End Sub
```

```
Sub EvaluateAll()
' Keyboard Shortcut: Ctrl+Shift+E
  Dim UsedArray(25) As Integer      ' Table that represents that a technology has
been evaluated
  Sheets("Model").Select             ' Select Sheet Model
  xRow = 9
  Cells(1, 59).Value = "Processing Data"
  Cells(1, 58).Value = Time
  Application.ScreenUpdating = False
  For xBH = 0 To 1
   For xBI = 0 To 1
    If xBH + xBI < 2 Then
     For xBJ = 0 To 1
      If xBH + xBJ < 2 Then
       For xBK = 0 To 1
        For xBL = 0 To 1
         If xBK + xBL < 2 Then
          For xBM = 0 To 1
           For xBN = 0 To 1
            If xBM + xBN < 2 Then
             For xBO = 0 To 1
              If xBM + xBN + xBO < 2 Then
               For xBP = 0 To 1
                If xBM + xBN + xBO + xBP < 2 Then
                 For xBQ = 0 To 1
                  If xBP + xBQ < 2 Then
                   For xBR = 0 To 1
                    If xBQ + xBR < 2 Then
                     For xBS = 0 To 1
                      If xBQ + xBR + xBS < 2 Then
                       For xBT = 0 To 1
                        If xBQ + xBR + xBS + xBT < 2 Then
                         For xBU = 0 To 1
                          If xBQ + xBR + xBS + xBT + xBU < 2 Then
                           For xBV = 0 To 1
                            If xBS + xBT + xBU + xBV < 2 Then
                             For xBW = 0 To 1
                              For xBX = 0 To 1
                               For xBY = 0 To 1
                                For xBZ = 0 To 1
                                 For xCA = 0 To 1
                                  For xCB = 0 To 1
                                   For xCC = 0 To 1
                                    For xCD = 0 To 1
                                     For xCE = 0 To 1
                                      For xCF = 0 To 1
                                       'VALID COMBINATION
                                      Cells(xRow, 60).Value = xBH
                                      Cells(xRow, 61).Value = xBI
                                      Cells(xRow, 62).Value = xBJ
                                      Cells(xRow, 63).Value = xBK
                                      Cells(xRow, 64).Value = xBL
                                      Cells(xRow, 65).Value = xBM
                                      Cells(xRow, 66).Value = xBN
                                      Cells(xRow, 67).Value = xBO
                                      Cells(xRow, 68).Value = xBP
                                      Cells(xRow, 69).Value = xBQ
                                      Cells(xRow, 70).Value = xBR
```

```
                                    Cells(xRow, 71).Value = xBS
                                    Cells(xRow, 72).Value = xBT
                                    Cells(xRow, 73).Value = xBU
                                    Cells(xRow, 74).Value = xBV
                                    Cells(xRow, 75).Value = xBW
                                    Cells(xRow, 76).Value = xBX
                                    Cells(xRow, 77).Value = xBY
                                    Cells(xRow, 78).Value = xBZ
                                    Cells(xRow, 79).Value = xCA
                                    Cells(xRow, 80).Value = xCB
                                    Cells(xRow, 81).Value = xCC
                                    Cells(xRow, 82).Value = xCD
                                    Cells(xRow, 83).Value = xCE
                                    Cells(xRow, 84).Value = xCF
                                     xRow = xRow + 1
                                    Next 'xCF
                                   Next 'xCE
                                  Next 'xCD
                                 Next 'xCC
                                Next 'xCB
                               Next 'xCA
                              Next 'xBZ
                             Next 'xBY
                            Next 'xBX
                           Next 'xBW
                          End If
                         Next 'xBV
                        End If
                       Next 'xBU
                      End If
                     Next 'xBT
                    End If
                   Next 'xBS
                  End If
                 Next 'xBR
                End If
               Next 'xBQ
              End If
             Next 'xBP
            End If
           Next 'xBO
          End If
         Next 'xBN
        Next 'xBM
       End If
      Next 'xBL
     Next 'xBK
    End If
   Next 'xBJ
  End If
 Next 'xBI
Next 'xBH
Cells(1, 59).Value = "Done"
Cells(2, 58).Value = Time
Application.ScreenUpdating = True
End Sub
Sub EvaluateAll()
```

APPENDIX 13 – AERODYNAMIC DRAG OF A TRACTOR UNIT DAF CF85.

The outcome of aerodynamic drag forces simulations for a DAF CF85 with and without roof and side collar aerodynamic improvements indicates that the drag coefficients are 0.49 and 0.72 respectively. This shows that these devices have a real impact on the C_D parameter that appear in Equations 2-3 (Page 33).

Via Computational Fluid Dynamics (CFD) it has been found that the drag forces of a tractor unit with no aerodynamic improvements (Figures 132-133 left) at 36 km/h (a speed typical of urban environments) and 90 km/h (a speed typical of motorway driving) are 294N and 1,831N respectively. With aerodynamic improvements drag forces at 36 km/h and 90 km/h are 275.5 N and 1,734 N respectively (Figures 132-133 right).

At low speeds (36km/h) the difference in drag between having or not aerodynamic improvements is around 184W (Figures 132 right and left). Over an hour this represents 0.66 MJ. Assuming that the energy density of diesel is around 38.6 MJ, this means that the savings are around 17.18 mL over an hour or 0.047 L/100km which represents savings of 0.26%. At higher speeds (90 km/h) the difference in drag is around 2,419 W (Figures 133 right and left). This adds up to 8.71 MJ or 225 mL/h or 0.25L/100 km. Roughly speaking for a tractor unit (with no trailer) consuming 28L/100km this represents around 1%. This is a very small benefit; however no one uses the tractor unit by itself. It is when a trailer is installed when most benefits materialise.

This indicates that aerodynamic drag has a considerable impact at high speeds. However this is not the case for a tractor unit driving in urban areas as the low speeds do not produce significant savings.

This technique also shows the impact that wind speed has on aerodynamic drag. Taking for example the vehicle with aerodynamic improvements (Figures 132-133 right) it can be calculated that the difference of 1,459N equates to 40.6 kW or 146 MJ per hour, which would represent a difference of almost 4 Litres just for drag forces.

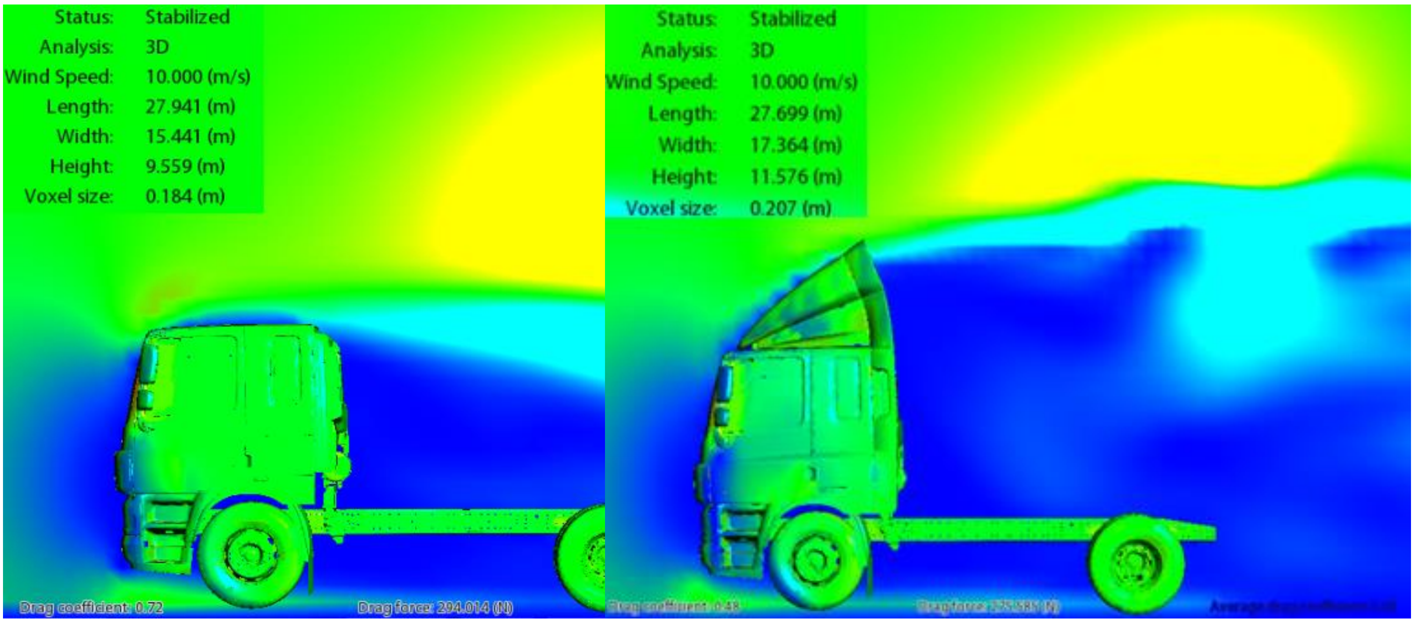


Figure 132. Drag coefficient of a DAF CF85 sleeper cab tractor unit withouth and with aerodynamic fairings at 36 km/h.

