SELECTING LOW CARBON TECHNOLOGIES FOR HEAVY GOODS VEHICLES: A CASE STUDY IN THE UK FAST FOOD SUPPLY CHAIN

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ABSTRACT

The fast food supply chain is facing increased operating costs due to rising food and energy prices. Based on a case study of a major fast food logistics operator, this paper uses a metaheuristic evolutionary algorithm to find the optimal combination of low carbon vehicle, powertrain and transport refrigeration technologies that minimise net present costs for a heterogeneous fleet of heavy goods vehicles operating in the chilled and frozen food sector.

Based on the financial and operational constraints of the live case study, the model suggests that rigid trucks should include spray reduction mud-flaps, new generation single-wide tyres, light weighting materials and flywheels. Depending on the duty cycle and fuel used, other additional technologies can further enhance the net present savings. Conventional diesel vehicles can reduce their net present costs by 10.25% and 11.43% in urban and regional duty cycles

The model suggested that alternative refrigeration technologies had less potential for reducing costs unless working more than 10 hours per day; however they could make a considerable contribution to lower carbon emissions. As fast food logistic operators have access to used cooking oil, they can buy cheaper biodiesel while reducing GHG emissions by up to 84%. When comparing a conventional powered rigid truck using DERV with one using B65, cost savings were estimated to be £32,000 for urban duty cycles and over £42,000 for regional duty cycles per truck over their 5 year lifespans, reducing their CO_2 by 231 and 273 tonnes respectively.

1   **INTRODUCTION**
2
3   UK logistics fleets are predominantly made of vehicles with internal combustion engines running on
4   diesel. The combustion of fuels results in air quality and greenhouse gas (GHG) emissions and these
5   are further increased in the transportation of refrigerated goods due to power and refrigerant leakages
6   from transport refrigeration units (TRU). The link between carbon emissions and global warming is
7   well established [1-3] and governments around the World are now defining policies and legislation
8   that seek to mitigate their negative impacts. The European Commission [4] have set about reducing
9   them by 80-95% below 1990 levels by 2050. With this in mind, the EU is committed to achieving a
10 series of climate and energy targets by 2020, which include a reduction in EU GHGs of at least 20%
11 below 1990 levels, [5]. The EU White Paper, 'Roadmap to a Single European Transport Area' [6],
12 suggests that it is possible to achieve a 60% reduction in GHGs emissions by 2030, with respect to
13 1990 levels, by improving 'vehicle's efficiency through new engines; materials and designs; cleaner
14 energy use through new fuels and propulsion systems'. The model developed for this paper contributes
15 to the discussion in this area by demonstrating the combination of low carbon technologies most
16 appropriate for adoption by vehicle fleets used in the fast food supply chain, contributing to the
17 decarbonisation of city logistics.
18
19   Currently, around a quarter of the UK anthropogenic GHGs emissions are produced by
20 transport [7] from which HGVs represent around 18% [8]. The whole UK food chain emitted around
21 115 million tonnes of CO_2 equivalent in 2009[1] [9]. Commercial Transportation of food for UK
22 consumption represents around 9% of the GHGs emissions of the food chain [9] and between 1.8%
23 [10, 11] and 2.5% [12] of total UK carbon emissions.
24
25   For conventional trucks, lower carbon emissions translate into lower fuel consumption and
26 this leads to lower operating costs. When the additional capital expenditure of procuring these
27 technologies is kept to an optimal level, it is possible to achieve lower net present costs, resulting in
28 the highest profits for specific operating conditions This is of critical importance in the UK where fuel
29 costs have risen by 41% since January 2009 [13], representing almost 30% of the total 16-18t rigid
30 vehicle and driver costs [14]. Over the same period, the FAO Food Price Index has risen by 47% [15]
31 increasing competitive pressures among fast food supply chains even further.
32
33   In the UK, urban deliveries of fast food products are mainly undertaken by refrigerated rigid
34 vehicles due to access restrictions affecting articulated vehicles in many urban centres. Regional
35 deliveries are conducted by a mix of rigid and articulated vehicles. This research focusses on rigid
36 vehicles; however, changing parameters allow the same model to be applied to different vehicles, duty
37 cycles and refrigeration units. Rigid trucks with 18t GVW are categorised in the EU as type N_3,
38 designed for the carriage of goods, having a maximum mass exceeding 12 tonnes (Directive
39 2007/46/EC and Commission Directive 678/2011)).
40
41   The fleet renewal decision making criteria used by the case study company was the payback
42 period method, but this suffers from several flaws as it does not i) consider the time value of money,
43 ii) provide a monetary value that allows a clear comparison of what alternatives are preferable and iii)
44 consider returns beyond the payback period. The model described in this paper considers the net
45 present value (cost) as a more suitable tool for decision making, as it allows the evaluation of specific
46 rates of return, economic flows at different points in time, and a more realistic scenario analysis.
47
48 **LITERATURE REVIEW**
49

