

Sim-Heuristics Low Carbon Technologies Selection Framework for Reducing Costs and Carbon Emissions of Heavy Goods Vehicles

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UK logistics fleets face increasing competitive pressures due to volatile fuel prices and the small profit margins in the industry. By reducing fuel consumption, operational costs and carbon emissions can be reduced. While there are a number of technologies that can reduce fuel consumption, it is often difficult for logistics companies to identify which would be the most beneficial to adopt over the medium and long term. With a myriad of possible technology combinations, optimising the vehicle specification for specific duty cycles requires a robust decision making framework. This paper combines simulated truck and delivery routes with a metaheuristic evolutionary algorithm to select the optimal combination of low carbon technologies that minimise the GHG emissions of long haul heavy goods vehicles during their lifetime cost. The framework presented is applicable to other vehicles including road haulage, waste collection fleets and buses by using tailored parameters in the heuristics model.

Keywords: Sim Heuristics, freight, heavy goods vehicles, energy, GHG, technology

1. Introduction

The combustion of fossil fuels results in poor air quality and greenhouse gas (GHG) emissions. The link between carbon emissions and climate change is well established (Stern 2007; IPCC 2013) and governments around the world are now defining policies and legislation that seek to mitigate the negative impacts. The European Commission (2010a) aims to reduce its GHG emissions by 80-95% below 1990 levels by 2050 with intermediate climate and energy targets by 2020, which include a reduction in EU GHGs of at least 10% below 1990 levels for the transport sector (European Commission 2010b). By 2030, total GHG emissions should be reduced by 40% according to the 2030 policy framework for climate and energy signed in 2014 (Commission 2014).

According to DECC (2014a), around 4.2% of all the UK anthropogenic GHGs emissions are produced by heavy goods vehicles (HGV). Commercial Transportation of food for UK consumption represents around 9% of the GHGs emissions of the food chain (Defra 2011) and between 1.8% (FRPERC, The Grimpsby Institute, and University of Bristol 2010) and 2.5% (Garnett 2003) of all UK carbon emissions.

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, with respect to 1990 levels, by improving a vehicle's efficiency through new engines, materials and designs and cleaner energy use through new fuels and propulsion systems. Internal combustion engines running on diesel based fuels dominate UK heavy goods vehicle fleets with emissions from refrigerated food vehicles being particularly hightened due to energy consumption and gas leakage issues from transport refrigeration units (TRU).

Typically, for the same type of vehicle, lower fuel consumption leads to lower operating costs and carbon emissions. When the additional capital expenditure of procuring more efficient technologies is kept to an optimal level, it is possible to achieve the lowest net present costs, resulting in the highest profits for specific operating conditions. This is of critical importance in the UK where fuel costs rose by 41% between January 2009 to 2013 (DECC 2013), representing almost 30% of the total operating costs for a 16-18t rigid vehicle (FTA 2013). Over the same period, the Food Price Index rose by 47% (FAO 2013) increasing competitive pressures among food supply chains even further. Despite this trend being recently reversed with Brent Crude oil and natural gas prices declining by 40% and 17% respectively over the past 12 months (Thomson Reuters 2016), those logistics firms that gamble against the volatility of oil prices through financial instruments (e.g. calls options) are at a higher risk if they do not forecast fuel prices volatility correctly.

Logistics firms have to meet public policy targets regarding the carbon agenda. However, delivering freight sustainably is not only about reducing the negative environmental externalities of transport but also undertaking logistics operations in a cost efficient manner that meets customer expectations. . This paper proposes a sim-heuristics framework that can be used by

procurement decision makers to address these issues by specifying the right combination of low carbon technologies (LCT) that minimise the total vehicle cost of ownership. The fleet renewal decision making method used in this framework is based on the net present value (NPV); a more applicable technique compared to the typical payback period as it considers the time-value of money, provides a monetary value that allows a clear comparison between available alternatives, emphasises cash flow measures and considers returns beyond the payback period (Burns and Walker 1997).

The innovative framework developed in this research automates the selection of energy efficient technologies for road haulage vehicles. The approach taken is different and more powerful compared to existing models that can aid fleet managers calculate fuel savings and carbon emissions which currently require the users to pre-select the technologies they wish to investigate. The model created in this research automates the technology selection process on behalf of the user in order to minimise the GHG output of their vehicles cost-efficiently, according to their duty cycle. In practice, evaluating all the potential combinations of low carbon technologies cannot realistically be achieved without the help of a mathematical model as the number of potential combinations can include millions of vehicle configurations. It is also not technically or economically feasible to expect a company to conduct real live trials to ascertain the fuel savings of each possible technology package. This research presents a framework that can help logistics companies narrow down the combinations of technologies that yield the highest net present cost savings by using a mathematically robust decision making methodology.

Using a major fast food logistics provider as a case study, a framework has been created and applied to a real dataset to show the potential of the framework in action. HGV manufacturers will find the approach beneficial for tailoring the configuration of vehicles to the operating requirements of their customers whilst meeting vehicle efficiency standards such as the 'Phase 2 GHG Emissions Standards and Fuel Efficient Standards for Medium –and Heavy-duty Engines and vehicles (US EPA, US DOT, and NHTSA 2015) .

2. Literature Review

The 'Carbon Intervention Modelling Tool' developed by Heriot-Watt University (2011) is a decarbonisation prediction model that estimates how much CO₂ can be reduced from freight transport operations by applying one or more decarbonisation measures as chosen by the user. The UK DfT developed the 'Freight Best Practice Fuel Ready Reckoner' that allows fuel savings to be estimated for different fuel saving techniques (DfT 2010). In this model, the user can understand the cumulative savings of each option alongside the inter-relations between technologies. The model indicates total fuel savings per annum; however, it is the user who has to select the technologies until the combination that yields the greater savings are identified. This model also calculates air quality emissions but only to Euro V and capital expenditure is not included in the analysis.