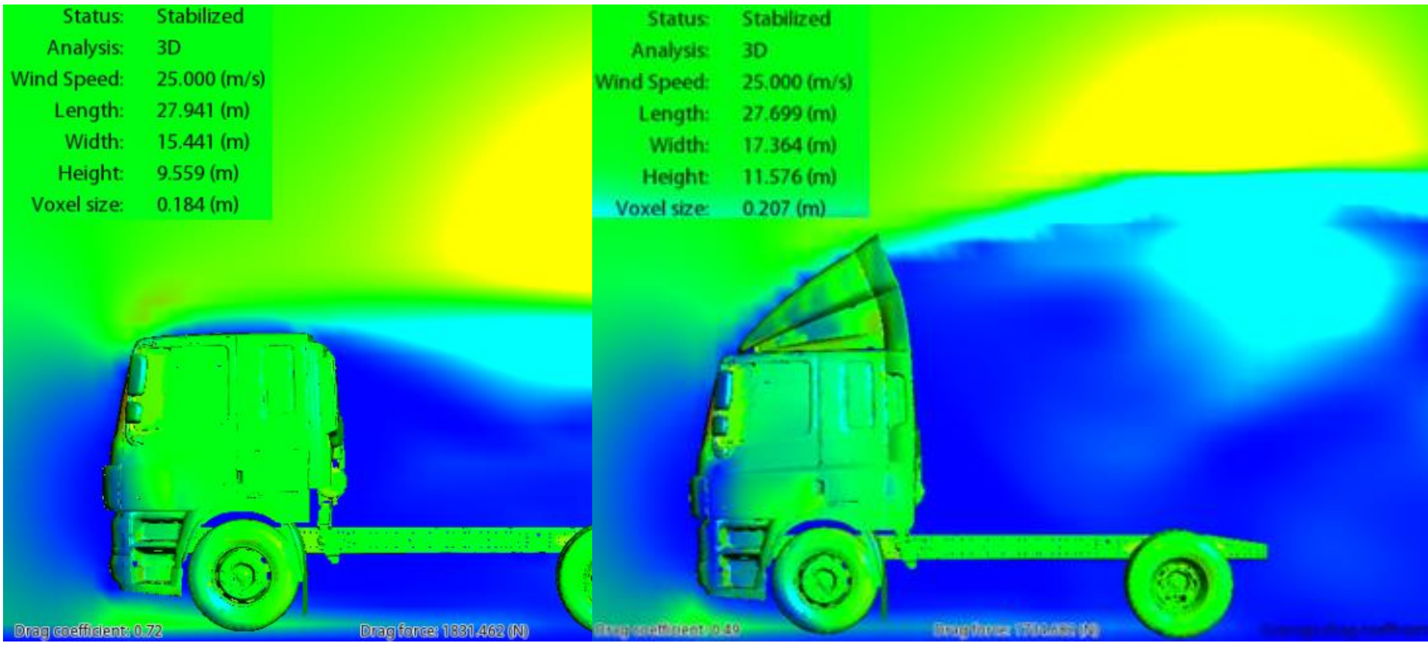


Figure 133. Drag coefficient of a DAF CF85 sleeper cab tractor unit withouth and with aerodynamic fairings at 90 km/h.

APPENDIX 14 – STATISTICAL POWER ANALYSES SAE-1321-TYPE II TRIAL

All the statistical analyses that appear in Appendix 14 were calculated with G*Power.

F-tests - Variance: Test of equality (two sample case)

Analysis:	**A priori: Compute required sample size**		
Input:	**Tail(s)**	**=**	**Two**
	Ratio var1/var0	**=**	**0.0820464**
	α err prob	**=**	**0.05**
	Power (1-β err prob)	**=**	**0.95**
	Allocation ratio N2/N1	**=**	**1**
Output:	**Lower critical F**	**=**	**0.2690492**
	Upper critical F	**=**	**3.7167919**
	Numerator df	**=**	**10**
	Denominator df	**=**	**10**
	Sample size group 1	**=**	**11**
	Sample size group 2	**=**	**11**
	Actual power	**=**	**0.9626958**

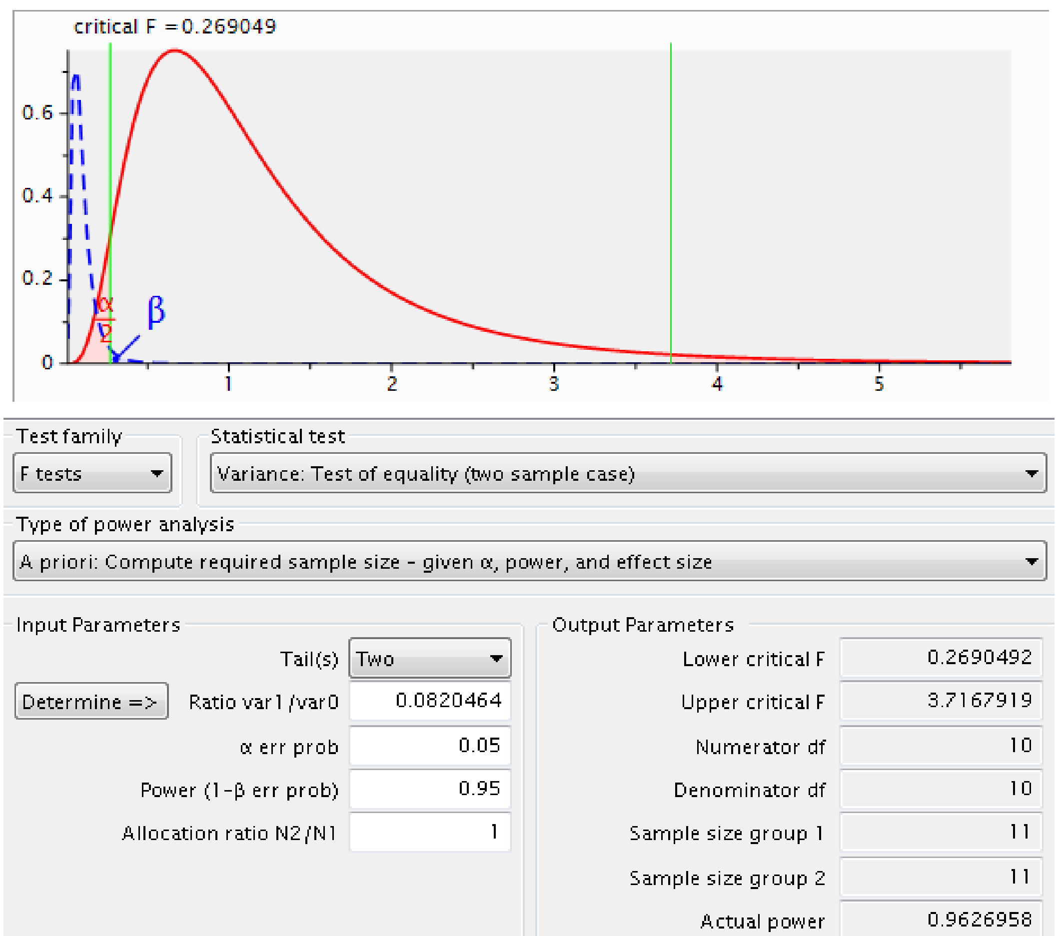


Figure 134. To achieve a confidence level of 95% in the F-Test eleven trips were necessary per day of trial and vehicle.

