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A total cost of ownership analysis of zero emission powertrain solutions for the heavy goods vehicle sector

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ABSTRACT

Transport-related activities represented 34% of the total carbon emissions in the UK in 2022 and heavy-duty vehicles (HGVs) accounted for one-fifth of the road transport greenhouse gas (GHG) emissions. Currently, battery electric vehicles (BEVs) and hydrogen fuel cell electric vehicles (FCEVs) are considered as suitable replacements for diesel fleets. However, these technologies continue to face techno-economic barriers, creating uncertainty for fleet operators wanting to transition away from diesel-powered internal combustion engine vehicles (ICEVs). This paper assesses the performance and cost competitiveness of BEV and FCEV powertrain solutions in the hard-to-abate HGV sector. The study evaluates the impact of battery degradation and a carbon tax on the cost of owning the vehicles. An integrated total cost of ownership (TCO) model, which includes these factors for the first time, is developed to study a large retailer's HGV fleet operating in the UK. The modelling framework compares the capital expenditures (CAPEX) and operating expenses (OPEX) of alternative technologies against ICEVs. The TCO of BEVs and FCEVs are 11% to 33% and 37% to 78% higher than ICEVs; respectively. Despite these differences, by adopting a longer lifetime for the vehicle it can effectively narrow the cost gap. Alternatively, cost parity with ICEVs could be achieved if BEV battery cost reduces by 56% or if FCEV fuel cell cost reduces by 60%. Besides, the pivot point for hydrogen price is determined at £2.5 per kg. The findings suggest that BEV is closer to market as its TCO value is becoming competitive, whereas FCEV provides a more viable solution than BEV for long-haul applications due to shorter refuelling time and lower load capacity penalties. Furthermore, degradation of performance in lithium-ion batteries is found to have a minor impact on TCO if battery replacement is not required. However, critical component replacement and warranty can influence commercial viability. Given the high costs, we propose financial incentives and vehicle tax reforms to reduce costs of critical components that will encourage the roll-out of zero emission HGVs.

1. Introduction

In 2015, the transportation sector in the UK surpassed the energy sector as the largest emitter of Greenhouse Gases (GHGs) (IEA, 2021). Annual emissions of the transport sector were estimated to be 113 million metric tonnes of carbon dioxide equivalent (CO_2e), accounting for 34% of total domestic emissions in 2022 (Department for Energy Security and Net Zero, 2023). Considering the anticipated expansion in freight transport volume, as well as in the HGV industry before 2050 (European Commission, 2011; Shell and Deloitte, 2021), it is imperative that the decarbonisation of the Heavy Goods Vehicle (HGV) sector is expedited.

To accelerate the transition to a zero emission transport system, the UK's net-zero strategy mandates the sale of non-zero emission HGVs to stop by 2040. Markets for zero emission and low-carbon light goods vehicles and cars, particularly BEVs, have expanded substantially over the past decade. The Society of Motor Manufacturers and Traders (SMMT) reported that the domestic market share of new diesel and petrol automobiles in the UK (excluding hybrids) reduced from 58.1% to 49.7% during the 12 months following July 2021 (SMMT, 2022a). In contrast, at least 99.8% of road freight vehicles worldwide were

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Nomenclature

Abbreviations

BEIS	Department for Business, Energy & Industrial Strategy
BEV	Battery electric vehicle
CAPEX	Capital expenditures
CCS	Carbon capture and storage
DfT	Department for Transport
ERS	Electric road system
FCEV	Fuel cell electric vehicle
GBP	British pound sterling
GCW	Gross combined weight
GHG	Greenhouse gas
GVW	Gross vehicle weight
H2	Hydrogen
HDT	Heavy-duty truck
HGV	Heavy goods vehicle
kWh	Kilowatt-hour
ICCT	The International Council on Clean Transportation
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
LCO	Lithium Cobalt Oxide
LDV	Light-duty vehicle
LFP	Lithium Iron Phosphate
LHV	Lower heat value
Li-ion	Lithium-ion
MDT	Medium-duty truck
NREL	National Renewable Energy Laboratory
O&M	Operating and maintenance
OEM	Original equipment manufacturer
OPEX	Operating expenditures
PEM	Proton exchange membrane
PEST	Political, Economic, Social, and Technological
SMR	Steam methane reformation
SWOT	Strengths, Weaknesses, Opportunities and Threats
TACMO	Transport Application Based Cost Model
TCO	Total cost of ownership
VAT	Value-added tax
VED	Vehicle excise duty
WHVC	World harmonised vehicle cycle

powered by fossil fuels in 2021 (SMMT, 2022b). This contrast could be attributed to the disparities in technology readiness and more importantly, commercial fleet operators are more exposed to financial risks and more reluctant to transition to fleets with alternative powertrain technologies than individuals (Earl et al., 2018).

Considering the wide diversity of logistics applications, prospective customers, *i.e.,* hauliers, are continually evaluating different low-carbon technologies for each weight segment and when they should commence the transition (SMMT, 2021). However, owing to the multitude of technical and non-technical factors influencing the problem, decision-makers are unlikely to make substantial investments. Currently, the two most promising technologies to decarbonise the HGV sector are the battery electric vehicles (BEVs) and the hydrogen fuel cell electric vehicles (FCEVs), which both require an electric motor that replaces the internal combustion engine (ICE). A PEST-SWOT analysis of HGV fleet operators suggested that trials and uptake of BEVs or FCEVs need to start by 2025, with careful consideration of trade-offs between commercial readiness, operational performance, carbon-saving potential, and total cost of ownership (TCO) (Li et al., 2022).