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

1   There is an abundant literature on low carbon technologies for heavy goods vehicles operating in the
2   US [16-19] and Europe [20-23]. The power required by an engine to overcome air and rolling
3   resistance, acceleration resistance and gradient is shown in Equation 1 (road load power equation). As
4   only 42% of the energy is transferred into break power [17, 18, 20], engine technologies that improve
5   engine efficiency are key to reducing fuel consumption. When developing the road load Equation, it
6   can be seen that mass, rolling resistance, drag coefficient, frontal area of the truck, gradient and speed
7   are critical factors in fuel consumption (Equation 2). Examples of the latter include improvements in
8   combustion, air mix and fuel injection, reducing wasted heat, friction and avoidance of auxiliary losses
9   (e.g. oil/water pump, auxiliary power unit). As speed is a common factor in all parameters in the
10   power equation, it is fundamental to appreciate that simulations and trials involving different transient
11   driving cycles produce very different power requirements, even if the same vehicles are used over the
12   same distances. From Equation 2, at higher speeds, aerodynamic improvements can make the greatest
13   contribution to fuel savings while at lower speeds, rolling resistance is more important to overcome
14   the forward forces.
15

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

16   **Equation 1 Source: [17]**

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

17   **Equation 2 Source: [17]**
18
19   Where
20   P_{res} = Power demand to overcome tractive forces (to propel a vehicle)
21   F_{roll}=Rolling force
22   F_{air}=Aerodynamic drag forces
23   F_{acc}=Acceleration forces
24   F_{grd}=Gradient forces
25   m = Vehicle mass (kg)
26   g = Gravitational constant (9.81 m/s^2)
27   C_{rr} = Tire rolling resistance coefficient
28   ϱ_a = Density of air (kg/m^3)
29   C_D = Aerodynamic drag coefficient
30   A_F = Frontal area (m^2)
31   v = Speed (m/s)
32   a = Acceleration (m/s^2). This is (dv/dt).
33   θ = Road gradient (degrees from horizontal)
34
35   Reducing rolling resistance is possible by reducing mass, speed, or the rolling resistance
36   coefficient of the tyres. The latter is possible by using low rolling resistance tyres or single wide base
37   tyres while aerodynamic vehicles with a lower drag coefficient, smaller frontal area and lower speed
38   require less power. Predictive cruise control has also been suggested as a method for delivering fuel
39   savings by influencing the energy required for overcoming the gradient factor of the power equation
40   [16, 20, 22]. Climbing resistance is the factor that influences power requirements the most [21] and for
41   this reason, reducing mass and understanding clearly if the vehicle is going to run in relatively flat
42   areas will help specify the most appropriate powertrain.
43
44   Fuel consumption over the same distance can also differ significantly depending on the type
45   load carried and as a result, it is typically normalised with a unit of payload (e.g. fuel consumption per
46   tonne-km). This also allows the integration of other technologies such as double decker trailers or
47   draw-bar combination vehicles that, despite increasing mass and fuel consumption, reduce fuel
48   consumption per tonne-km.

1
2   **Fuel Consumption Reduction Studies**
3
4   Studies conducted using US vehicles and operations, suggest that fuel consumption reductions of 50%
5   are possible in the period to 2020 [16-18] . As speed limits differ between the EU and US, driving
6   cycles employed in trials and simulations also differ (Table 1). As an example, in the UK, the typical
7   medium duty truck undertaking urban deliveries is a 7.5t 2-axle rigid whereas heavy duty (freeway
8   work) is carried out by articulated vehicles with GVW over 32.5t and 3-axles [20]. Regional
9   deliveries are carried out by a mix of rigid and articulated vehicles. There are also considerable
10   differences in vehicle length where in the UK, the maximum length for rigid vehicles is 12 m and 16.5
11   m for articulated vehicles (or 18.75 for a lorry with a trailer). In the US, the total length of articulated
12   vehicles can be as much as 21.3-22.9 m [23].
13
14   **Table 1 Typical baseline parameters for HGVs trials and simulations in the EU and US. Adapted**
15   **from [23-26]**

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)	21.0	20-47	25.3	29-59	30.6	31-59
Vehicle Class	N3	Class 5/6	N3	Class 7	N3	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	80	Up to 121	96	Up to 121 (Texas up to 137)
Examples of HGV Driving Cycles	ETC (Urban)	HT Class 6 Parcel Delivery Cycle	ETC (Rural)	CARB HHDDT	ETC(Motorway)	NESCAUM/SwRI