The 'Low Emission Toolkit' was developed by the 'Low Emissions Strategies Partnership of UK Local Authorities' and helps to estimate the transport emissions associated with new technological developments. It also compares low emissions vehicle technologies on an individual vehicle basis, calculating emissions and benefits of lower carbon vehicles (Strategies.co.uk 2013). The model includes eight LCT's, not all of them available to HGV's (fairings, shaped trailers, spray suppression, low rolling resistance tires, single wide tires, auto tyre pressure adjustment, predictive cruise control and vehicle platooning) in addition to driver behaviour improvements. In a similar approach to the one applied by Baker et al. (2009), this model looked at costs, technology maturity and limitations related to the lack of infrastructure. It also required the user to select the desired technologies in order to compute the likely carbon savings and uses the payback period. The model described in this paper considers the net present value (cost) as a more suitable investment appraisal technique for decision making than then payback period, as it allows the evaluation of specific rates of return, economic flows at different points in time, and a more realistic scenario analysis in combination to heuristics techniques for the optimisation of the vehicles' configuration (Ashford, Dyson, and Hodges 1988; Lefley 1996).

The Lumped Parameter Model (US EPA 2015) is an application that estimates the CO₂ reduction of various technology combinations or packages for light-duty vehicles (as selected

by the user), accounting for synergies between the technologies. This selection model cannot be applied to HGVs, it does not consider driving cycles and does not provide an economic assessment of the technologies chosen by the user.

There are many studies on low carbon technologies for heavy duty vehicles that inform decision makers of the fuel savings of individual or packages of technologies. This paper is novel in that it proposes a mathematical approach (sim-heuristics) to aid logistics companies choose the most optimal selection of low carbon technologies to reduce their carbon footprint cost-efficiently. Most of the literature reviewing full vehicles is focus on U.S. (Cooper et al. 2009; National Research Council 2010, 2012; Harrington and Krupnick 2012; Meszler, Lutsey, and Delgado 2015; Delgado and Lutsey 2015; Committee to Review the 21st Century Truck Partnership 2015) or European fleets (Baker et al. 2009; Connelly et al. 2011; Hill et al. 2011; Law, Jackson, and Chan 2012). The results of studies from different geographical areas can vary considerably due to differences in vehicle standards, regulations and legislation. As an example, the typical medium duty truck undertaking urban deliveries in the UK is a 7.5t 2-axle rigid lorry whereas heavy duty (motorway work) is typically carried out by articulated vehicles with GVW over 32.5t and 3-axles (Baker et al. 2009). Table 1 summarises the findings from the literature with regard to the main differences between EU and USA vehicle categories with regional deliveries being carried out by a mix of rigid and articulated vehicles. There are also considerable differences in vehicle length which in the UK equates to a maximum length for rigid vehicles of 12 m and 16.5 m for articulated vehicles (or 18.75 for a lorry with a trailer). In the U.S., the total length of articulated vehicles can be as much as 21.3-22.9 m (Law, Jackson, and Chan 2012). As speed limits differ between the EU and US, so driving cycles employed in trials and simulations (Table 1). Based on studies published by US EPA (2008), Law, Jackson, and Chan (2012), Gov.UK (2013) and Ecopoint Inc. (2013), Table 1 shows the main differences between US and EU HGV vehicles including operational data related to duty cycles and speed limits.

Table 1. 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 Carriage ways	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 ¹
Examples of Driving Cycles	WHVC (Urban)	EPA HD-UDDS	WHVC (Rural)	CARB HHDDT	WHVC (Motorway)	NESCAUM /SwRI

Studies conducted using US vehicles and operations suggest that fuel consumption reductions of 50% are possible in the period to 2020 (Cooper et al. 2009; National Research Council 2010, 2012). 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. Similarly, the National Research Council (2010) suggested that Class 8 vehicles could achieve 51% fuel consumption reduction (FCR) between 2015-2020 with a FCR of 20% coming from advanced engines, 11.5% from aerodynamic improvements, 11% from lower rolling resistance, 7% from transmissions and drivelines, 10% from hybrids and 1.25% from weight reductions. A medium duty class 6

¹ Texas up to 137.

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 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%), drivers training (over 1.9%) and allowing greater vehicle payloads through larger and heavier vehicles (up to 28%). In urban duty cycles, the main potential savings came from hybridisation (38%), intelligent transport systems (up to 15%) and driver training (up to 17%). Increasing size and weight also presented an opportunity to save up to 28% fuel on a unit payload basis for any cycle. In contrast, several other studies suggest fuel savings 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). In highway driving, the National Research Council (2012) indicated considerable fuel savings from aerodynamic improvements (19%), waste heat recovery (almost 17% FCR) and single wide base tyres (15% FCR).

Delgado and Lutsey (2015) focused on USA class 8 vehicles and the fuel savings that could be achieved in the 2020-2030 timeframe. The fuel savings expected in real world highway operations by 2017 compared to the 2010 baseline varied between 8% and 42%; by 2020 these could reach between 21% and 46%; and by 2030 as much as 48%-52% depending on the engine, transmission and tractor-trailer technologies (the latter included only aerodynamics and rolling resistance improvements). The results show that fuel economy in the U.S. for this type of HGV could increase from 2.33 km/L in 2010 (around 57.9 L/ 1000 ton-km) to 5.23 km/L (around 25.9 L/1000 ton-km) by 2030 by using hybrid systems with 60% braking regeneration efficiency). The savings from individual technologies ranged from 0.4% from friction reduction in transmissions to 22.2% for aerodynamic tractor-trailer improvements. An comprehensive

evaluation of the cost-effectiveness of these technologies is given by Meszler, Lutsey, and Delgado (2015).