A TCO model provides a robust framework to evaluate the cost competitiveness between the powertrain technologies in a real-world setting. Cost parity between zero emission and conventional technologies has been a critical indicator for fleet switching especially in the commercial vehicle sector (Basma et al., 2021; ExxonMobil, 2021). TCO calculates the capital expenditures (CAPEX) and lifetime operating expenditures (OPEX) of the vehicles until decommissioning or resale, using a discounted cash flow approach. Several studies have been published recently in this area and are outlined next.

The Transport Application Based Cost Model (TACMO) was developed by the Institute of Vehicle Concepts (Kleiner and Friedrich, 2017a) with Fig. 1 illustrating its workflow applicable to specified duty cycle. This work summarises well the cost components and performance metrics required for a comprehensive TCO analysis. Meanwhile, NREL introduced its Transportation Technology Total Cost of Ownership methodology named T3CO, enabling levelized TCO assessments of advanced technology commercial vehicles using vehicle operating data from NREL's Fleet DNA repository. The main attributes of T3CO are that it quantifies indirect costs posed by new technologies—such as dwell

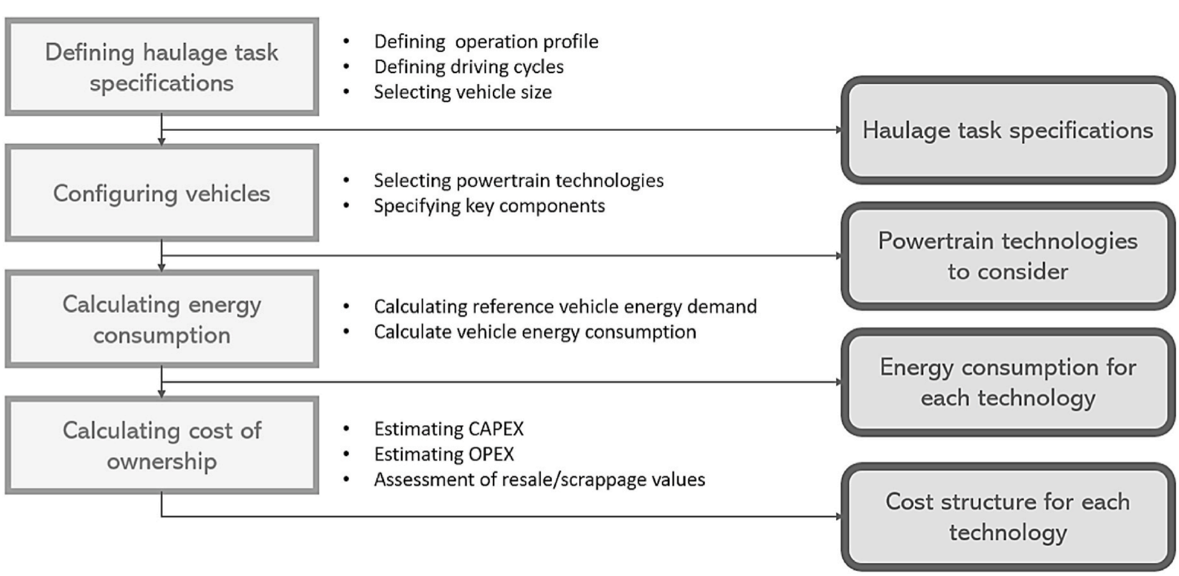

Fig. 1. Summarised Workflow of the TACMO model.

time to charge/fuel, cargo capacity impacts associated with varied powertrain mass, and zero-emission infrastructure costs (Hunter et al., 2021; NREL, 2021). Some other studies provide comparative TCO and component cost analyses for but are not limited to HGVs specifically in the UK (Rout et al., 2022; Transport, 2020). A comprehensive TCO study focusing on 10 European countries has been presented by researchers at ETH Zurich (Noll et al., 2022) which classifies a vehicle into its glider, powertrain and energy storage components. Some key findings of this work highlight that low-carbon vehicles are largely competitive in light and medium-duty segments, but for heavy-duty segments, they are competitive only in selected countries. In another valuable contribution to the literature, the International Council on Clean Transportation (ICCT) published advanced studies that dynamically assess the low carbon HGV cost trajectory in Europe and China (Basma, 2021; Mao et al., 2021; Mulholland, 2022).

These TCO studies have been able to cover the wide scopes of geographies, technologies and vehicle applications. Nonetheless, some research gaps are identified. Limited study has been conducted on the effect of electrifying HGVs on insurance premiums, and most insurance providers may not have a thorough understanding of the risks associated with electric HGVs (VISTA, 2022). However, it is generally believed that insurance premiums for electric HGVs are linked directly to the cost of vehicle repairs and component replacements. Most existing TCO studies (Basma et al., 2021, 2021, 2021; Mao et al., 2021; Rout et al., 2022) determine insurance costs by assuming fixed proportions of vehicle purchase prices across technologies. Furthermore, the end-of-life values of various powertrain and energy storage components in zero-emission technologies are subject to significant uncertainty, casting doubt on the resale or scrappage values of these vehicles. Lastly, at the time of writing, the impact of the capacity and power degradation of the key powertrain and energy storage components over time has not yet been quantitatively considered in existing HGV TCO studies.