16
17
18   Based on Class-8 heavy-duty long-haul semi-trailers and following a California Heavy Duty
19   Diesel Truck Drive Cycle, Cooper, Kamakaté [16] simulated 32 low carbon technologies combined
20   within 14 technology packages and found that fuel consumption could be reduced by 20% in 2012
21   and by 50% in 2017 while providing net savings for the operator. This was possible by combining
22   aerodynamic and lower rolling resistance improvements in hybrid powertrains with heat recovery and
23   limiting speed to 60 kph.
24
25   Other work [17] indicated that Class 8 vehicles could achieve 51% fuel consumption
26   reduction (FCR) between 2015-2020 with a FCR of 20% coming from advanced engines, 11.5% from
27   aerodynamic improvements, 11% from lower rolling resistance, 7% from transmissions and drivelines,
28   10% from hybrids and 1.25% from weight reductions. A medium duty class 6 box truck operating in
29   regional haul (241 km/day at an average speed of 48 km/h) could achieve almost 50% FCR with the
30   greatest potential coming from the use of hybrid powertrains (30% FCR) and waste heat recovery
31   (14% FCR). There was less potential for lightweight materials and transmissions (4% FCR each),
32   rolling resistance tyres (3%) and aerodynamic fairings (less than 1% FCR).
33
34   The Review of the 21st Century Truck Partnership [18] investigated advances in low carbon
35   technologies and identified the greatest potential savings for urban duty cycles coming from
36   hybridisation (38% FCR), intelligent transport systems (up to 15%) and driver training (up to 17%). In
37   contrast, other studies indicate that driver training can deliver 10% fuel savings, but these are likely to
38   diminish over time [21, 22] if training regimes are not maintained. Increasing size and weight also
39   present an opportunity to save up to 28% fuel on a unit payload basis for any cycle [18]. In highway
40   driving, aerodynamic improvements, such as those delivered by the Smartway program (19% FCR),

waste heat recovery (almost 17% FCR) and single wide base tyres (15% FCR) lead to substantial fuel savings[18].

In urban deliveries, electric trucks can save 100% GHG emissions at their point of use [20, 27] which depending on the energy grid mix may lead to considerably lower Well-to-Wheel emissions. This is only a realistic option for vehicles of 7.5t or under and would not be technically feasible for the 18t vehicles employed by the logistics company studied here. The Ricardo report [20] divides heavy duty vehicles (HDV) into medium duty (urban cycle 7.5 t 2-axle rigid with a box) and heavy duty (motorway cycle tractor-trailer combination over 32.5t 3-axle). This classification makes it difficult to extrapolate results, as the typical fleet in the case study is made of heavier vehicles (18t refrigerated trucks). 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). In the case of plug-in electric trucks, the final carbon emissions depend on the energy mix of the country and how electricity is generated. Long-haul duty cycles benefit the most from vehicle technologies such as aerodynamic trailers (10%), electric bodies and vehicle platooning (10%). Both duty cycles can benefit considerably from the use of biofuels and alternative fuels. The potential for reducing carbon emissions in the fast food supply chain is considerable as waste streams can be used to produce biofuels, such as biodiesel from used cooking oil (UCO) which delivers 83% GHG savings [28].

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 [21]. This was possible by integrating a parallel mild-hybrid powertrain with regenerative braking as well as downsizing the engine to reduce weight and 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 [18, 21].

The EAE report reviews different low carbon technologies for informing potential policy actions [22]. This report suggests that urban operations can benefit from 20-30% FCR, mainly from powertrain efficiency improvements on long haul operations targeting losses in efficiency due to vehicle drag. The reported savings are lower than other sources because neither fuel technologies nor operational measures are taken into consideration. Medium duty vehicles benchmarked in this study are those with GVW between 7.5t and 16t that follow an urban cycle with many stop-and-start activities. Heavy duty vehicles are those that exceed 16t and follow a highway cycle with long periods of constant high speed. In this case, the findings from long-haul HGVs can be extrapolated to fast food operations; however, the medium duty vehicles do not adjust well as GVW is heavier in the case studied. As this report quantifies the relatively up-to-date technology costs and fuel savings for urban, regional and long-haul operations in a European context, the technologies with both values are used as inputs in the model presented in this paper.

Models for aiding Low Carbon Technology Selection for fleet managers

There are tools that can help fleet managers calculate fuel savings and carbon emissions. They do so by aggregating the improvements of low carbon technologies that need to be selected by the user.

These tools however do not optimise the best combination of technologies with the aim of minimising the net present costs of the fleet.

The 'Carbon Intervention Modelling Tool' developed by Heriot-Watt University [29] 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 as indicated 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 [30]. The user can understand the cumulative savings of each option alongside the inter-relations between technologies. The model indicates total fuel savings per annum with the user combining technologies manually until the one with the highest savings is identified. Capital expenditure is not included in the analysis and the model also calculates air quality emissions but only to Euro V.