In Europe, according to Baker et al. (2009), EU semi-trailers under long-haul duty cycles benefit most from vehicle technologies such as aerodynamic trailers (10%), electric bodies (e.g. cryogenic nitrogen trailer refrigeration) and vehicle platooning (10%). Both duty cycles can benefit considerably from the use of biofuels and alternative fuels. Medium duty trucks 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). This study also covered the potential for reducing carbon emissions by using second generation biofuels (e.g. biomethane) and alternative fuels (e.g. natural gas) and it also covers trailer refrigeration technologies such as cryogenic systems.

Hill et al. (2011) reviewed different low carbon technologies for informing potential policy actions. Their report suggested that urban operations could achieve 20-30% FCR by mainly improving powertrain efficiency improvements on long haul operations and targeting losses due to vehicle drag. 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 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 represent the major contributor to fuel reduction while at low speeds; alternative powertrain (hybridisation) offers the greatest savings. In a rural cycle (a mix of high and low speeds), the contribution of both factors is

similar. An additional 9% of fuel can be saved through a better management of auxiliary power (Connelly et al. 2011).

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.

Electric trucks can save 100% GHG emissions at their point of use (Baker et al. 2009; Hausberger et al. 2012) which depending on the energy grid mix may lead to considerably lower Well-to-Wheel emissions; however, at the moment there are no plug-in electric articulated semi-trailers anywhere in the world beyond port drayage (also known as shunting) or trunking operations in distribution centres. A similar concept known as tram trucks (trolley trucks) are being trialled by Siemens in the US and Germany with their e-highway traction system (Siemens 2014), where electric rigid HGVs are powered by a catenary and are combined with hybrid powertrains to allow overtaking other vehicles.

The impact of energy efficient technologies on reducing fuel consumption and GHG emissions focus on reducing the forces acting upon a vehicle, avoiding efficiency losses, allowing the use of decarbonised fuels and changing refrigerant gases for others with a lower global warming potential. Reducing the tractive power requirements of a vehicle to overcome forces acting upon it follows Newton's second law of motion. The force required to overcome air and rolling resistance, acceleration resistance and gradient are shown in Equation 1 (road load power equation). As only 42% of the energy is transferred into breaking power (National Research Council 2010, 2012; Baker et al. 2009), technologies that improve engine efficiency are key to reducing fuel consumption; however, there is a limit to the efficiency achievable by diesel engines. The US DoE (2013) considers that depending on the casting materials and the engine design used, the approximate diesel and gas engine maximum theoretical efficiencies are under 55%. Examples of beneficial powertrain technologies include devices and chemicals that improve combustion, systems that reduce wasted heat, friction and auxiliary losses (e.g. oil/water pump, auxiliary power units). To obtain the power required to overcome the forces shown in Equation

1, the resulting force has to be multiplied by the speed over time. Equation 2 shows that mass, rolling resistance, drag coefficient, frontal area of the vehicle, gradient and speed are critical factors in energy consumption. All things being equal, as the shape of the U.S. and EU trucks differ, their different aerodynamic coefficients produce different energy consumption demands to overcome aerodynamic forces. Similarly, as speed is a common factor in all parameters in Equation 2, different transient driving cycles produce very different power requirements, even when the same vehicles are used over the same distances. From Equation 2 it can be concluded that at higher speeds, aerodynamic improvements can make the greatest contribution to fuel savings while at lower speeds, rolling resistance is more important to overcome the forward forces.

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

Equation (1). 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

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

Equation (2). 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/s²)

C_{rr} = Tyre rolling resistance coefficient (dimensionless)

v = Speed (m/s)

ρ_a = Density of air (kg/m³)

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)

Reducing rolling resistance is possible by reducing mass, speed, or the rolling resistance coefficient of the tyres. This is possible by using low rolling resistance tyres or single wide base tyres. Aerodynamic vehicles with a lower drag coefficient, smaller frontal area and lower speed require less power. Predictive cruise control has also been suggested as a method for delivering fuel savings by influencing the energy required for overcoming the gradient factor of the power equation (Baker et al. 2009; Hill et al. 2011; Cooper et al. 2009). Climbing resistance is the factor that influences power requirements the most (Connelly et al. 2011) and for this reason, reducing mass and understanding clearly if the vehicle is going to run in relatively flat areas will help specify the most appropriate powertrain.

Equation 2 represents the energy needed for the vehicle without considering energy losses and the efficiency of the powertrain. It also assumes energy recovery when going downhill, which is not realistic unless the HGV has a technology that benefits from this such as flywheels or regenerative braking devices. This equation does not take into consideration the efficiency from engine maps and calculations would suggest that the lower the speed the lower the energy required by the vehicle. For this reason, a 3D simulation system to test LCT providing more degrees of freedom provides a much more accurate estimate of fuel consumption.

The fuel consumption of a vehicle is measured in litres per kilometre but this does not allow for a fair comparison of vehicle energy intensity between different haulage fleets, and it is for this reason that fuel consumption is typically normalised by unit of payload (e.g. fuel consumption per tonne-km or per m^3 -km). This makes it possible to appraise certain technologies that increase fuel consumption per vehicle-km (e.g. double decker trailers or draw-bar combination vehicles) due to their greater mass.

3. Methodology

The models found in the literature do not optimise the right combinations of LCT which highlights the importance and relevance of the framework presented here. The framework includes four main stages (Figure 1): i) a techno-economic analysis of the literature on low carbon technologies; ii) a statistical analysis of the industrial sponsor operations necessary to produce simulations and trials, iii) building statistically representative duty cycles and other inputs needed in later stages; iv) modelling and simulating vehicles' trips and technologies; and v) the application of a metaheuristics model for optimising the final vehicle specification according to the outputs generated in the previous stages.