In addition to these research gaps, key stakeholders such as fleet operators and policy-makers need to undertake a systematic assessment of how alternative vehicle technologies compare against each other to ensure sound environmental progress that meets private and public GHG mitigation targets. For fleet operators, this means conducting an in-depth analysis of their operational requirements to evaluate and plan cost-effective pathways that meet carbon mitigation targets while also being financially and technically viable. Similar studies for other energy technologies have been done by the authors; such as photovoltaic and battery systems (Mariaud et al., 2017), cogeneration (Cedillos et al., 2016), trigeneration (Acha et al., 2017), and low carbon heating solutions (Sarabia et al., 2022).

This paper proposes a framework to assess the technical performance and TCO of zero emission powertrain technologies in the HGV sector across two representative vehicle weight segments in the UK: the rigid medium-duty truck (MDT) and the tractor-trailer heavy-duty truck (HDT). A case study using real data provided by a fleet that comprises the two weight segments is established for a comprehensive TCO assessment. The model also employs a stochastic Monte Carlo simulation and a sensitivity analysis to evaluate the uncertainties and risks associated with the costs of fuel and critical vehicle components. This study of HGVs stands out from the literature as it considers battery degradation and carbon tax parameters to model realistic case studies. Additionally, it provides an overview of the environmental implications across the three powertrain technologies.

This work is structured as follows: Chapter 2 outlines the calculation framework and the methods used for comparing the TCO of three powertrain technologies; ICEVs, BEVs, and FCEVs. Chapter 3 details information on the MDT and HDT duty cycles as well as the data sources and input parameters used to inform the case study. Chapter 4 presents the main results from the TCO analysis. Chapter 5 discusses the findings and the underlying policy implications. Chapter 6 provides concluding remarks.

2. Methodology

2.1. Overview

In this two-dimensional TCO analysis, as displayed in Fig. 2, three types of powertrain technologies are assessed (x-axis) and two vehicle weight classes are modelled to simulate regional and long-haul HGV fleet operations (y-axis).

The MDT and HDT modelled in this study are defined as rigid and tractor-trailer units with a maximum gross vehicle weight of 18 and 44 metric tonnes; respectively. For each vehicle weight class, BEV and FCEV are compared with diesel ICE trucks. It is found that some FCEVs support onboard battery chargers that can be complemented with hydrogen refuelling to achieve a higher range (ELECTRA, 2022). Nevertheless, this study defines FCEV as a technology that is solely powered by hydrogen fuel but with a Li-ion battery system as an intermediate energy storage system.

Most studies assume 7–10 years of vehicle lifetime (Noll et al., 2022; Rout et al., 2022; Transport, 2020) whereas in this study a five-year period is set as the vehicle's first-use lifetime for the baseline scenario because surveys show that fleet operators in the UK prefer to replace vehicles more frequently to maintain their operational performance (Langshaw et al., 2020). A prolonged seven-year lifetime will also be included in the scenario analysis to evaluate the impact of extending the vehicle lifetime on the TCO. Throughout the analysis, it is assumed that component replacements (*e.g.,* battery pack and fuel cell system) are

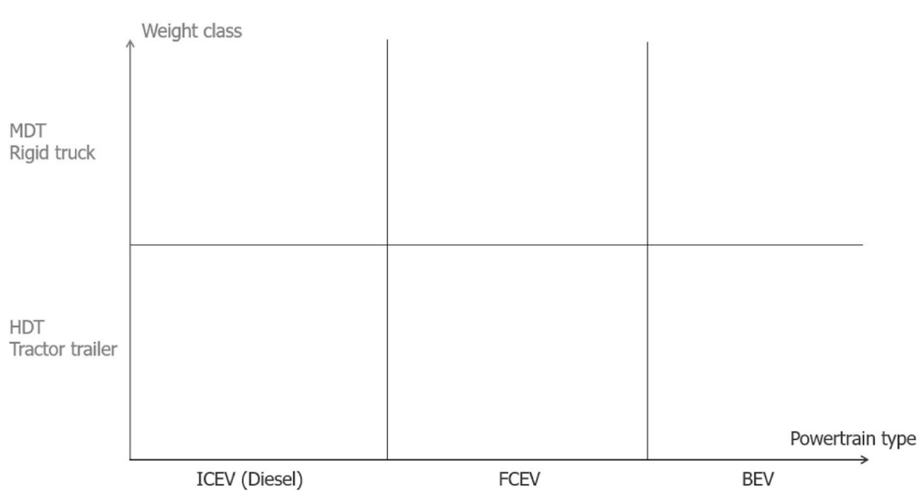

Fig. 2. Framework illustration of the comparative TCO analysis. The x- and y-axes denote to the powertrain technologies and HGV weight classes.

unnecessary over the vehicle lifetime whereas battery degradation is considered for both BEV and FCEV.