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 developments. It also compares low emissions vehicle technologies 'on an individual vehicle basis', calculating emissions and benefits of lower carbon vehicles [31]. The model includes eight low carbon technologies in addition to driver behaviour improvements. In a similar approach to that used by Baker et al., [20], 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. As this model uses the payback period instead of NPV, the costing exercise covers the issues previously mentioned.

Evolutionary Metaheuristic Algorithms for Technology Selection

The expansion of the model presented here to 100 different technology combinations would require the evaluation of a total of 2^{100} (1.26×10^{30}) outcomes and considerable computational effort and time to find an optimal solution. Metaheuristic algorithms are one of the most practical approaches to solve combinational optimisation problems [32, 33]. They have been used for function optimisation of multiple parameters [34] and optimisation of engineering problems [35, 36] including technology selection that impacts on performance and economic parameters [37].

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 [34]. Tabu search (TS) is a metaheuristic that guides a local heuristic search procedure to explore the solution space beyond local optimality [38] by using adaptive memory and associated memory-exploiting mechanism [39]. Scatter search (SS) 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 couple with TS to take advantage of its adaptive memory [39]. Despite all being evolutionary programs, TS and SS provide better quality solutions than GA [40].

 METHODOLOGY

Despite the fact that a bespoke context-dependent program could yield better solutions when applying the same computational effort [33], time is not a critical factor in the problem being here evaluated and for this reason, a "black box" optimizer was used. This sort of solver does not use context information and does not take advantage of the problem's specific structure[33]. OptQuest is a "black-box" optimisation framework whose main optimisation engine is based on a scatter search methodology combined with tabu search strategies to obtain high quality solutions for non-linear non-smooth

complex problems [33] where a mix of continuous, integer, permutation, binary and other types of variables are allowed [36]. Design of experiments, cross entropy, genetic algorithms, particle swarm optimisation, simultaneous perturbation stochastic approximation, linear and mixed integer programing and complete enumeration technologies included in OptQuest contribute also to generate the optimal solution[33]. Taking as a baseline a heterogeneous fleet of diesel urban or regional refrigerated rigid vehicles, the model uses OptQuest to find the optimal combination of low carbon technologies that minimise the vehicles net present costs during their lifetime while maximising its aggregated fuel consumption reduction (FCR) in a cost efficient manner. As the evaluation of the model is context independent, logistics operators do not need to develop programming skills 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 for evaluating a base case plus three variables [17].

The model considers different levels of technology maturity, scenarios with different prices of carbon, fuel prices and economic growth, alternative costs as well as other specific operating parameters which allow the operator to obtain customised forecasts of the fuel reductions and GHG emissions savings. Two of the most critical parameters in the model are the FCR of individual technologies and their costs. Due to different driving cycles, speed limits, weights, dimensions and aerodynamic characteristics among European and US HGVs, the FCR used in the model is based on European trials conducted by a single independent source [22], and some of the prices have been updated with information from commercial sources.

The fuel consumption reduction (FCR) achievable by a combination of low carbon technologies is defined in Equation 3. The potential FCR represents the fuel savings of each individual technology for a particular duty cycle. This formula is used to calculate total fuel savings but does not take into account the different levels of maturity, safety and limitations in terms of lack of refuelling infrastructure or biodiesel availability. The model corrects for these restrictions by including these factors as penalties of the FCR in Equation 3. Also, the interactions between technologies must be properly considered and a number of constraints have been added. Some technologies are incompatible (e.g. hydraulic and electric hybridisation) due to packaging and technical issues. An example of a technical issue occurs when waste heat recovery systems need a good quality source of heat. This interacts with the selective catalytic reduction system. Other technologies may benefit from working together (e.g. heat recovery and turbo compounding); however, caution must be taken to avoid double counting effects. Other technologies may need to be re-modelled and included as a package (e.g. full aerodynamic packages including camera rear mirrors, cab collar gap reduction and fairing installations). These factors are constraints that will determine the appropriateness of the solution.