F-tests - Variance: Test of equality (two sample case)

Analysis:	**Post hoc: Compute achieved power**		
Input:	**Tail(s)**	**=**	**Two**
	Ratio var1/var0	**=**	**0.0820464**
	α err prob	**=**	**0.05**
	Sample size group 1	**=**	**3**
	Sample size group 2	**=**	**3**
Output:	**Lower critical F**	**=**	**0.0256410**
	Upper critical F	**=**	**39.0000000**
	Numerator df	**=**	**2**
	Denominator df	**=**	**2**
	Power (1-β err prob)	**=**	**0.2402054**

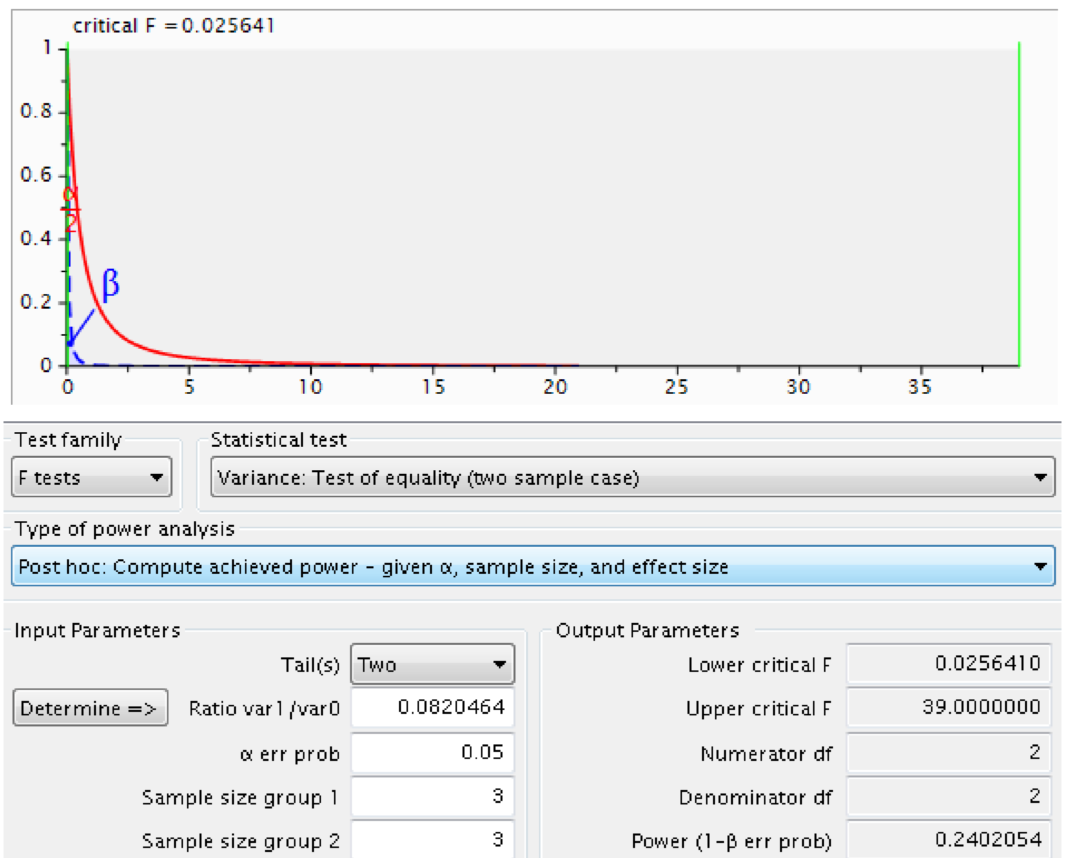


Figure 135. The confidence level achieved in the F-Test with three trips per trial day and vehicle was just 24%.

t-tests - Means: Difference between two independent means (two groups)

Analysis:	**A priori: Compute required sample size**		
Input:	**Tail(s)**	**=**	**Two**
	Effect size d	**=**	**0.7010188**
	α err prob	**=**	**0.05**
	Power (1-β err prob)	**=**	**.95**
	Allocation ratio N2/N1	**=**	**1**
Output:	**Noncentrality parameter δ**	**=**	**3.6426005**
	Critical t	**=**	**1.9825973**
	Df	**=**	**106**
	Sample size group 1	**=**	**54**
	Sample size group 2	**=**	**54**
	Total sample size	**=**	**108**
	Actual power	**=**	**0.9504712**

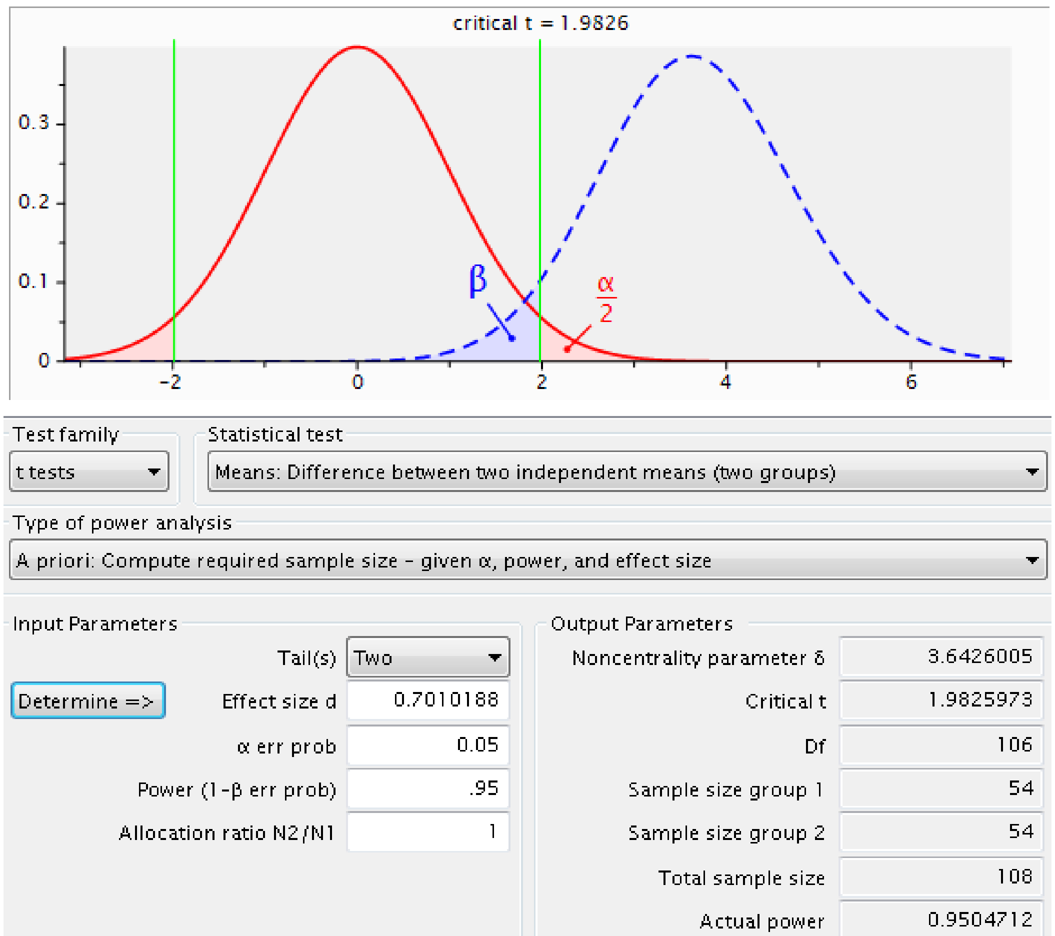


Figure 136. To achieve a confidence level of 95% in the t-Test 54 trips were necessary per day of trial and vehicle.