2.2. TCO framework

CAPEX and OPEX are fundamental components of the TCO analysis, with end-of-life vehicle scrappage values and subsidies also needing to be considered. In this model, the infrastructure costs for vehicle charging or refuelling are not considered and are assumed to be available for use. For FCEVs and BEVs, fleet-wise private refuelling facilities are in their infancy (Li et al., 2022), and there is an absence of adequate cost data, particularly for hydrogen, which is subject to various production and transportation methods. Moreover, the deduction of infrastructure costs per vehicle is overly sensitive to fleet size and other contextual factors. For example, due to the much longer refuelling durations for BEVs compared to ICEVs and FCEVs, these fleets would require an additional layer of intelligent charging scheduling, which is outside of the scope of this study. For the zero emission HGV market, the variations in vehicle purchase costs are greater than conventional ICEV units, owing to their immaturity. The TCO model calculates the vehicle CAPEX as a sum of the component costs for the powertrain, energy storage unit and the rest of truck (glider). This expression is subsequently multiplied with a gross margin to incorporate manufacturing costs and distribution overheads. This approach is based on Noll et al. with the gross margin adjusted according to the different powertrain technologies. A gross margin of 24.3% is applied to the ICEVs, whereas 35.2% is applied to FCEVs and BEVs to simulate the higher indirect cost for manufacturing, trading, and deliveries of zero emission trucks (Hill et al., 2012). The glider costs which represent the costs of rest of truck including the vehicle body, chassis, cabin, wheels, axles, etc., are only dependent on the weight class of the trucks regardless of the powertrain technologies.

The vehicle CAPEX is therefore expressed as stated in Eq. (1):

$$CAPEX = \frac{C_{PT} + C_{ES} + C_G}{1 - GM} \tag{1}$$

where C_{PT} is the powertrain component cost (£), C_{ES} is the energy storage component cost (£), C_G is the glider cost (£) and GM is the gross margin (%).

The vehicle OPEX comprises the vehicle taxes, levies, fuel costs, insurance costs, and maintenance & repair costs. The OPEX for ICEVs includes the cost of AdBlue which is used to reduce nitrous oxide emissions in diesel vehicles. The annual insurance cost is estimated as a percentage of the vehicle CAPEX, whereas the fuel costs are determined by using the fuel unit price (£/kWh), the annual distance travelled (km) and the vehicle energy consumption performance (kWh/km). OPEX can therefore be calculated using the terms in Eqs. (2)–(4):

$$OPEX_{(n)} = C_{F(n)} + C_{MR} + C_I + C_{TL} \tag{2}$$

$$C_{F(n)} = UEC_{(n)} * ADT * UFP \tag{3}$$

$$C_{TL} = VED + RUL \tag{4}$$

where $C_{F(n)}$ is the fuel cost at year n (£), C_{MR} is the annual maintenance & repair cost (£), C_I is the annual insurance cost (£), C_{TL} is the annual taxes and levies (£), $UEC_{(n)}$ is the unit energy consumption at year n (kWh/km), ADT is the annual distance travelled (km), UFP is the unit fuel price (£/kWh), VED is the vehicle excise duty (£) and RUL is the road user levy (£).

In addition to CAPEX and OPEX, other input parameters of the TCO model consist of the discount rate, the vehicle lifetime, the scrappage value, the purchase subsidy, and the inflation rate. The vehicle lifetime TCO (£) and the TCO per km (£/km) are calculated by using Eq. (5) and Eq. (6), which are derived from the ones proposed by Wu et al. and Noll et al. with minor adjustments made to account for inflation:

$$TCO = CAPEX - SS + \sum_{n=1}^{N} \frac{OPEX_{(n)} * (1+i)^n}{(1+r)^n} - \frac{SC}{(1+r)^N} \tag{5}$$

$$TCO/km = \frac{\left(CAPEX - SS - \frac{SC}{(1+r)^n}\right) * \frac{r(1+r)^N}{(1+r)^N - 1} + \frac{1}{N}\sum_{n=1}^{N} \frac{OPEX_{(n)} * (1+i)^n}{(1+r)^n}}{ADT} \tag{6}$$

where n denotes the year in operation, N is the vehicle lifetime (years), i is the inflation rate, r is the discount rate, SS is the subsidy (£) on the vehicle purchase price, SC is the vehicle scrappage value (£) that is dependent on the vehicle purchase price, $\frac{r(1+r)^N}{(1+r)^N-1}$ is the capital recovery factor (Wu et al., 2015). The discount rate is influenced by the interest rate that the fleet operator can get for a short term loan the expected return on the investment (Hayes, 2021). An overview of the TCO cost structure and all considered subcomponents is presented in Fig. 3.

2.3. Data sources

Using specified CAPEX parameters, the component costs can be determined. Five primary sources are referenced, together with the secondary sources and data available from the market (den Boer et al., 2013; Hill et al., 2012; Kleiner and Friedrich, 2017a; Noll et al., 2022; Transport, 2020). Unit prices of diesel, AdBlue, electricity and hydrogen are obtained from the fleet operator and the grey literature (Department for Business Energy & Industrial Strategy, 2020a; 2020b). Costs for vehicle maintenance and repair are estimated from existing TCO studies. The CAPEX and OPEX parameters and sources are tabulated in Table A1 and Table A2 in the Appendix.

2.3.1. Discount rate and inflation

To factor in the impact of higher investment risks (Hargrave, 2022) involved in adopting BEV and FCEV fleets, discount rates are modelled ranging from 5% to 8% for the ICEV, and 6% to 10% for the zero emission powertrain technologies, based on information provided by the fleet operator and are validated by figures reported in several UK-based studies. The average UK consumer price inflation rate of 3.6% during the second half of 2021 (Office for National Statistics, 2022) is used to predict the increase in future operating expenses for all vehicles.