Technologies have been divided into four categories: vehicle, powertrain, TRUs and fuel technologies. No electric powertrains or alternative fuel technologies have been examined in detail because: 1) the operating characteristics of urban refrigerated fast food delivery operations is energy intensive and there are no electric trucks capable of satisfying operational requirements; 2) there are few developed infrastructures in the UK for Hydrogen or Biomethane gas likely to produce a noticeable change in the 2015-20 scenario. As a result, the model focuses on diesel and biodiesel trucks; and the costs of the technologies and FCR used in the model are the ones that appear in Table 1.

$$\text{Combined FCR (\%)} = 100 \times \left(1 - \left(1 - \frac{\% FCR1}{100}\right) \times \left(1 - \frac{\% FCR2}{100}\right) \times \ldots \times \left(1 - \frac{\% FCRn}{100}\right)\right)$$

Equation 3. Source: [16, 17]

1   As 21 technologies are evaluated (Table 2) a total of 2,097,152 combinations have to be tested
2   with multiple 'if' and 'or' conditions making this problem complex to solve in a reasonable time by
3   any other method.
4
5   **TABLE 2 Costs and FCR for each technology according to different duty cycles and updated**
6   **according to UK GDP forecasts. (Adapted from [22]). Parameters for the three phase alternator**
7   **refrigeration unit was provided by the case study company. Spray reduction mudflaps**
8   **information was supplied by [41]**

Technologies		Additional Costs			Fuel Consumption Reduction		
Duty Cycle		Urban (£)	Regional (£)	Long haul (£)	Urban (%)	Regional (%)	Long haul (%)
1 Aerodynamic Trailers		3,242	3,242	3,242	1.0	11.0	11.0
2 Aerodynamic Irregular body shape		815	815	815	1.0	6.5	5.0
3 Aerodynamic Fairings		1,093	1,093	1,093	0.0	1.0	0.4
4 Spray Reduction Mud Flaps		129	129	172	0.5	1.0	2.0
5 Low rolling resistance tires		324	324	324	1.0	3.0	5.0
6 New generation wide-base single tires		764	764	1,204	4.0	6.0	5.0
7 Automatic tire pressure adjustment		10,921	10,921	10,921	1.0	2.0	3.0
8 Lightweighting Materials		347	347	1,482	2.2	2.2	2.2
9 Predictive Cruise Control		1,297	1,297	1,297	0.0	5.0	5.0
10 Controllable air compressor		130	130	176	0.0	1.0	1.5
11 Heat Recovery (in general)		10,717	10,717	10,717	1.5	2.5	5.0
12 Electrical Drive Turbocompound		6,484	6,484	6,484	1.0	2.5	3.0
13 Automated Manual Transmission		3,242	3,242	4,369	5.0	1.5	5.0
14 Flywheels Hybrid		3,242	3,242	5,465	15.0	7.5	5.0
15 Stop-Start: Electric		593	593	871	6.0	3.0	1.0
16 Pneumatic Booster - Air Hybrid		741	741	741	1.5	1.5	3.5
17 Full Hybrid: Series / Parallel Electric		22,232	22,232	22,232	20.0	10.0	7.0
18 Series / Parallel hydraulic		12,227	12,227	12,227	10.0	0.0	0.0
Refrigeration (-20℃ Frozen)		6.2m/33.42 m3	0.4m/61.15 m3	13.4/78.79 m3	6.2m/33.42 m3	0.4m/61.15 m3	13.4/78.79 m3
19 3 phase alternator Unit		4,000	5,000	5,000	100.0	100.0	100.0
20 Hybrid Refrigeration Unit		2,000	3,000	3,000	11.0	11.0	11.0
21 Vacuum Isolated Panels		1,290	2,163	2,787	1.0	5.0	5.0

9
10
11   **Objective function**
12
13   The objective function seeks to minimise the net present cost of a rigid refrigerated heavy goods
14   vehicle. The function includes capital and operating expenditure of the vehicle and add-on
15   technologies (decision variables). The objective function represents the fitness function of the GA.
16
17   **Decision Variables**
18
19   The technologies that appear in Table 2 are binary variables that combine to yield the optimal
20   combination of technologies for the lifetime of the investment (5 years) considering capital and
21   operating costs (e.g. fuel, maintenance) and FCR. Capital costs of the baseline truck and refrigeration
22   unit are specified and updated with the on-top costs and combined FCR of the technologies selected.
23
24   **Constraints**
25
26   *Vehicle Technologies*
27
28   It has been assumed that aerodynamic trailers with irregular bodies (e.g. teardrop shape) already have
29   the same aerodynamic enhancements compared to typical aerodynamic trailers; therefore, they are
30   mutually exclusive.
31

This is a 2 axle rigid vehicle with 2 steering wheels and 4 driven tyres, all of the same type. It is assumed that if a vehicle uses low rolling resistance tyres, it cannot simultaneously use new generation single wide tyres.

Powertrain Technologies

A constraint to avoid mild and full hybrid technologies working together has been added. This includes pneumatic booster, a systems that injects compressed air from an auxiliary tank into a turbocharged internal combustion engine's (ICE) manifold increasing torque and fuel efficiency. It has been assumed that this technology cannot work with hybrid powertrains as the FCR found in the literature do not reflect the outcome of combining this technology with downsized engines from hybrid trucks. Further evaluation/simulation of this technology in combination with hybrids is needed.