t-tests - Means: Difference between two independent means (two groups)

Analysis:	**Post hoc: Compute achieved power**		
Input:	**Tail(s)**	=	**Two**
	Effect size d	=	**0.7010188**
	α err prob	=	**0.05**
	Sample size group 1	=	**3**
	Sample size group 2	=	**3**
Output:	**Noncentrality parameter δ**	=	**0.8585692**
	Critical t	=	**2.7764451**
	Df	=	**4**
	Power (1-β err prob)	=	**0.1030880**

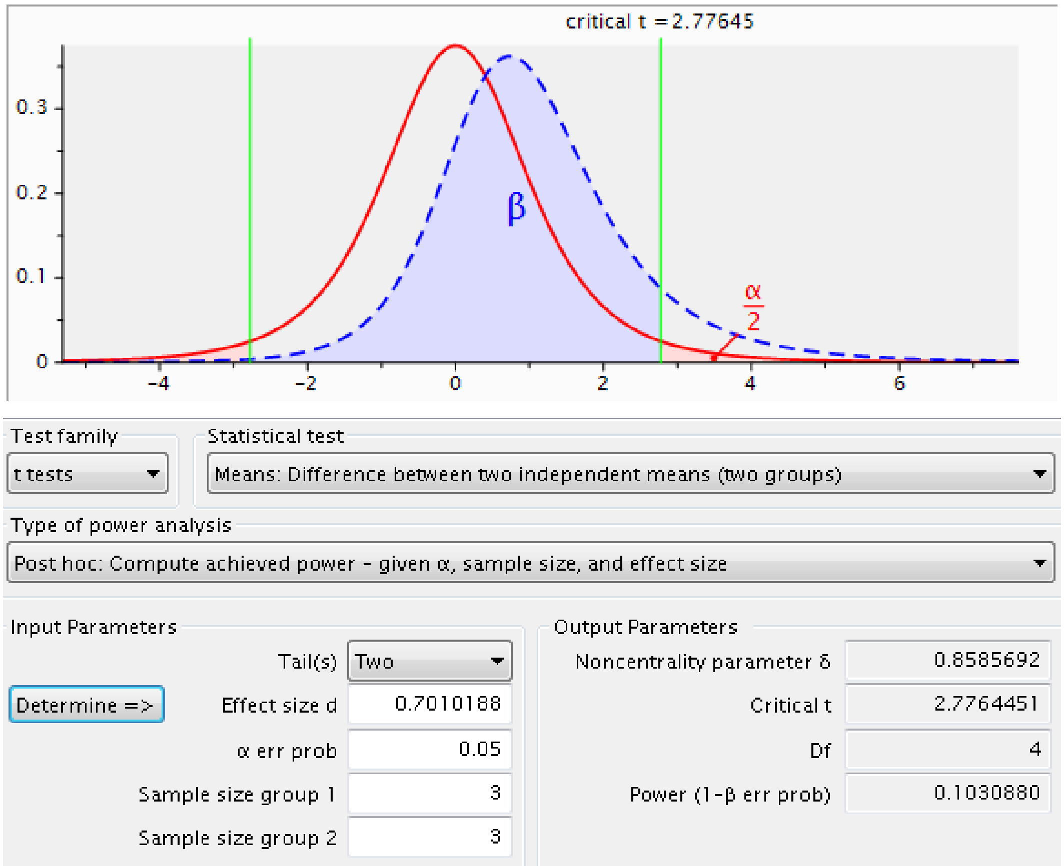


Figure 137. The confidence level achieved in the t-Test with three trips per trial day and vehicle was just 10%.

APPENDIX 15 – SENSITIVITY ANALYSIS MILEAGE OVER NPC URBAN HGVS.

Table 124. Sensitivity analysis of the impact of each year's mileage on NPC for urban HGVs, under strategy S1 (scenario UB-UNLTD2).

Inputs Ranked by Mean				Output			
Name	Book	Analysis	Value	Mean	Min	Max	StdDev
km year / 16	SENSITIVITY FINAL MODEL.xlsx	Base -20.00%	90671.90625	-247584.7581	-247584.7581	-247584.7581	0
km year / 17	SENSITIVITY FINAL MODEL.xlsx	Base -20.00%	91125.2625	-247962.0006	-247962.0006	-247962.0006	0
km year / 18	SENSITIVITY FINAL MODEL.xlsx	Base -20.00%	91580.8875	-248156.0066	-248156.0066	-248156.0066	0
km year / 18	SENSITIVITY FINAL MODEL.xlsx	Base -20.00%	91580.8875	-248156.0066	-248156.0066	-248156.0066	0
km year / 18	SENSITIVITY FINAL MODEL.xlsx	Base -20.00%	91580.8875	-248156.0066	-248156.0066	-248156.0066	0
km year / 15	SENSITIVITY FINAL MODEL.xlsx	Base -20.00%	90220.8	-248162.1293	-248162.1293	-248162.1293	0
km year / 19	SENSITIVITY FINAL MODEL.xlsx	Base -20.00%	92038.79375	-248363.0091	-248363.0091	-248363.0091	0
km year / 17	SENSITIVITY FINAL MODEL.xlsx	Base +0.00%	113906.5781	-251473.0273	-251473.0273	-251473.0273	0
km year / 19	SENSITIVITY FINAL MODEL.xlsx	Base +0.00%	115048.4922	-251473.0274	-251473.0274	-251473.0274	0
km year / 15	SENSITIVITY FINAL MODEL.xlsx	Base +0.00%	112776	-251473.0275	-251473.0275	-251473.0275	0
km year / 16	SENSITIVITY FINAL MODEL.xlsx	Base +0.00%	113339.8828	-251473.028	-251473.028	-251473.028	0
km year / 19	SENSITIVITY FINAL MODEL.xlsx	Base +20.00%	138058.1906	-254583.0458	-254583.0458	-254583.0458	0
km year / 15	SENSITIVITY FINAL MODEL.xlsx	Base +20.00%	135331.2	-254783.9258	-254783.9258	-254783.9258	0
km year / 17	SENSITIVITY FINAL MODEL.xlsx	Base +20.00%	136687.8938	-254984.054	-254984.054	-254984.054	0
km year / 16	SENSITIVITY FINAL MODEL.xlsx	Base +20.00%	136007.8594	-255361.2979	-255361.2979	-255361.2979	0

APPENDIX 16 – SENSITIVITY ANALYSIS OF LH-UNLTD2 SCENARIO WHEN EXCLUDING INDIVIDUAL TECHNOLOGIES.

Table 125. Optimisation of low carbon technologies selection under scenario LH-UNLTD2 for long-haul duty HGV (using B65) and constraining individual technology choices.