2.3.2. Scrappage value

The scrappage value of a vehicle corresponds to the achievable selling price after deducting the dismantling and disposal costs at the decommissioning stage. For the diesel-ICE HGVs, a regression model of the ratio between scrappage value and the initial vehicle purchase price is used, which leverages existing resale market data. However, considering that most current zero emission trucks are awaiting retirement, the resale market in Europe is not yet mature to define the scrappage values of these vehicles (Noll et al., 2022). In this analysis, the scrappage values are estimated using the model and figures reported in (Kleiner and Friedrich, 2017b) with results shown in Table A3 in the Appendix. The mileage values used for the calculation are presented in Section 3.1.

2.3.3. Battery degradation

Lithium-ion battery ageing from common usage reduces its energy and power capacity (S. Edge J et al., 2021). Capacity reduction shortens vehicle range (Pelletier et al., 2017), and increases the number of required charging cycles for a given long-haul delivery. Battery degradation dynamics in this model influence the OPEX as it affects the gross electricity consumption and impacts the vehicle fuel economy.

One study in the US suggests that BEV energy consumption increases from battery degradation are primarily dependent on ambient temperature and travel demand (Yang et al., 2019). It was found that the state

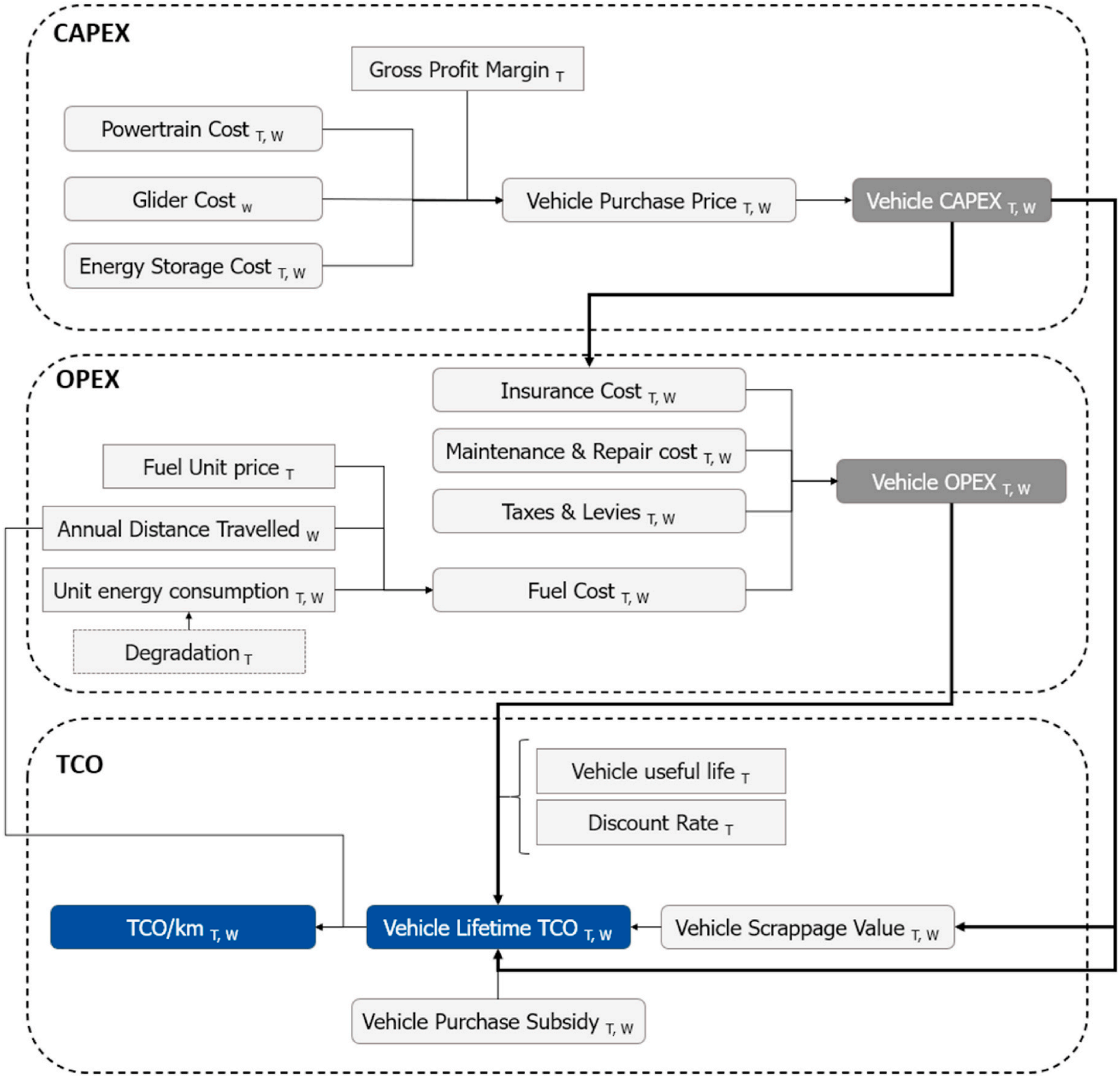

Fig. 3. An illustration of the TCO structure, the subscripts T and W refer to the dependencies on powertrain technology and weight class respectively.

of Washington has the most similar climate to the UK (Weather Spark, 2022a; 2022b). Therefore, the generic degradation model developed for this region was adopted to simulate a mild-to-moderate vehicle use case. The details can be found in Figure A1 in the Appendix.

The degradation dynamics of the fuel cell system are not included in this analysis due to the absence of available data. Instead, FCEV is modelled with the same degradation model applied to BEV considering it also uses the Li-ion battery as part of its energy storage system. This battery storage degradation model determines the unit energy consumption of both BEVs and FCEVs in year n, compared to year 1 during their operation, which directly reflects the fuel costs to be factored in the OPEX calculations.