Stop-start hybrids stop the engine running when the vehicle stops and store energy through regenerative braking. Full hybrids (electric or hydraulic) can also stop the engine and run with the power stored and these technologies are mutually exclusive. Flywheel hybrids store kinetic energy in a flywheel and are in competition with the other energy storage technologies.

Refrigeration Technologies

If a trailer has a 3 phase alternator unit, it cannot have a hybrid refrigeration unit at the same time, as only 1 unit is required. For electric trucks, an inverter could be installed to make it work [42]; however batteries should be considerably larger, producing a penalty on freight payload. After conversations with manufacturers [42], it has been assumed that hybridisation is incompatible with hybrid and 3 phase alternator refrigeration units as such devices take their power from an alternator connected to the main tractor engine and they need the engine running. Working together, the refrigeration unit would be in competition for the energy available with the hybrid powertrain system. When considering the suitability of this technology with electric battery trucks, an inverter could deliver the right voltage to the alternator but it would drain the battery and oversized batteries would be necessary. So far, as there are no battery electric trucks with a GVW of 18, this alternative has not been considered in this study.

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, prices of energy (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.

Operating costs are influenced by the technologies chosen, as fuel costs diminish when fuel consumption reductions are obtained. The model also allows for the selection of biodiesel at any concentration. This influences operating costs as the case study company is able to purchase biodiesel at a cheaper price than conventional mineral diesel (DERV) and also when a cost is assigned to carbon emissions. In this case study the reverse logistics of the conversion of UCO into biodiesel represents negligible GHG emissions as the same vehicles that deliver the goods also collect the UCO barrels as well as other waste streams in their empty back haul trips. The UCO barrels are consolidated in the distribution centres and transported from there to a biodiesel plant by dedicated trucks that return the

processed biofuel to the DC refuelling points. Furthermore, the model is capable of adapting the fuel consumption of the baseline vehicle to the concentration of biodiesel. The consumption of vehicles using biodiesel B100 (fatty acid methyl-ester) 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).

Distances

Data regarding driving distances and trips per day have been provided by the case study company. Urban delivery trips cover around 182 km and regional trips around 214 km. In both cases, trucks do an average of 1.35 trips per day for 362 days a year (in 2012). Trips per day increase year-on-year as efficiency improvements from routing and scheduling systems are expected.

Financial Parameters

To calculate the net present costs, the rate of return used required by the operator is 9.7% and the vehicles life is 5 years, as specified by its finance director.

Emission Factors

The emission factors are provided by the UK Defra [43]. The model considers only Scope 1 emissions as these 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. Further parameters considered in the model appear in Table 3.

RESULTS / FINDINGS

The fleet of this case study used B65 (65% biodiesel) as it was able to recycle the used cooking oil from the restaurant chip fryers into fatty acid methyl-ester biodiesel. As a result, fuel costs were much lower, as well as freight carbon emissions (Table 3). Scenarios 1 and 2 represent the real operating parameter of the fleet, scenarios 3 and 4 are built to contrast with other firms using regular diesel. Scenarios 5 and 6 show that only when refrigeration units work over 3,587 hours/year the model selects lower carbon refrigeration technology over hybrid powertrains. Scenario 7 represents the manual selection of flywheels over technology 19.

1   **TABLE 3 Results according to different duty cycles and fuels**

Scenario 2015-2020

Financial Parameters

Rate of Return	9.70%		Price DERV in 2015	£1.21
Period	5 years (Lifetime of the Investment)		Price B100 in 2015	£0.84
GDP	Central growth (Bank of England Forecasts)		Price Red Diesel in 2015	£0.72
Price of Carbon	0			

Vehicle Parameters   **Refrigeration Unit Parameters**

Type of Vehicle	Rigid Lorry			
GVW	18t		Reefer	Conventional Genset
Axles	2		Refrigerant	R-404A
Tires	295/80R22.5		Reefer Fuel	Red Diesel
Box	10.4m/61.15 m3		(If a 3 phase alternator TRU is not selected)	

Operating Parameters

	B65		DERV		DERV		
Type of Fuel	B65		DERV		DERV		
Scenario	1	2	3	4	5	6	7
Duty Cycle Type	Urban	Regional	Urban	Regional	Urban	Urban	Urban
Km per year	91,256	107,442	91,256	107,442	91,256	91,256	91,256
Fuel Consumption (l/100km)	29.95	29.30	27.57	26.97	27.57	27.57	27.57
Estimated Fuel Consumption Vehicle (l) (5 years)	136,654	157,393	125,775	144,863	125,775	125,775	125,775
Refrigeration (hrs/year)	1,650	1,650	1,650	1,650	3,587	3,588	3,588
Fuel Consumption (l/hrs)	2.50	2.50	2.50	2.50	2.50	2.50	2.50
Estimated Fuel Consumption TRU (l) (5 years)	20,625	20,625	20,625	20,625	44,838	44,850	44,850
Total Consumption Diesel+Red Diesel (l)	157,279	178,018	146,400	165,488	170,612	170,625	170,625
Tonnes delivered (5 years)	15,692	15,692	15,692	15,692	15,692	15,692	15,692
Carbon Emissions (tonnes) (Including Refrig. Leakages, 5 y)	200	219	400	449	465	465	465