Financial Parameters	Vehicle Parameters		Operating Parameters - Regional	
Rate of Return 9.7% Interest Rate Leasing 3% Life Investment 5 Years GDP Central Growth	GVW 32 tonnes Tractor 4x2 Semi-articulated (DAF CF85) Trailer 2 axles Tractor Fuel (65 % biodiesel)	Conventional Diesel TRU Initial Fuel: Red Diesel Initial Refrigerant Gas: R-404A Semi-Trailer: 13.4/78.79 m3	Tonnes delivered (5 years): 18815 Total Km (5y): 764955 Refrigeration (hrs./year):3550	Price B65 (2015) 80.51 p/L Price Red Diesel (2015) 57.95 p/L Price Electricity (2015) 13.02 p/kWh

Results			Long Haul										
			Optimisation with Unlimited Risk (S1)										
			Fuel Price Medium - LH-UNLTD2 Scenario										
Vehicle Technologies	Reduced Aerodynamic Resistance	Aerodynamic Trailers	1	0	1	1	1	1	1	1	1	1	1
		Aerodynamic Irregular body shape	0	0	0	0	0	0	0	0	0	0	0
		Aerodynamic Fairings	0	1	0	0	0	0	0	0	0	0	0
		Spray Reduction Mud Flaps	1	1	0	1	1	1	1	1	1	1	1
	Reduced Rolling Resistance	Low rolling resistance tyres	1	1	1	0	1	1	1	1	1	1	1
		New generation wide-base single tyres	0	0	0	1	0	0	0	0	0	0	0
		Automatic tyre pressure adjustment	1	1	1	1	0	1	1	1	1	1	1
	Vehicle Mass	Lightweighting Materials	1	1	1	1	1	0	1	1	1	1	1
	Intelligent VT	Predictive Cruise Control	1	1	1	1	1	1	0	1	1	1	1
	Auxiliary Systems	Controllable air compressor	1	1	1	1	1	1	1	0	1	1	1
Powertrain Technologies	Exhaust Heat Recovery	Heat Recovery (in general)	0	0	0	0	0	0	0	0	0	0	0
		Electrical Drive Turbo compound	0	0	0	0	0	0	0	0	0	0	0
	Transmissions	Automated Manual Transmission	0	0	0	0	0	0	0	0	0	0	0
	Mild Hybrid	Flywheels Hybrid	1	1	1	1	1	1	1	1	0	1	1
		Stop-Start: Electric Hybrid	0	0	0	0	0	0	0	0	0	0	0
		Pneumatic Booster - Air Hybrid	1	1	1	1	1	1	1	1	1	0	1
	Alternative PT	Full Hybrid: Series / Parallel Electric	0	0	0	0	0	0	0	0	0	0	0
		Series / Parallel hydraulic	0	0	0	0	0	0	0	0	0	0	0
	Total FCR (Vehicle & Powertrain)		31.1%	26.5%	30.1%	31.1%	29.0%	29.6%	27.5%	30.1%	27.5%	29.8%	31.1%
TRU	Refrigeration Technologies	3 Phase Aux. Alternator Unit (R410A)	1	1	1	1	1	1	1	1	1	1	0
		Hybrid Refrigeration Unit	0	0	0	0	0	0	0	0	0	0	0
		Cryogenic Nitrogen (LIN)	0	0	0	0	0	0	0	0	0	0	0
		Cryogenic CO_2	0	0	0	0	0	0	0	0	0	0	0
		Cryogenic Air (LAIR)	0	0	0	0	0	0	0	0	0	0	1
		Lower GWP Gas Unit (R744)	0	0	0	0	0	0	0	0	0	0	0
		Vacuum Isolated Panels	0	0	0	0	0	0	0	0	0	0	0
	Total FCR (TRU)		100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Combined FCR % (Vehicle, Powertrain & Refrigeration)		-34.0%	-30.0%	-33.1%	-34.0%	-32.2%	-32.7%	-30.9%	-33.1%	-30.9%	-32.9%	-41.6%
	New Average Fuel Consumption (l/ 100km)		25.64	27.16	25.98	25.64	26.34	26.15	26.83	25.98	26.83	26.07	22.68
	New TRU Fuel Consumption (l/hrs.)		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Improvement in Costs		13.1%	11.22%	12.65%	13.0%	12.3%	12.7%	11.6%	12.6%	12.7%	12.6%	12.8%

The cells in yellow identify a technology that if unconstrained is chosen by the model but that its selection has been excluded. The orange cell represent a change in the solution (in the combination of technologies) when the technology from the yellow cell has been constrained.

Table 126. Outcome of the meta-heuristics optimisation of the vehicle specification based on LH-UNLTD2 scenario and the constraint of individual technology choices.

Output for Multicriteria Decision Analysis	STRATEGY 1										
	Fuel Price Medium LH-UNLTD2 Scenario										
Net Present Cost	383,693	392,095	385,806	384,429	387,254	385,787	390,408	385,802	385,745	385,943	385,184
GHG Emissions (ton kg CO_2 eq.)	324	343	329	324	333	331	339	329	339	330	406
Risk Technology Maturity	4	4	4	4	4	4	4	4	4	6	4
Risk Safety & Limitations	4	4	4	4	4	4	4	4	4	4	4

Table 127. Emissions (ton CO_2 eq.) and KPIs for long-haul duty HGVs under LH-UNLTD2 scenario with individual technologies excluded.

GHG Emissions (ton kg CO_2 eq.)	Long Haul										
	Optimisation with Unlimited Risk (S1)										
	Fuel Price Medium LH-UNLTD2 Scenario										
Scope 1	208.0	220.0	210.7	208.0	213.5	212.0	217.4	210.7	217.4	211.4	179.0
Difference	-50.2%	-47.28%	-49.52%	-50.2%	-48.8%	-49.2%	-47.9%	-49.5%	-47.9%	-49.3%	-57.1%
Scope 2	0	0	0	0	0	0	0	0	0	0	0
Scope 3	116.4	123.4	118.0	116.4	119.6	118.7	121.8	118.0	121.8	118.4	227.3
Difference	-34.7%	-0.30779049	-0.337946065	-34.7%	-32.9%	-33.4%	-31.6%	-33.8%	-31.6%	-33.6%	27.5%
All Scopes (baseline)	324.4	343.4	328.7	324.4	333.1	330.7	339.2	328.7	339.2	329.8	406.3
Difference	-45.53%	-42.34%	-44.81%	-45.53%	-44.07%	-44.47%	-43.04%	-44.81%	-43.04%	-44.62%	-31.79%
Outside Scopes (baseline)	363.8	385.4	368.7	363.8	373.7	371.0	380.7	368.7	380.7	370.0	321.8
Difference	-22.64%	-18.02%	-21.60%	-22.6%	-20.5%	-21.1%	-19.0%	-21.6%	-19.0%	-21.3%	-31.6%
Total Emissions (Inside/Outside)	688	729	697	688	707	702	720	697	720	700	728
Difference	-35.43%	-31.61%	-34.57%	-35.43%	-33.68%	-34.16%	-32.45%	-34.57%	-32.45%	-34.34%	-31.69%
g CO_2eq./km (all scopes)	377	399	382	377	387	384	394	382	394	383	472
g CO_2eq./tonne-km (all scopes)	0.0200	0.0212	0.0203	0.0200	0.0206	0.0204	0.0209	0.0203	0.0209	0.0204	0.0251
g CO_2eq./cage-km (all scopes)	0.0053	0.0056	0.0054	0.0053	0.0055	0.0054	0.0056	0.0054	0.0056	0.0054	0.0066
g CO_2eq./case-km (all scopes)	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0003

APPENDIX 17 – SENSITIVITY ANALYSIS MILEAGE OVER NPC LONG-HAUL HGVS.