2.4. Monte Carlo simulation

A stochastic Monte Carlo simulation is employed to assess the impact of uncertainties in the key input variables on the TCO. Key variable inputs include fuel cell system cost, Li-ion battery cost and hydrogen (Langshaw et al., 2020; Noll et al., 2022; Rout et al., 2022) with a triangular distribution based on literature estimates, as detailed in Table A2 and Figure A2 in Appendix. 10,000 samples are taken from each variable's distribution to generate the TCO. Collated input variables which are comparatively predictable or those that have a minor effect on TCO are not included in this stochastic simulation. Discount rate and battery degradation for each year are modelled by generating random values between the upper and lower bounds.

2.5. Sensitivity analysis

A deterministic sensitivity analysis compares the impacts of modifying input variables on the TCO of the three powertrain technologies. In the following sections, the sensitivities of parameters are investigated using tornado charts. The 'high' and 'low' input values for the targeted variables are defined as±30% of the baseline, while the remaining variables are kept at their baseline values. These charts illustrate how the TCO can change with respect to variation in one of the key input variables.

3. Case study

This section defines the requirements of the MDT and HDT operating duty cycles and relevant data sources which are used to inform the simulations. The total diesel fuel use and odometer records over a two-week period of the HGV fleet that consists of 123 vehicles were analysed.

The fleet is based at a supermarket depot in East London and is responsible for freight logistics in the Greater London area.

3.1. Operating profiles

Engagement with the industrial partner has revealed that the delivery trucks are rarely provided with daily routine haulage tasks. Instead, fleets usually run on fully flexible routes and the distance travelled can be affected by vehicle conditions, driver schedules, maintenance and repair activities, etc. For this case study, the HGV fleet's vehicle odometer records for June 2022 were collated. Results show that the distance driven by trucks of the same weight class during a given period can vary significantly as some vehicles are used more than others. Average values of the daily distance travelled by ICEVs for various weight classes are shown in Table 1 alongside the annual distance travelled (ADT), assuming 5 working days per week. It is to be noted that the mileage values of this depot located in East London are considered moderate compared to fleets based in other regions. In this case study, the distance requirements are applied across all weight classes and technologies, irrespective of the gravimetric payload. It is based on the average UK road freight gravimetric load factor of around 60% during laden trips (EEA, 2011), and that the industrial partner has entailed that the majority of haulages carried out in the retail industry are volume-weighted. Therefore, it is important to note that this analysis may not be suitable for operations that are payload-weighted in other regions. Nevertheless, the forthcoming section includes a presentation of payload penalties in Table 2.

3.2. Performance modelling

The configuration of vehicle key components and their associated costs impact the vehicle CAPEX. The total costs of the powertrain and energy storage components are highly dependent on technical parameters such as the power output (kW), and energy capacity (kWh). Configurations of the ICEVs are based on real-life reference vehicles used by the fleet operator (*i.e.,* Mercedes-Benz Antos 1824 L -MDT, and Mercedes-Benz Actros 2545 L (HDT)). Existing TCO studies (Kleiner and Friedrich, 2017a; Noll et al., 2022; Transport, 2020) have assumed that the power ratings of major output units are independent of the powertrain technologies. However, existing BEV and FCEV truck models provided by a range of suppliers including Hyundai, Volvo, and Hyzon among others (AB Volvo, 2022; Hyundai, 2020; Hyzon Motors, 2022), are usually equipped with electric drive units that have significantly higher maximum power outputs than their ICEV counterparts. The maximum power ratings for electric traction motors used in both FCEV and BEV models are set to be 100% and 34% higher than the ICE units for MDT and HDT respectively, based on reference vehicle specifications given in Table 2.

This approach was also applied with regard to the energy storage parameters. As discussed in previous sections, lithium-ion battery performance and price vary widely with different chemistries. Existing zero emission truck models, for example, the Electra e-cargo FCEV (ELECTRA, 2022) and the DAF CF Electric (DAF, 2022a) have demonstrated the feasibility of using Lithium Iron Phosphate (LFP) batteries for HGVs in the UK. Current LFP battery energy densities are at approximately 359 W h/L (Aronov, 2022) or 165 W h/kg (Earl et al., 2018), which is not yet comparable to diesel or hydrogen storage. However, LFP cells have been found to have the highest cycle lifetime against degradation than other common EV cell chemistries under all conditions, indicating the capability of achieving at least 2500 charge/discharge cycles before dropping below 80% capacity (Preger et al., 2020). Therefore, this model assumes LFP cells are used in both FCEV and BEV categories. To account for the impact of capacity degradation, the energy storage capacities are specified based on existing reference vehicles and under the requirement that they must remain capable of achieving the 115-km and 408-km range without recharging at 80% capacity. The modelled vehicle specifications are presented in Table 2.

The recorded fleet-average unit fuel consumption for MDT and HDT were 22.99 L/100 km (10.23 miles per gallon) and 28.70 L/100 km (8.19 miles per gallon); respectively. These values are found to be 7.7% and 3.7% lower than the UK average HGV fuel consumption estimated in 2016 (Department for Transport, 2017) published by Department for Transport, owing to the recent improvements in ICE powertrain efficiency. The AdBlue usage was found to be approximately 4.5% of diesel consumption.