Results

Vehicle Technologies	Reduced Aerodynamic Resistance	1	Aerodynamic Trailers	0	1	0	1	0	0	0
		2	Aerodynamic Irregular body shape	0	0	1	0	1	1	1
		3	Aerodynamic Fairings	0	0	0	0	0	0	0
		4	Spray Reduction Mud Flaps	1	1	1	1	1	1	1
	Reduced Rolling Resistance	5	Low rolling resistance tires	0	0	0	0	0	0	0
		6	New generation wide-base single tires	1	1	1	1	1	1	1
		7	Automatic tire pressure adjustment	0	0	0	0	0	0	0
	Vehicle Mass	8	Lightweighting Materials	1	1	1	1	1	1	1
	Intelligent VT	9	Predictive Cruise Control	0	1	0	1	0	0	0
	Auxiliary Systems	10	Controllable air compressor	0	1	0	1	0	0	0
PowerTrain Technologies	Exhaust Heat Recovery	11	Heat Recovery (in general)	0	0	0	0	0	0	0
		12	Electrical Drive Turbocompound	0	0	0	0	0	0	0
	Transmissions	13	Automated Manual Transmission	1	0	1	0	1	1	1
	Mild Hybrid	14	Flywheels Hybrid	1	1	1	1	1	0	1
		15	Stop-Start: Electric Hybrid	0	0	0	0	0	0	0
		16	Pneumatic Booster - Air Hybrid	0	0	0	0	0	0	0
	Alternative PT	17	Full Hybrid: Series / Parallel Electric	0	0	0	0	0	0	0
		18	Series / Parallel hydraulic	0	0	0	0	0	0	0
Total FCR (Vehicle & Powertrain)				-24.56%	-29.53%	-25.32%	-29.53%	-25.32%	-12.14%	-25.32%
TRU	Refrigeration Technologies	19	3 phase alternator Unit	0	0	0	0	0	1	0
		20	Hybrid Refrigeration Unit	0	0	0	0	0	0	0
		21	Vacuum Isolated Panels	0	0	0	0	0	0	0
Total FCR (TRU)				0%	0%	0%	0%	0%	100%	0%
Combined FCR (Vehicle, Powertrain & Refrigeration)				-21.34%	-26.11%	-21.75%	-25.85%	-18.66%	-30.74%	-18.66%
Carbon Emissions Baseline (t CO2 eq)				199.9	218.8	399.7	449.0	464.5	464.6	464.6
Carbon Emissions Solution (t CO2 eq)				169.2	176.3	317.4	338.5	382.3	324.9	382.3
Carbon Emissions				-15.38%	-19.41%	-20.58%	-24.61%	-17.71%	-30.07%	-17.71%

Net Present Costs

Baseline	£234,469	£251,099	£248,797	£267,602	£262,116	£262,123	£262,123
Optimised Solution	£217,006	£225,373	£227,748	£237,003	£241,067	£241,070	£241,074
Costs	-7.45%	-10.25%	-8.46%	-11.43%	-8.03%	-8.03%	-8.03%

4   The minimal technology specification for any rigid truck using B65 or DERV under similar
5   operating characteristics to the ones here assessed should include spray reduction mud-flaps, new
6   generation single-wide tyres, light weighting materials (e.g. aluminium chassis) and flywheel
7   hybridisation (when the refrigeration unit works less than 3,588h/y). The model also indicates that
8   urban duty trucks should include automated manual transmissions and regional ones would benefit the
9   most from aerodynamic trailers, predictive cruise control and controllable air compressors. As

reflected in Table 2, predictive cruise control can deliver 5% FCR; however, these savings are only materialised in routes with some gradient. Controllable air compressor reduces fuel consumption by avoiding parasitic losses by eliminating the idling of the airbrake.

In regional deliveries (scenario 1) fuel savings from vehicle technologies (21.3%) are higher than powertrain technologies (7.5%). Consistent with the literature [17, 20, 22] lower speed city logistics vehicles do not benefit greatly from aerodynamic improvements and the model exclude these from the solution (scenario 1). However the model shows that when the fuel costs increase (e.g. by using DERV instead of B65) irregular body shape trucks (e.g. tear drop box) contribute to delivering the lowest net present cost (scenarios 3, 5, 6, 7). In regional duty cycles, aerodynamic packages (e.g. deflectors, cab collar and fairings) are a cost efficient technology recommendation.