The analysis of the literature suggested suitable technologies that could reduce the fuel consumption of HGV's, along with their respective advantages, challenges, synergies and constraints.

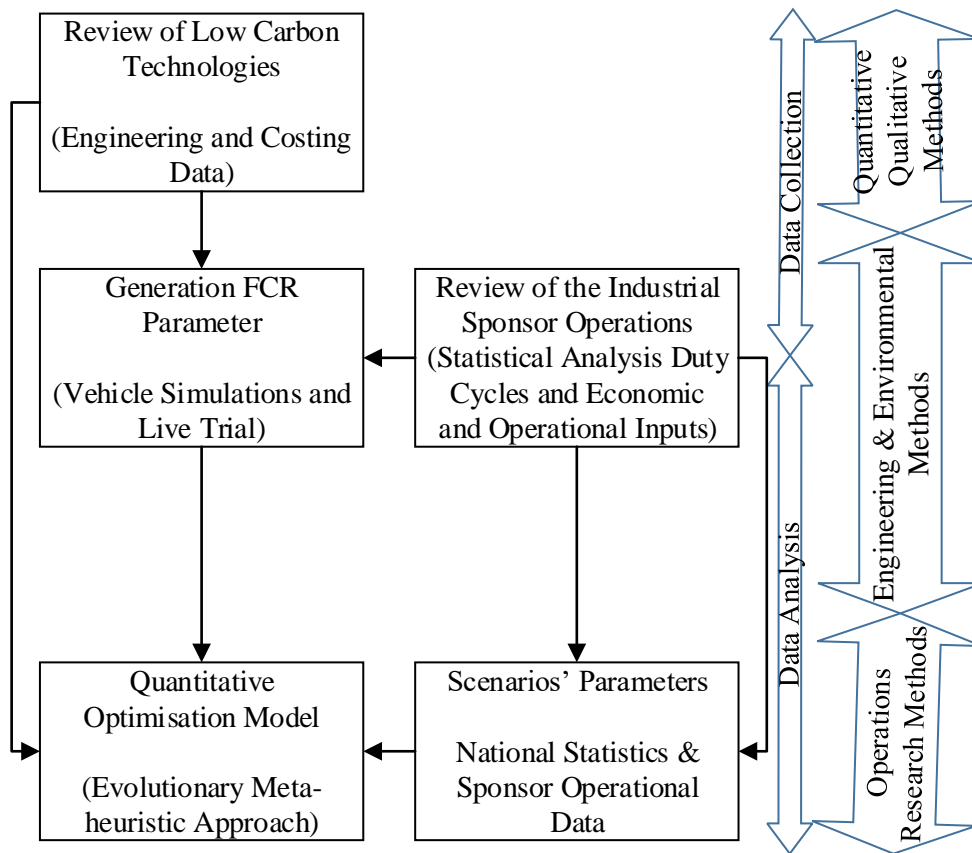


Figure 1. Structure of the methodology.

3.1 Review of the Industrial Sponsor Operations

Operational data from the fast food logistics provider have been used to produce the inputs needed in the metaheuristics model, and to build statistically representative duty cycles to simulate routes (e.g. speed, number of stops per trip). Dynamic analysis refers to the use of instrumenting software to monitor and collect data (Wieringa and Heerkens 2007) and via a telematics system through which real time operating data are captured and processed to build driving cycles. This information is uploaded to a server that can be interrogated using the SOAP protocol (Simple Object Access Protocol) or recorded via a data logger following a communication specification such as the NMEA 0183. The parameters that are available from the ECU and telematics unit include among other values; time, date, GPS coordinates, vehicle speed, rpm of the engine, clutch and exhaust brake.

The driving cycle, operational parameters and route coordinates are used to simulate vehicles and trips, allowing the evaluation of the FCR yield by different LCT. Several software packages can assist in the statistical analysis of driving cycles (e.g. Excel, NREL DRIVE, Matlab). Vehicle manufacturers can avoid this stage by using the standard driving cycles used to measure air quality emissions (e.g. ETC, US HDDT or the WHDC). To make like for like comparisons, once a driving cycle has been established, all simulations have to test different technologies using the same driving cycle.

3.2. Generation of the 'Fuel Consumption Reduction' Parameter

A virtual DAF CF-85 truck and trailer combination was modelled customising a baseline articulated semi-trailer included in the simulation environment (IPG Truckmaker) with parameters from technical DAF data sheets. The representative duty cycle from the previous stage and a real route were imported into the simulator. The digital road was built from the GPS coordinates of the telematics unit of the vehicles. A simulated driving style was selected based on the driving behaviour shown during a trial. The simulations replicated vehicle stops and weight reduction of the vehicles due to lower fuel load due to the fuel consumed during the trips. Once the FCR of a baseline control vehicle was simulated, a test vehicle was built

incorporating the low carbon technology being evaluated. The differences in fuel consumption between the control and test HGV were attributed to the technology improvement. The parameter obtained, 'FCR' constitutes one of the main inputs to the metaheuristics optimisation model.

The framework presented here encourages the use of simulations to avoid the issues associated with conducting live trials. Some technologies such as aerodynamic improvements that require computational fluid dynamics simulations are difficult to simulate by non experts . In the cases when conducting simulations is not feasible, relying on secondary sources or conducting a real world trial is a valid alternative .