Tank-to-wheel unit energy consumptions of BEVs and FCEVs are

Table 1
Vehicle travelling distance requirements obtained from a representative two-week period, despite a minimal seasonal effect across the year (Kuhn and Sternbeck, 2013).

	Max. Gross weight (kg)	Daily distance travelled (km)	Annual distance travelled (km)
MDT	18,000	115	29,900
HDT	44,000	408	106,000

Table 2
Configured vehicle specifications and data sources for the three vehicle technologies assessed (note that the gaseous hydrogen storage is specified at a representative 350 bar).

	ICEV (Diesel)		FCEV		BEV	
Weight Class	MDT	HDT	MDT	HDT	MDT	HDT
Reference vehicle model	Mercedes Antos 1824	Mercedes Actros 2545 L	Hyundai Xcient Fuel Cell	Hyzon Hymax	DAF LF Electric	Nikola TRE
Sources:	Lectura-specs (2022a)	Lectura-specs (2022b)	Hyundai (2020)	Hyzon Motors (2022)	DAF (2022b)	Nikola (2022)
Powertrain						
Max. Weight (kg)	18,000	44,000	18,000	44,000	18,000	44,000
Axle configuration	4 × 2	6 × 2	4 × 2	6 × 2	4 × 2	6 × 2
Vehicle curb weight (kg)	8306	14,960	9475	16,747	9754	18,648
ICE power (kW)	175	336	/	/	/	/
E-motor power (kW)	/	/	350	450	350	450
Fuel cell system power (kW)	/	/	190	244	/	/
Payload penalty	/	/	12%	6%	15%	13%
Energy Storage						
Diesel tank capacity (L)	270	610	/	/	/	/
Diesel tank capacity (kWh)	2888	6525	/	/	/	/
Li-ion battery capacity (kWh)	/	/	73	146	282	730
H_2 storage capacity (kg)	/	/	19	48	/	/
H_2 storage capacity (kWh) (LHV)	/	/	640	1610	/	/
Efficiency						
Tank-to-wheel efficiency	35.5%		43%		76%	

Sources: (den Boer et al., 2013; Hill et al., 2012; Kleiner and Friedrich, 2017a; Noll et al., 2022; Transport, 2020)

Table 3
Vehicle energy consumption and fuel consumption.

	ICEV (Diesel)		FCEV		BEV	
Weight Class	MDT	HDT	MDT	HDT	MDT	HDT
Unit energy consumption at tank (kWh/km)	2.46	3.07	2.03	2.53	1.15	1.43
Annual energy consumption at tank (kWh/year)	73,540	325,370	60,710	268,620	34,350	151,980
Annual diesel consumption (L/year)	6,880	30,420	/	/	/	/
Annual hydrogen consumption (kg/year)	/	/	1,820	8,060	/	/
Annual AdBlue consumption (L/year)	309	1370	/	/	/	/
Maximum range (km)	1,170	2,130	315	637	245	490

Table 4
List of modelling scenarios.

Scenario	Description	ICEV lifetime (years)	FCEV & BEV lifetime (years)	FCEV & BEV CAPEX subsidy (£)	Battery degradation
1	Baseline	5	5	0	No
2	Plug-in grant	5	5	25,000	No
3	7-year lifetime	7	7	0	No
4	Degradation	7	7	0	Yes

calculated using the system efficiencies. This implies that vehicles of the same class consume the same amount of energy at the wheels per km travelled. Listed in Table 3 are the resulting unit energy consumption, annual fuel consumption, and the vehicle maximum ranges. The fuel-specific assumptions are tabulated in Table A4 in the Appendix.

3.3. Scenario analysis

Four scenarios are established to analyse the robustness of this study. Model inputs are adjusted for each of the scenarios listed below in Table 4. The 1st scenario serves as a reference based on current market conditions and fleet operator requirements. The other scenarios evaluate the impact of the £25,000 plug-in grant (GOV.UK, 2017), an extension of the vehicle lifetime, and battery degradation on the TCO. Vehicle CAPEX is handled in the same way in all scenarios using inputs from vehicle specifications and cost data, whereas OPEX varies based on lifetime assumptions. For Scenario 2, the capped £25,000 subsidy is deducted from the CAPEX values of zero emission vehicles. In Scenario 3, an extended lifetime implies higher total OPEX, higher total vehicle mileage, and hence a lower vehicle scrappage value. In Scenario 4, battery degradation (Figure A1 in the Appendix) is reflected in the TCO structure which is discussed in Section 2.3.3. A 7-year lifetime is also assumed in Scenario 4 as it is in Scenario 3, to model the enlarged impact of degradation due to a longer vehicle lifetime.

3.4. GHG emissions

The fuel and energy consumption data as given in Table 3 are used to calculate the annual GHG emissions of these vehicles. The well-to-wheels GHG emissions associated with diesel are presented as well as the electricity and hydrogen supply emissions. The TCO model takes only the tailpipe emissions as an input to model the carbon tax for diesel HGV. The average carbon intensity from the UK's grid electricity supply estimated by BEIS in 2022 is used (Department for Business Energy & Industrial Strategy, 2022). Three hydrogen production pathways are considered for FCEVs, *i.e.,* a) steam methane reforming (SMR) with and b) without carbon capture and storage (CCS), also known as blue and grey hydrogen; respectively, and c) hydrogen produced from grid electrolysis (electrolysis using average grid carbon intensity). The emission factors and carbon intensities used as model input are presented in Table 5.