Inputs Ranked by Mean			Output		
Name	Analysis vs. Base	Value	Mean	Min	Max
km year / 16	-20.00%	137006.3375	-376600.752	-376600.752	-376600.7526
km year / 17	-20.00%	137691.375	-377291.601	-377291.601	-377291.6012
km year / 18	-20.00%	138379.8375	-377644.918	-377644.918	-377644.9185
km year / 15	-20.00%	136324.725	-377669.704	-377669.704	-377669.7042
km year / 19	-20.00%	139071.7375	-378022.464	-378022.464	-378022.4643
km year / 16	-13.33%	148423.5323	-378964.825	-378964.825	-378964.8258
km year / 17	-13.33%	149165.6563	-379425.392	-379425.392	-379425.3921
km year / 18	-13.33%	149911.4906	-379660.937	-379660.937	-379660.9373
km year / 15	-13.33%	147685.1188	-379677.461	-379677.461	-379677.4611
km year / 19	-13.33%	150661.049	-379912.634	-379912.634	-379912.6345
km year / 16	-6.67%	159840.7271	-381328.899	-381328.899	-381328.899
km year / 17	-6.67%	160639.9375	-381559.183	-381559.182	-381559.1829
km year / 18	-6.67%	161443.1438	-381676.956	-381676.956	-381676.9561
km year / 15	-6.67%	159045.5125	-381685.218	-381685.21	-381685.218
km year / 19	-6.67%	162250.3604	-381802.805	-381802.804	-381802.8048
km year / 16	+0.00%	171257.9219	-383692.972	-383692.972	-383692.9722
km year / 17	+0.00%	172114.2188	-383692.974	-383692.973	-383692.9737
km year / 15	+0.00%	170405.9063	-383692.975	-383692.974	-383692.9749
km year / 18	+0.00%	172974.7969	-383692.975	-383692.974	-383692.9749
km year / 19	+0.00%	173839.6719	-383692.975	-383692.975	-383692.975
km year / 19	+6.67%	185428.9833	-385583.145	-385583.145	-385583.1453
km year / 15	+6.67%	181766.3	-385700.731	-385700.731	-385700.7318
km year / 18	+6.67%	184506.45	-385708.993	-385708.993	-385708.9938
km year / 17	+6.67%	183588.5	-385826.764	-385826.764	-385826.7645
km year / 16	+6.67%	182675.1167	-386057.045	-386057.045	-386057.0454
km year / 19	+13.33%	197018.2948	-387473.315	-387473.315	-387473.3155
km year / 15	+13.33%	193126.6938	-387708.488	-387708.488	-387708.4886
km year / 18	+13.33%	196038.1031	-387725.012	-387725.012	-387725.0126
km year / 17	+13.33%	195062.7813	-387960.555	-387960.555	-387960.5553
km year / 16	+13.33%	194092.3115	-388421.118	-388421.118	-388421.1186
km year / 19	+20.00%	208607.6063	-389363.485	-389363.485	-389363.4858
km year / 15	+20.00%	204487.0875	-389716.245	-389716.245	-389716.2455
km year / 17	+20.00%	206537.062	-390094.346	-390094.346	-390094.346
km year / 16	+20.00%	205509.506	-390785.192	-390785.192	-390785.192

APPENDIX 18 – AHP SCORING FOR REGIONAL HGVS STRATEGIES

Net Present Cost (£)	S1 (UB-UNLTD2)	S2 (UB-GHG2)	S3 (UB-RITM2)	S4 (UB-RISL2)
S1 (UB-UNLTD2)	1	4	2	5
S2 (UB-GHG2)	1/4	1	1/4	1/2
S3 (UB-RITM2)	1/2	4	1	4
S4 (UB-RISL2)	1/5	2	1/4	1
	1.95	11.00	3.50	10.50

					SCORE
S1 (UB-UNLTD2)	0.513	0.364	0.571	0.476	0.481
S2 (UB-GHG2)	0.128	0.091	0.071	0.048	0.085
S3 (UB-RITM2)	0.256	0.364	0.286	0.381	0.322
S4 (UB-RISL2)	0.103	0.182	0.071	0.095	0.113
	1.00	1.00	1.00	1.00	1.00

n2= 4

	AWT		
		Consistency Index	0.04334207
S1 (UB-UNLTD2)	2.0263	Random Index	0.9
S2 (UB-GHG2)	0.3416	Comparison	0.04815786
S3 (UB-RITM2)	1.3514		
S4 (UB-RISL2)	0.4585		
	4.13	Under 0.10?	YES

GHG Emissions (t CO_2 eq.)	S1 (UB-UNLTD2)	S2 (UB-GHG2)	S3 (UB-RITM2)	S4 (UB-RISL2)
S1 (UB-UNLTD2)	1	1/2	2	5
S2 (UB-GHG2)	2	1	2	6
S3 (UB-RITM2)	1/2	1/2	1	5
S4 (UB-RISL2)	1/5	1/6	1/5	1
	3.70	2.17	5.20	17.00

					SCORE
S1 (UB-UNLTD2)	0.270	0.231	0.385	0.294	0.295
S2 (UB-GHG2)	0.541	0.462	0.385	0.353	0.435
S3 (UB-RITM2)	0.135	0.231	0.192	0.294	0.213
S4 (UB-RISL2)	0.054	0.077	0.038	0.059	0.057
	1.00	1.00	1.00	1.00	1.00

n2= 4

	AWT		
		Consistency Index	0.03128748
S1 (UB-UNLTD2)	1.2239	Random Index	0.9
S2 (UB-GHG2)	1.7934	Comparison	0.03476386
S3 (UB-RITM2)	0.8633		
S4 (UB-RISL2)	0.2312		
	4.0939	Under 0.10?	YES

Risk Technology Maturity	S1 (UB-UNLTD2)	S2 (UB-GHG2)	S3 (UB-RITM2)	S4 (UB-RISL2)
S1 (UB-UNLTD2)	1	1	1/3	1/5
S2 (UB-GHG2)	1	1	1/3	1/5
S3 (UB-RITM2)	3	3	1	1/4
S4 (UB-RISL2)	5	5	4	1
	10.00	10.00	5.67	1.65

					SCORE
S1 (UB-UNLTD2)	0.100	0.100	0.059	0.121	0.095
S2 (UB-GHG2)	0.100	0.100	0.059	0.121	0.095
S3 (UB-RITM2)	0.300	0.300	0.176	0.152	0.232
S4 (UB-RISL2)	0.500	0.500	0.706	0.606	0.578
	1.00	1.00	1.00	1.00	1.00

n2= 4

	AWT
S1 (UB-UNLTD2)	0.3829
S2 (UB-GHG2)	0.3829
S3 (UB-RITM2)	0.9465
S4 (UB-RISL2)	2.4561
	4.0977

Consistency Index	0.03255307
Random Index	0.9
Comparison	0.03617007
Under 0.10?	YES

Risk Safety & Limitations	S1 (UB-UNLTD2)	S2 (UB-GHG2)	S3 (UB-RITM2)	S4 (UB-RISL2)
S1 (UB-UNLTD2)	1	3	1	1/5
S2 (UB-GHG2)	1/3	1	1/3	1/7
S3 (UB-RITM2)	1	3	1	1/5
S4 (UB-RISL2)	5	7	5	1
	7.33	14.00	7.33	1.54

					SCORE
S1 (UB-UNLTD2)	0.136	0.214	0.136	0.130	0.154
S2 (UB-GHG2)	0.045	0.071	0.045	0.093	0.064
S3 (UB-RITM2)	0.136	0.214	0.136	0.130	0.154
S4 (UB-RISL2)	0.682	0.500	0.682	0.648	0.628
	1.00	1.00	1.00	1.00	1.00

n2= 4

	AWT
S1 (UB-UNLTD2)	0.6251
S2 (UB-GHG2)	0.2562
S3 (UB-RITM2)	0.6251
S4 (UB-RISL2)	2.6157
	4.0739

Consistency Index	0.02461734
Random Index	0.9
Comparison	0.0273526
Under 0.10?	YES

APPENDIX 19 – AHP SCORING FOR LONG-HAUL HGVS STRATEGIES

Net Present Cost (£)	S1 (LH-UNLTD2)	S2 (LH -GHG2)	S3 (LH -RITM2)	S4 (LH -RISL2)	