3.3 Evolutionary Metaheuristic Model for Technology Selection

The quantitative model developed in this research is in essence a combinatorial binary optimisation problem that yields complex, non-smooth and non-linear solutions. A bespoke metaheuristics mathematical model based on evolutionary algorithms (tabu search and scatter search) was developed to optimise the selection of low carbon technologies for different types of HGV. Metaheuristic algorithms are one of the most practical approaches to solve combinatorial optimisation problems (Yagiura and Ibaraki 2001; Laguna 2011). Evolutionary algorithms have been previously used for function optimisation of multiple parameters (Mitchell 1998) and optimisation of engineering problems (Togun and Baysec 2010; Laguna et al. 2013) including technology selection that impacts on performance and economic parameters (Patel, Kirby, and Mavris 2006). Simple 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). On the other hand, Tabu search is a metaheuristic that 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, Laguna, and Glover 2006). Scatter search is another metaheuristic optimisation method that uses strategies (rules) for diversifying and intensifying search rather than relying on randomisation (as genetic algorithms do) and it can join TS to take advantage of

its adaptive memory (Martí, Laguna, and Glover 2006). Using simpler GA techniques increases the probability of the optimisation becoming stuck in a local optimum and therefore TS and SS approaches are used in this framework in order to maximise the chance of finding the global optima.

Taking an HGV as a baseline, the model uses OptQuest to find the optimal combination of LCT that minimise the net present cost during its 5 years life expectancy while simultaneously reducing its energy consumption and carbon emissions. OptQuest is an optimisation framework whose main optimisation engine uses tabu search and Scatter Search to obtain high quality solutions for non-linear non-smooth complex problems where a mix of continuous, integer, permutation, binary and other types of variables are allowed (Laguna et al. 2013).

3.3.1 Objective function

The model considers financial parameters such as the opportunity cost of capital; total costs of ownership of vehicles and LCT; taxation; fuels, refrigerant gases and carbon emissions prices over time based on fuels and gases emission factors; and economic growth trends under several scenarios to calculate the net present cost (NPC) of the lifetime of the HGV (equation 3).

Operating parameters include the annual mileage and tonnage delivered as well as the specified duty cycle that is used to find out the FCR of each technology. Equation 3 minimises the NPC of a long haul refrigerated HGV and it does so by combining linear (e.g. addition of fixed maintenance costs) and non-linear equations (equation 4). The function includes capital and operating expenditure of the HGV and add-on technologies (decision variables). The objective function represents the fitness function of the evolutionary algorithm.

$$NPC (\text{£}) = R_0 + \sum_{t=0}^n \frac{R_t}{(1+i)^t}$$

Equation (3)

Where:

NPC is the net present cost of the vehicle (£)

t is the lifetime in years of the HGV from 0 to n years

R₀ is the initial investment when procuring the vehicle

R_t is the net cash flow (cost) at time period t

i is the discount rate (also known as opportunity cost of capital)

3.3.2 Decision Variables

The FCR of a combination of technologies is non-linear and it is the product of the FCR of each individual technology selected (Equation 4) considering any potential constraint that excludes a particular set of technologies.

$$\text{Combined FCR (\%)} = 100 \times \left[1 - \prod_{i=0}^n (1 - FCR_i) \right]$$

Equation (4)

Where:

i is the number of technologies and

FCR_i is the fuel consumption reduction of technology i when this technology is chosen and it meets the constraints.

FCR is the aggregated percentage of fuel consumption reduction from a combination of i technologies

Due to different driving cycles, speed limits, weights, dimensions and aerodynamic characteristics among European and US HGV, to obtain better consistency the FCR inputs used in the model are the ones that appear in Table 2 and are mainly based on the results published by Hill et al. (2011) amended according to information provided by Continental (2015); Frigoblock UK Ltd (2013); Centre for Low Carbon Futures (2014); GKN Hybrid Power (2015); MarshallWeb (Thermoking) (2015); Kevothermal (2015); Spraydown (2013, 2015)). Each technology in Table 2 is considered to be a binary variable that when selected, combines its FCR with that of other technologies yielding the optimal combination of technologies that contributes to minimising the objective function. This affects not only the fuel consumption but also the capital costs of the purchased HGV by adding additional cost for each selected technology and the costs associated with the carbon emissions.

3.3.3 Constraints.

The model potentially evaluates a total of 2^n combinations, where n represents the number of

independent technologies. As 21 technologies are currently included in the model, a total of 2,097,152 combinations could be tested, reduced to 170,501 once all constraints are considered. At 30 technologies, over a billion combinations are created with multiple 'if' and 'or' conditions making this problem complex and time consuming to solve by other non-heuristic methods.

A technical analysis revealed that some low carbon technologies were incompatible (e.g. hydraulic and electric hybridisation powertrains) or are mutually exclusive as they had the same function (e.g. aerodynamic trailers, irregular body shapes and aerodynamic fairings; new generation wide-base and lower rolling resistance tyres). Other constraints were more subtle; 3 phase alternator unit refrigeration systems cannot work with stop-start mild hybrid trucks.

Table 2. Costs and fuel consumption reduction for each technology applied to long haul HGV updated to 2015 prices.

Low Carbon Technology		Number	Areas for improvement	FCR	Added Cost
Vehicle Technologies	Reduced Aerodynamic Resistance	1	Aerodynamic Trailers	11.00%	£3,242
		2	Aerodynamic Irregular body shape	5.00%	£815
		3	Aerodynamic Fairings	0.40%	£1,093
		4	Spray Reduction Mud Flaps	2.00%	£172
	Reduced Rolling Resistance	5	Low rolling resistance tyres	5.00%	£324
		6	New generation wide-base single tyres	5.00%	£1,204
		7	Automatic tyre pressure adjustment	3.00%	£10,921
	Vehicle Mass	8	Lightweighting Materials	2.20%	£1,482
	Intelligent VT	9	Predictive Cruise Control	5.00%	£1,297
	Auxiliary Systems	10	Controllable air compressor	1.50%	£176
Powertrain Technologies	Exhaust Heat Recovery	11	Heat Recovery (in general)	5.00%	£10,717
		12	Electrical Drive Turbocompound	3.00%	£6,484
	Transmissions	13	Automated Manual Transmission	5.00%	£4,369
	Mild Hybrid	14	Flywheels Hybrid	5.00%	£5,465
		15	Stop-Start: Electric Hybrid	1.00%	£871
		16	Pneumatic Booster - Air Hybrid	3.50%	£741
	Alternative PT	17	Full Hybrid: Series / Parallel - Electric	7.00%	£22,232
		18	Series / Parallel - Hydraulic	0.00%	£12,227
Refrigeration on Unit	Refrigeration Technologies	19	3 phase alternator Unit	100.00%	£5,377
		20	Hybrid Refrigeration Unit	11.00%	£3,226
		21	Vacuum Isolated Panels	5.00%	£2,997