Consistent with the literature [20, 22], in urban duty cycles powertrain technologies present a higher fuel consumption reduction potential (19.2%) than vehicle technologies (6.5%) as it is possible to take advantage of the abundant stop-start cycles to reduce energy consumption or energy recovery. However the model also selects flywheels for regional duty cycles as long as the refrigeration unit works under a certain amount of hours per year. Flywheels are devices that store kinetic energy into a flywheel that releases the energy for a limited time when needed.

From the model, it can be seen that simple aerodynamic fairings, low rolling resistance tires, automatic tire pressure adjustment and exhaust heat recovery systems are not good value for money. Wasted heat recovery and electrical turbo compound were the most expensive technologies after automatic tire pressure adjustment with costs of £7,145 and £6,484 for each one per cent of fuel savings in urban deliveries and £4,287 and £2,594 for each technology in regional deliveries.

Technologies 14 to 20 are mutually exclusive and only one of them can be selected due to technical reasons. Conducting a sensitivity analysis of the hours that the refrigeration unit should work to yield a different solution has revealed that when the unit works 3,588 hours (scenario 6) a 3 phase alternator refrigeration unit is a better choice than any other hybridisation technology. This not only yields the lowest net present cost solution but also increases GHG savings from 18.6% to 30.7% saving in the process more than 57t $CO_{2eq.}$ in the 5 years period. This indicates that assigning a price to carbon can produce a very different solution. This is because this technology eliminates the emissions of the independent gen-set of the TRU by using an alternator connected to the tractor unit despite a fuel consumption penalty on it. In scenario 7, the selection has been manually reversed to prove that scenario 6 is optimal (in economic terms) in comparison as it was £4 cheaper.

For scenarios 1 to 4, urban fleets can save around a quarter of fuel (excluding red diesel) by integrating the technologies suggested in scenarios 1 and 3. This leads to net present savings between 7.4% and 8.5%. When the fleet runs on B65 net present costs of £17,463 and almost 31 t $CO_{2eq.}$ can be saved per truck. Fleets running on conventional DERV can save £21,049 and 82.3 t $CO_{2eq.}$ over their lifetime. Regional fleets' gains can be even higher with 29.5% savings by requesting technologies suggested in scenarios 2 and 4 (excluding red diesel). Regional duty cycle fleets running on B65 can reduce their costs by £25,726 per truck and their carbon emissions by 42.5 t $CO_{2eq.}$ Those using DERV can reduce costs by £30,599 and more than 110 t $CO_{2eq.}$ during their 5 years lifetime (costs here exclude drivers' wages). Urban fleets that choose to replace DERV with B65 and apply the model here presented can reduce their costs from £248,797 to £217,006 and their emissions from 400 t $CO_{2eq.}$ to 169 t $CO_{2eq.}$ Regional ones will reduce costs by £42,229 and emissions by 273 t $CO_{2eq.}$

CONCLUSIONS

Using a major fast food supply chain as a case study, the findings show that urban refrigerated food haulage fleets can benefit from ordering vehicles with certain combinations of low carbon technologies. When refrigeration represents a small percentage of the total fuel consumption of the vehicle there is little scope for selecting alternative refrigeration technologies based on economic grounds; however these can make a significant contribution to carbon reductions. Refrigerated transport represents around a fifth of the total fuel consumed by refrigerated rigid vehicles and targeting refrigeration technologies is important for rigid vehicles working around 10 h per day or more. The literature should consider these vehicles as a special case within the low carbon technologies landscape and pursue specific trials of relevant technologies.

The selection of low carbon technologies depends greatly on the fuel costs, duty cycle, capital costs and the fuel savings that they can deliver. These fuel savings strategies can be further complemented with fuel efficient driving techniques, increased loading factors as well as other non-technology based initiatives. Choosing the optimal combination of technologies can help logistics companies improve their triple bottom line (people, planet, profits) which in turn will strengthen the competitiveness of the whole supply chain. For the same type of fuel and emission standard lower consumption translates to lower GHG emissions and better air quality. This will benefit the human health, the environment and will help to mitigate the effects of climate change.

There is nevertheless scope for exploring if an improvement in brand image associated to more sustainable policies and lower costs will translate to more orders leading to rebound effects that may increase total tonnes-kilometre transported, and therefore emissions.

The model presented can be adapted to many other operations and represent a much cheaper alternative to real world fleet trials and therefore, a tool that fleet operators could use without having to invest heavily in time or money. The findings can also help vehicle manufacturers to design more efficient vehicles for fast food fleets or for any particular fleet by adapting the different operating parameters.

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