S1 (UB-UNLTD2)	1	5	2	3	
S2 (UB-GHG2)	1/5	1	1/4	1/2	
S3 (UB-RITM2)	1/2	4	1	2	
S4 (UB-RISL2)	1/3	2	1/2	1	
	2.03	12.00	3.75	6.50	
					SCORE
S1 (UB-UNLTD2)	0.492	0.417	0.533	0.462	0.476
S2 (UB-GHG2)	0.098	0.083	0.067	0.077	0.081
S3 (UB-RITM2)	0.246	0.333	0.267	0.308	0.288
S4 (UB-RISL2)	0.164	0.167	0.133	0.154	0.154
	1.00	1.00	1.00	1.00	1.00

	AWT		
	n2=	4	
	AWT	Consistency Index	0.00704262
S1 (UB-UNLTD2)	1.9226	Random Index	0.9
S2 (UB-GHG2)	0.3258	Comparison	0.00782514
S3 (UB-RITM2)	1.1605		
S4 (UB-RISL2)	0.6199		
	4.0211	Under 0.10?	YES

GHG Emissions (t CO_2 eq.)	S1 (LH-UNLTD2)	S2 (LH -GHG2)	S3 (LH -RITM2)	S4 (LH -RISL2)	
S1 (UB-UNLTD2)	1	1/3	2	5	
S2 (UB-GHG2)	3	1	2	6	
S3 (UB-RITM2)	1/2	1/2	1	5	
S4 (UB-RISL2)	1/5	1/6	1/5	1	
	4.70	2.00	5.20	17.00	
					SCORE
S1 (UB-UNLTD2)	0.213	0.167	0.385	0.294	0.265
S2 (UB-GHG2)	0.638	0.500	0.385	0.353	0.469
S3 (UB-RITM2)	0.106	0.250	0.192	0.294	0.211
S4 (UB-RISL2)	0.043	0.083	0.038	0.059	0.056
	1.00	1.00	1.00	1.00	1.00

	n2=	4	
	AWT	Consistency Index	0.05935011
S1 (UB-UNLTD2)	1.1212	Random Index	0.9
S2 (UB-GHG2)	2.0187	Comparison	0.06594457
S3 (UB-RITM2)	0.8564		
S4 (UB-RISL2)	0.229		
	4.1781	Under 0.10?	YES

Risk Technology Maturity	S1 (LH-UNLTD2)	S2 (LH -GHG2)	S3 (LH -RITM2)	S4 (LH -RISL2)
S1 (UB-UNLTD2)	1	1	1/3	1/5
S2 (UB-GHG2)	1	1	1/3	1/5
S3 (UB-RITM2)	3	3	1	1/4
S4 (UB-RISL2)	5	5	4	1
	10.00	10.00	5.67	1.65

					SCORE
S1 (UB-UNLTD2)	0.100	0.100	0.059	0.121	0.095
S2 (UB-GHG2)	0.100	0.100	0.059	0.121	0.095
S3 (UB-RITM2)	0.300	0.300	0.176	0.152	0.232
S4 (UB-RISL2)	0.500	0.500	0.706	0.606	0.578
	1.00	1.00	1.00	1.00	1.00

	AWT		
	n2=	4	
		Consistency Index	0.03255307
S1 (UB-UNLTD2)	0.3829	Random Index	0.9
S2 (UB-GHG2)	0.3829	Comparison	0.03617007
S3 (UB-RITM2)	0.9465		
S4 (UB-RISL2)	2.4561		
	4.0977	Under 0.10?	YES

Risk Safety & Limitations	S1 (LH-UNLTD2)	S2 (LH -GHG2)	S3 (LH -RITM2)	S4 (LH -RISL2)
S1 (UB-UNLTD2)	1	3	1	1/5
S2 (UB-GHG2)	1/3	1	1/3	1/7
S3 (UB-RITM2)	1	3	1	1/5
S4 (UB-RISL2)	5	7	5	1
	7.33	14.00	7.33	1.54

					SCORE
S1 (UB-UNLTD2)	0.136	0.214	0.136	0.130	0.154
S2 (UB-GHG2)	0.045	0.071	0.045	0.093	0.064
S3 (UB-RITM2)	0.136	0.214	0.136	0.130	0.154
S4 (UB-RISL2)	0.682	0.500	0.682	0.648	0.628
	1.00	1.00	1.00	1.00	1.00

	AWT		
	n2=	4	
		Consistency Index	0.02461734
S1 (UB-UNLTD2)	0.6251	Random Index	0.9
S2 (UB-GHG2)	0.2562	Comparison	0.0273526
S3 (UB-RITM2)	0.6251		
S4 (UB-RISL2)	2.6157		
	4.0739	Under 0.10?	YES

APPENDIX 20 – FRAMEWORK FOR SHARING REFUELLING INFRASTRUCTURE

Models such as THRIVE (Lebutsch and Weeda, 2011) can help to evaluate the future evolution of refuelling infrastructure in a geographical area. This models assume a number of first movers (seeds) when creating an initial market. However, logistics firms cannot be expected to rely on this type of predictions in regards to future refuelling infrastructure developments. They need reliable and secure fuel supplies before investing of fuel technologies. To overcome the chicken-and-egg cycle between demand and supply of alternative lower carbon fuels, in the absence of a strong governmental support, a potential solution is to share the investment costs with other companies. A framework for sharing refuelling infrastructure was developed (Figure 138); however this was not implemented by the industrial sponsor. This could facilitate supply chain collaboration between logistics organisations by improving the business case for innovative low carbon fuel technologies. This framework could be reviewed to include other partners (e.g. local authorities' fleets). This framework was inspired by the 7 steps process for transport collaboration (ECR UK, 2008); adapted for sharing filling stations instead of lorry lanes.

Developing supply chain collaboration opportunities requires a great deal of trust between partners and commitment to deliver a good quality of service. The outcome of the framework facilitate the discussions regarding who bears the costs and risk of infrastructure deployment and maintenance. This framework can also be applied to the refilling of cryogenic refrigeration gases and electric plug-in points. The framework consists of seven stages.

1. INVENTORY OF REFUELLING AND INFRASTRUCTURE NEEDS

A statistical analysis of daily routes show the distances and therefore, the fuel consumption requirements for each HGV. The results should look similar to Table 109. Compiling other technical information such as vehicles and fuel types, filling pressures and noise levels will indicate the needs of the fleet. This should be matched with the characteristics of the refuelling points. Considerations may include restricted night access and availability of geofencing systems to alert and give enough time to the staff controlling the refuelling station to be ready when the HGV arrives. Once a list of owned filling stations and their characteristics and constraints is complete, this information will help other partners to analyse the suitability of such resources and the feasibility of business arrangements.