Regarding vehicle technologies, it was assumed that aerodynamic trailers and irregular bodies (e.g. teardrop shape) were mutually exclusive as the latter also included aerodynamic fairings. This was also the case between low rolling resistance tyres and new generation single-base wide tyres. With regards to powertrain technologies, it was considered that just one hybrid technology could be chosen as it would make no sense to have two or three powertrain systems duplicating the same function. For example, flywheel and electric and hydraulic hybrids have similar functions and all have a stop-start technology embedded that powers the battery, hydraulic compressor or the flywheel. The constraint specifies that $0 \leq \text{flywheels} + \text{stop-start} + \text{electric hybrid} + \text{hydraulic hybrid} \leq 1$. Another of the powertrain technologies available is pneumatic boosters; 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). This technology is therefore not compatible with electric engines; as it is a technology that works with internal combustion engines. However, it is compatible with hybrid powertrains as these also have an small internal combustion engine (typically downsized). As there are no battery electric long-haul HGV at commercial stage yet, electric trucks were excluded in the model. Regarding low carbon refrigeration technologies, it was assumed that a trailer could not have more than one TRU, as there is no space in a trailer to fit them and it would not make sense to duplicate the same function. The sum of the binary decision variables is constrained to up to 1 technology in total: $0 \leq 3 \text{ phase alternator unit} + \text{hybrid unit} \leq 1$. When using start-stop technology, three-phase alternator units could not be selected as these draw power from the engine. If a vehicle stops in congestion, the engine would switch off and after a while the cold chain would be broken. For this reason, a constraint was added where: $0 \leq \text{stop-start} + 3 \text{ phase alternator} \leq 1$. Regarding refrigerant gases, conventional and hybrid TRUs were constrained to use R404A while 3 phase alternator refrigeration machines to R410A. 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, while this was 7.5% for refrigeration units running with R410A gas (e.g. three phase alternator refrigeration units).

3.3.4 Parameters

Taking the 2015-2020 period as a baseline scenario, the model permits the impacts of different technology scenarios to be projected. Parameters that are considered include fluctuating year-on-year national growth forecasts, energy prices (diesel, biodiesel and red diesel), carbon costs and GHG emission factors. Operating parameters include mileage forecasts, the fuel consumption of tractor and refrigeration units, the number of trips made per day, the working hours of the refrigeration unit per trip, refrigerant leakage rates, freight loads (e.g. cages, cases and tonnage) and maintenance costs. The cost of tyres per km and the percentage of diesel exhaust fluid (DEF) per litre of fuel are also considered. Examples of some of the parameters considered by the heuristics model are included in Table 3. *Distances*. Data regarding driving distances and trips per day have been provided by the case study company as appear in Table 3 and it has been assumed that trips per vehicle and day rise year on year due to routing and scheduling software and personnel efficiency improvements.

3.3.4.1 *Financial Parameters*. To calculate the net present costs, the rate of return used required by the operator was 9.7% and the vehicles life 5 years, as specified by the finance director of the logistics organisation on which this research is based.

3.3.4.2 *Emission Factors*. The results presented in this paper used the official emissions factors suggested by DECC (2014b). This includes the EF of fuels and refrigerant gases leakages. The model considers only Scope 1 emissions as this emissions fall within the boundaries of the operator organisation. It is assumed that diesel average blend (B5) produces 2.58 kg CO_{2eq} per litre, Red diesel (mineral diesel 2.67 kg CO_{2eq} per litre and B100 total direct GHG emissions are 0.0175 kg CO_{2eq} per litre.

4 Results

The technology specification that minimises the NPC for any articulated semi-trailer using any diesel or biodiesel mixture consists of aerodynamic trailers (e.g. deflectors, cab collar and fairings), the installation of a patented spray suppression mud-flap kit, low rolling resistance tyres, light weight tractor and trailer chasses (e.g. constructed from aluminium, composites, etc.),

Table 3. Baseline parameters considered in the heuristics model

Scenarios 2015-2020 (common baseline parameters)	
<u>Financial Parameters</u>	
Rate of Return	9.70%
Period	5 years (Lifetime of the Investment)
GDP	Central growth (Bank of England Forecasts)
Price DERV in 2015	£1.21
Price B100 in 2015	£0.84
Price Red Diesel in 2015	£0.72
Price of Carbon	£0.00
<u>Vehicle Parameters</u>	
Type of Vehicle	Articulated DAF CF-85
GVW	36t
Tires	295/80R22.5
Axles	4
<u>Refrigeration Unit Parameters</u>	
Semi-Trailer	13.4/78.79 m ³
Carrier	Transicold Vector 1950
Reefer	
Refrigerant	R-404A
<u>Operating Parameters Baseline Vehicle (before selecting technologies)</u>	
Duty Cycle	Long-Haul
Km per year	175,723
Tonnes delivered per year	3,138

Baseline	Scenarios								
	1	2	3	4	5	6	7	8	9
Fuel Tractor Unit	DERV	B65	B100	DERV		B65		B100	
FC (L/ 100km)	34.35	37.08	38.67	34.35	34.35	37.08	37.08	38.67	38.67
FC Tractor (5 y) in '000s L	301.8	325.8	339.7	301.8	301.8	325.8	325.8	339.7	339.7
Refrigeration (hrs./year)	3,800	3,800	3,800	2,227	2,228	1,940	1,941	1,764	1,765
FC Refrigeration Units (5 y) in '000s L	77.9	77.9	77.9	45.7	45.7	39.8	39.8	36.2	36.2

controllable air compressors (devices that avoid parasitic losses by eliminating the idling of the airbrake), and automated manual transmissions. Consistent with the literature (National Research Council 2010; Baker et al. 2009; Hill et al. 2011) the higher speed achieved in long-haul freight lends itself to aerodynamic technologies which yield the most improvements. The model focuses diesel engine technology for HGV and divides all LCTs into four categories: vehicle, powertrain,

refrigeration and fuel technologies. The fleet used in this case study uses Euro V trucks capable of running on any diesel mix up to B100; however the average mix for the case study organisation is B65 and this is the reason that this was also included in the analysis.

Table 4 shows 9 scenarios, where scenarios 1, 2 and 3 represent the choice of LCTs selected when the TRUs work 3,800 hrs/year. Scenarios 4 and 5, 6 and 7 and 8 and 9 show the sensitivity of the number of hours that a TRU has to work to trigger the selection of three phase alternator refrigeration units, instead of conventional gen-sets for each fuel. Over the specific amount of hours per year that appear in the scenarios, 3-phase TRUs are the recommended option over hybrid TRUs or mild hybridisation powertrains. Under this amount of working hours, air hybrid pneumatic boosters were selected by the metaheuristics model. This also considered the constraint that these TRUs cannot work with hybrid powertrains or with stop-start devices.

Compared to a baseline vehicle without LCT, in scenarios 1, 2 and 3 the model indicates that the optimal combination yields combined fuel savings (tractor and TRU) of 38.8%, 38.2% and 37.9% respectively. As 3-phase alternator refrigeration units are selected, the avoidance of using red diesel for refrigeration purposes decreases GHG emissions by 39.2%, 52.9% and 89.7% in each scenario. This considered a penalty in the fuel consumption of the tractor unit due to the additional power consumption of the alternator. The optimal vehicle specification leads to net present costs savings of around 17.6%, 17.4% and 17.2% over the 5 years life expectancy of the vehicles, reducing costs by £90,058, £83,598 and £78,811 respectively for scenarios 1 to 3.

Table 4. Carbon emissions and NPC savings obtained by the evolutionary algorithm using different scenarios.

		Scenarios								
		1	2	3	4	5	6	7	8	9
Fuel Type		DERV	B65	B100	DERV		B65		B100	
N.	Technology	Selection of Technology from the Heuristics Model								
1	Aerodynamic Trailers	1	1	1	1	1	1	1	1	1
2	Aerodynamic Irregular body shape	0	0	0	0	0	0	0	0	0
3	Aerodynamic Fairings	0	0	0	0	0	0	0	0	0
4	Spray Reduction Mud Flaps	1	1	1	1	1	1	1	1	1
5	Low rolling resistance tyres	1	1	1	1	1	1	1	1	1
6	New generation wide-base single tyres	0	0	0	0	0	0	0	0	0
7	Automatic tyre pressure adjustment	0	0	0	0	0	0	0	0	0
8	Lightweighting Materials	1	1	1	1	1	1	1	1	1
9	Predictive Cruise Control	1	1	1	1	1	1	1	1	1
10	Controllable air compressor	1	1	1	1	1	1	1	1	1
11	Heat Recovery (in general)	0	0	0	0	0	0	0	0	0
12	Electrical Drive Turbocompound	0	0	0	0	0	0	0	0	0
13	Automated Manual Transmission	1	1	1	1	1	1	1	1	1
14	Flywheels Hybrid	0	0	0	0	0	0	0	0	0
15	Stop-Start: Electric Hybrid	0	0	0	0	0	0	0	0	0
16	Pneumatic Booster - Air Hybrid	0	0	0	1	0	1	0	1	0
17	Full Hybrid: Series / Parallel - Electric	0	0	0	0	0	0	0	0	0
18	Series / Parallel - Hydraulic	0	0	0	0	0	0	0	0	0
Total FCR (Vehicle & Powertrain)		27.96%	27.96%	27.96%	30.48%	27.96%	30.48%	27.96%	30.48%	27.96%
19	3 phase alternator Unit	1	1	1	0	1	0	1	0	1
20	Hybrid Refrigeration Unit	0	0	0	0	0	0	0	0	0
21	Vacuum Isolated Panels	0	0	0	0	0	0	0	0	0
Total FCR (Refrigeration Unit)		100%	100%	100%	0%	100%	0%	100%	0%	100%
Combined FCR (all technologies)		38.9%	38.2%	37.9%	26.5%	33.2%	27.2%	31.8%	27.6%	31.0%
Carbon Emissions Baseline (t CO2 eq.)		969,243	526,405	234,037	882,922	882,977	424,335	424,389	122,308	122,363
Carbon Emissions Solution (t CO2 eq.)		589,716	247,976	24,102	656,995	589,716	333,399	247,976	120,496	24,102
Carbon Emission Savings (t CO2 eq.)		379,526	278,428	209,935	225,927	293,260	90,936	176,413	1,813	98,261
Carbon Emissions Difference		-39.2%	-52.9%	-89.7%	-25.6%	33.2%	-21.4%	-41.6%	-1.5%	-80.3%
Net Present Cost Baseline (£)		512,559	480,735	458,526	494,821	494,832	459,761	459,772	435,566	435,578
NPC - Optimised Solution (£)		422,502	397,137	379,715	422,494	422,502	397,135	397,137	379,711	379,715
NPC Savings (£)		90,058	83,598	78,811	72,327	72,331	62,626	62,635	55,856	55,863
Net Present Cost Difference		-17.6%	-17.4%	-17.2%	-14.6%	14.6%	-13.6%	-13.6%	-12.8%	-12.8%

In contrast to scenario 1, scenario 5 showed that when TRUs run over 2,227 hrs. /year (6 hrs. 16 min/day) 3 phase TRUs represent good value for money and reduce carbon emissions from 26.5% (scenario 4) to 33.2% despite applying a fuel consumption penalty on the tractor unit. Influenced by the differences in fuel prices, scenarios 6 and 7 show that HGV's running on B65 should fit 3-phase TRUs when they work over 1,940 hrs. /year (5 hrs. 28 min/day). Similarly, when running on B100 the sensitivity point appears at 1,764 hrs. /year (4 hrs.58 min/day).