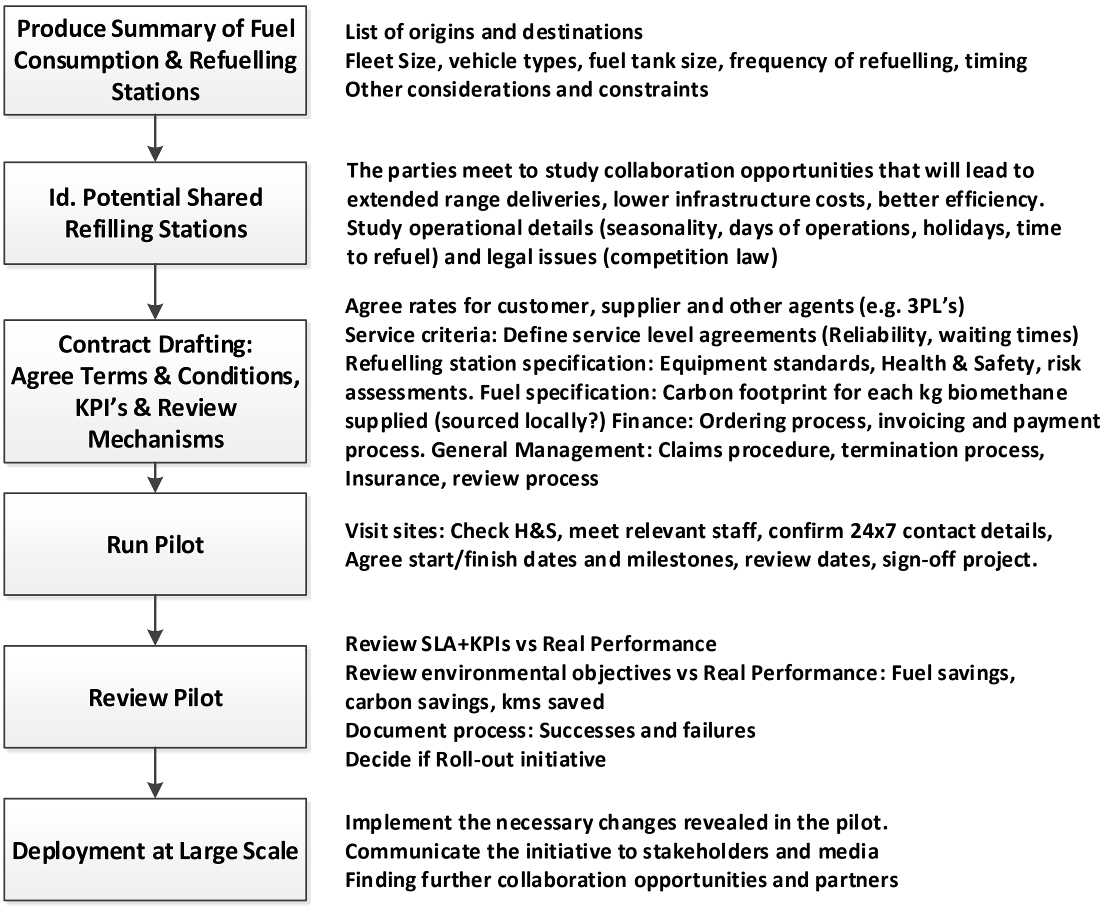


Figure 138. Framework for sharing refuelling infrastructure.

Table 128. Example of a summary of fuel demand needs.

From	To	Trucks	Type Truck	Fuel	Pressure	Fuel Tank	Daily Freq	Total Nee	Departure	Hours	Other Considerations
					atm	kg		kg			
Basingstoke	SW5 4EP	1	38T	Biomethane	250	300	1	300	06:00	12	
Basingstoke	SO17 1BJ	2	18T	CNG	250	250	1	500	09:00	8	
Basingstoke	Liverpool	1	38T	Biomethane	250	300	1	300	12:00	6	
			(space)	(spec)	(standard)	(quantity)	Daily refu	Total Q	Time sensitive? Whe		Constraints

2. IDENTIFYING REFUELLING STATIONS TO BE SHARED

Once the partners have shared information regarding refuelling needs and available resources, they need to analyse which filling stations are of their interest for economical or operational reasons. This analysis may consider constraints during peaks of activity (e.g. seasonality), working time and the internal cost of delivering the service to external fleets. At this point, the impact of detours to the location of the partners' filling stations should be evaluated. If there are not enough filling stations, the parties should consider placing new ones at the optimal locations.

3. AGREEING KPIs & REVIEWING MECHANISMS

Once there is an interest for using certain filling stations the technical aspects have to be negotiated. Ideally, with Service Level Agreements (SLAs) that specify aspects such as refuelling waiting times, reliability of filling stations, health and safety standards, fuel specification, risk assessments and other financial and IT terms and conditions (e.g. EDI, credit facilities, payment processes). Environmental performance indicators should also be agreed at this stage. Examples of these could be the standard for measuring GHG emissions, indirect land use changes, water footprints, etc.

As any other service contracts, a review process must be agreed to evaluate the business relationship. This includes SLA terms and conditions and procedures for termination and renewal of the contracts.

4. AGREEING RATES ON STATION BY STATION BASIS

After agreeing the technicalities of the service, costs per unit of energy must be decided upon. Different refuelling points may have different costs structure due to factors such as fuel (e.g. different suppliers of fuels will charge different prices) and running costs (e.g. 24/7 availability may require extra qualified personnel at night). The contracts should provide financial information that should be input in the mathematical model.

5. RUNNING THE PILOT PROJECT

Following the spirit of the EU White Paper Roadmap to a Single European Transport Area (2011) that encourages large demonstration projects to encourage market take-up, if there has been a solid business case for sharing refuelling stations, the next step should be conducting a pilot project. Recording all the relevant information is crucial to allow a thorough analysis at the end of this stage. Regular meetings to evaluate performance and milestones may help to avoid future issues.

6. REVIEWING PILOT PROJECT

Each partner should have to evaluate if the operational, environmental and financial expectations of the collaboration agreement have been met. Changes may arise at this stage, which means that KPIs, review mechanisms and costs may be renegotiated. The experience has to be documented and if successful, precede to the last stage.

7. DEPLOYMENT AT LARGE SCALE

In the roll-out stage, changes revealed in the review of the project have to be implemented. At this stage, the partnership should be announced to the

stakeholders and press releases agreed among the partners. Communicating the benefits may represent reputational benefits that might produce an interest from future partners. Exploring the possibilities of environmental awards could also be considered.

GLOSSARY

CONTROL VEHICLE (CV)

The Control Vehicle is used to obtain reference data for the Test and is not modified in any way or used for any other purpose during the entire Test.

DUTY/ DRIVING CYCLE

The cycle is comprised of; length in miles, number of complete stops, distance between stops, average road speed using only rolling time, number of idle periods, length of total idle time and length of idle periods, engine speed and accessories used during idle period, reverse driving, and any unique shifting transmission or operational activity.

FLOW METER

An instrument used to measure the rate of flow or volume of a fluid.

GLOBAL WARMING POTENTIAL

It is a measure of how much heat a mass of GHG gas traps in the atmosphere, and it compares it with a the one of carbon dioxide.

GOODS LIFTED

Freight activity measured in terms of the weight of goods (tonnes) carried taking no account of the distance they are carried.

GOODS MOVED

Freight activity measured in terms of the weight of goods (tonnes) and distance (kilometres) carried. It is measured in tonne-kilometres, as a result of weight of the load multiplied by the distance it is carried. Goods moved is a better measure of the activity done by road haulage vehicles.

GRAVIMETRIC

Measurement by weight.

GROSS COMBINATION WEIGHT (GCW)

Applies to combination vehicles. The combination of the total weight of the tractor (powered unit) the total weight of the trailer and the weight of the freight load.

GROSS VEHICLE WEIGHT (GVW)

Applies to single unit vehicles. The total weight of a vehicle with maximum freight load.

GROSS VEHICLE WEIGHT RATING (GVWR)

The maximum allowable total mass of a road vehicle when loaded including the weight of the vehicles, fuel, passengers, cargo and trailer tongue weight.

RADIATIVE FORCING

It expresses the change in energy in the atmosphere due to GHG emissions.

SCALE
The scale is used to weigh the fuel weight tank and its contents during the test process. The scale must have sufficient capacity and resolution to support the testing process as described in section 4.3 (page 145).
TARE WEIGHT (TW)
Weight of empty vehicle with full fuel tanks, lubricants and trailer but without occupants or load.
TEST (T)
A test is composed of a Baseline Segment and a Test Segment
TEST ROUTE, ON-ROAD
The route shall be representative of the desired drive cycle under investigation. The route should have minimal traffic to increase repeatability. For consideration, roadways using a cloverleaf at the turn around point will allow consistent and repeatable operation of both vehicles for every run. The route shall have a common start and end point.
RUN (R)
A complete and simultaneous circuit of the specified test route by both the Test Vehicle(s) and the Control Vehicle. Each Run generates one Data Point for the Test Vehicle and one Data Point for the Control Vehicle.
TEST SEGMENT
A minimum of three (3) Runs with both the Control Vehicle and a modified Test Vehicle.
TEST VEHICLE
The Test Vehicle is used to evaluate modifications to a vehicle between the Baseline Segment and Test Segment of a Test. The modifications to the Test Vehicle may be components, technologies, or system changes.
WIND VELOCITY (VW)
The rate of motion of the air past a fixed point.

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