The costs that represent each pair of scenarios (4-5, 6-7 and 8-9) are very similar as the decrease in fuel consumption of red diesel in scenarios 5, 7 and 9 are mitigated by the lower taxation of this fuel and the increase on fuel consumption of the fuel of the tractor unit (scenarios 4, 6 and 8). However, as the GHG emission factors of red diesel are higher than DERV (assuming 5% biodiesel mix) and other higher biodiesel mixes, this explains that differences in fuel consumption are not proportional to carbon savings. This is even more visible among scenarios 8 and 9, where the already very low carbon emission of the baseline vehicle can decrease from 122,308 to 24,102 to CO₂ eq. if no fuel is consumed by the TRU just for the marginal cost of running the TRU an additional hour at £11.38.

LCTs that do not seem to be cost-efficient for long-haul trailers of the operating characteristics of the case study are automatic tyre pressure adjustment systems, exhaust heat recovery systems, mild hybrid powertrains (more typical in urban deliveries), full hybrids as these produce modest fuel savings at very high costs and vacuum isolated panels. The constraint between technologies 1, 2 and 3 shows that technology 1 represents better value than just fairings or tear-drop shaped trailers. The same occurs between technologies 5 and 6 where both yield the same FCR but at different costs. Super single tyres are not allowed in the UK however if the model would have selected them it would have become relevant to policy maker to change EU regulations on this area. Technologies 14 to 20 are mutually exclusive and only one of them can be selected due to technical reasons (a flywheel cannot power a refrigeration unit for more than a few seconds).

5 Discussion and Conclusions

The findings show that long-haul refrigerated haulage fleets can reduce carbon emissions considerably regardless of the fuel used with the optimal combination of low carbon technologies while reducing their net present cost. Organisations using the sim-heuristics approach presented here can obtain a solution that yields carbon savings at the lowest cost, however, in some operations, there might be a critical point at which a marginal increase in cost yields considerably higher carbon savings. This highlights the importance of carbon pricing policies as a way to avoid this happening.

For the same type of fuel and emission standard, lower consumption translates to lower GHG emissions and better air quality. This benefits human health, the environment and helps to reduce the impact of freight on climate change. Choosing the optimal combination of technologies can help logistics companies to improve their triple bottom line (people, planet, profits) which in turn strengthens the competitiveness of their supply chains.

The selection of LCT not only depends on their cost and the fuel savings they can yield, but also on their operating conditions (mileage, duty cycle, temperature differential between inside and outside the refrigerating box), financial considerations, the capital costs of the vehicles and infrastructure required, losses related to poor technology reliability, carbon prices and quotas, and the costs of conducting simulations and/or trials.

This framework also allows the impact of fuel prices on the cost effectiveness of low carbon technologies to be assessed and conclusions drawn on the most effective investment strategies.

This research set out to fill a knowledge gap by developing a framework where consumers can assess quantitatively the benefits of each particular technology and optimal combinations of technologies according to the characteristics of their vehicles and operations. 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 greatest barriers regarding the adoption of more energy efficient technologies: the knowledge gap. Decision makers do not have independent fuel consumption information and robust methods to assess the investment in HGV technologies. This is of special interest to smaller companies, as they do not normally have the resources required to research all the technologies available that may benefit them and conduct the trials to validate the claims of the manufacturers. By using reliable inputs (e.g. fuel consumption reduction) this model can support the decision making criteria of logistics firms by using heuristics techniques while saving them high costs regarding preliminary low carbon technology trials. The results presented relate to specific driving cycles, vehicles and operating conditions; however, the model can be used across other types of operation by amending the inputs. This framework represents the best approach to help decision makers choose the optimal vehicle specification as no other model has been found to solve this particular problem.

6 Recommendations for Future Research

The results presented in this paper focus on long-haul diesel HGV. Further research to include regional and urban duty cycles is recommended. The framework could be easily adapted to indicate the optimal specification of other types of heavy duty vehicle such as urban buses and coaches, refuse trucks, military and off-road heavy duty vehicles and their specific duty cycles. The model assumed that the vehicles consumed diesel, however expanding the model to other types of fuels (e.g. biomethane, bioDME) and alternative powertrain technologies (e.g. battery electric and fuel cell trucks) as a logical step forward is advocated. This would however require new constraints and synergies to be considered e.g. 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 varies from one fuel to another (e.g. diesel vs. CNG); compounded aerodynamic impacts of several aerodynamic packages such as sprya suppression mudflaps with trailer undertray fairings. Also, some technologies may not be compatible (e.g. heat recovery and electrical turbo compound; automated manual transmissions with battery electric vehicles; battery electric vehicles and three phase alternator refrigeration

units) and others may become redundant (e.g. electric and hydraulic hybridisation working simultaneously).

Expanding the model to consider qualitative objectives such as the risk of technology maturity or specific limitations of use would be beneficial.

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, recycle and dispose of HGV's and their parts, as well as their embedded GHG emissions.

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