Table 5
GHG emission intensity data used for diesel combustion, UK grid electricity, hydrogen produced from UK grid electricity, hydrogen produced from SMR, and hydrogen produced from SMR with CCS.

Diesel (tailpipe + fuel production)	Electricity from UK grid	Hydrogen from electrolysis using grid electricity	Grey Hydrogen [SMR]	Blue Hydrogen [SMR with CCS]
(kg CO_2e per MJ)				
0.0690 + 0.017	0.0550	0.0784	0.0836	0.0160
Mao et al. (2021)	Department for Business Energy & Industrial Strategy (2022)	Department for Business Energy & Industrial Strategy, 2021	Department for Business Energy & Industrial Strategy, 2021	Department for Business Energy & Industrial Strategy, 2021

4. Results

4.1. TCO

4.1.1. Overview

The baseline TCO results (Scenario 1) for each vehicle technology type are shown in Fig. 4. Overall, ICEVs have the lowest TCO for both MDT and HDT, at £164k and £431k respectively, followed by BEVs at £218k and £477k. FCEVs are the most expensive option for both weight classes at £292k and £590k for MDT and HDT. The range of TCO values for HDTs is greater than MDTs as high mileage leads to greater variations in the fuel costs when factoring in the volatility in fuel prices. The following sections will present a more detailed breakdown of the vehicle cost components and explore the key reasons for the variation in TCO values across each technology and weight class.

4.1.2. Medium-duty trucks (MDT)

The breakdowns for CAPEX and OPEX costs of MDTs are given in Fig. 5. The CAPEX of FCEVs and BEVs is much higher than conventional ICE vehicles, at 148% and 93%, respectively. In both cases, this is largely driven by the energy storage costs. The powertrain component cost of FCEV is around £48k higher than the other two options. Even with a relatively low lifetime mileage of 150,000 km, current BEVs can provide 11% overall savings in OPEX compared to ICEVs, primarily due to a 39% saving in fuel costs. By contrast, the OPEX of FCEVs is approximately 29% higher than that of ICEVs mostly due to higher insurance costs despite having comparable fuel costs.

The TCO results in £/km of the four scenarios are showcased in Fig. 6. The £25k plug-in grant (Scenario 2) reduces TCO/km of FCEVs and BEVs by 9% and 12% respectively compared to the baseline (Scenario 1). This brings BEVs closer to the performance of ICEVs with a difference of £0.56/km, however, the gap between FCEVs and ICEVs has a wider gap at £0.92/km. With an extended vehicle lifetime of 7 years (Scenario 3), the TCO/km is reduced by 11%, 16%, and 15% for ICEVs, FCEVs and BEVs; respectively. But gaps still exist largely due to the high weight of CAPEX costs in the TCO value, which would require even longer asset utilisation to offset sufficiently. When considering efficiency

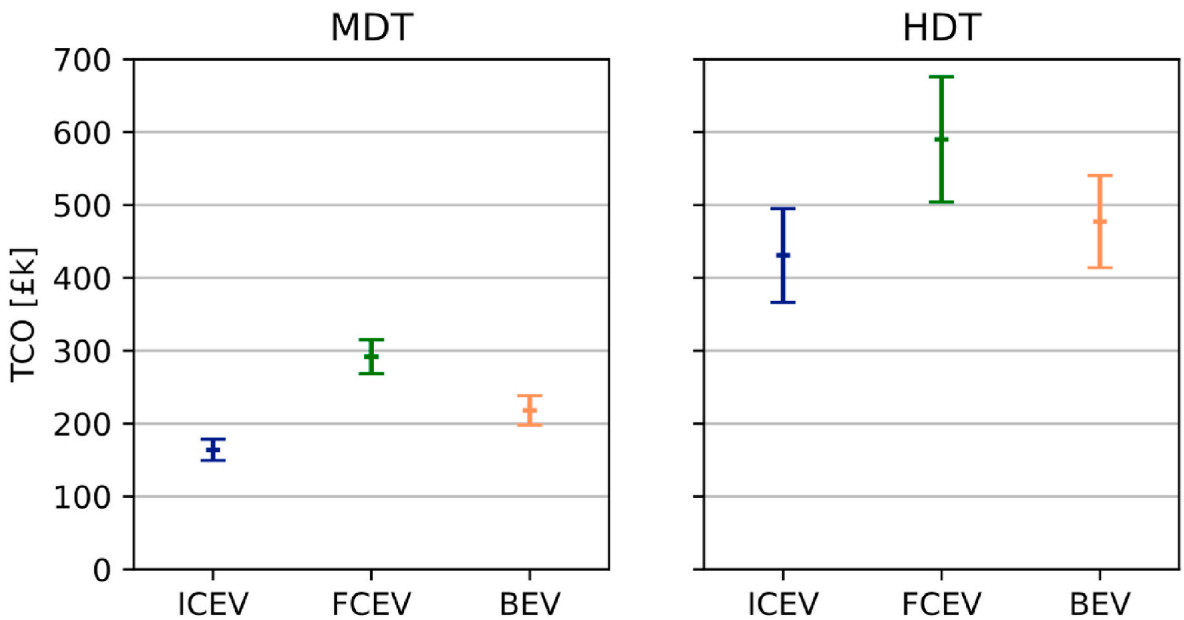

Fig. 4. Baseline (Scenario 1) lifetime TCO results ± 2 standard deviations from the mean.

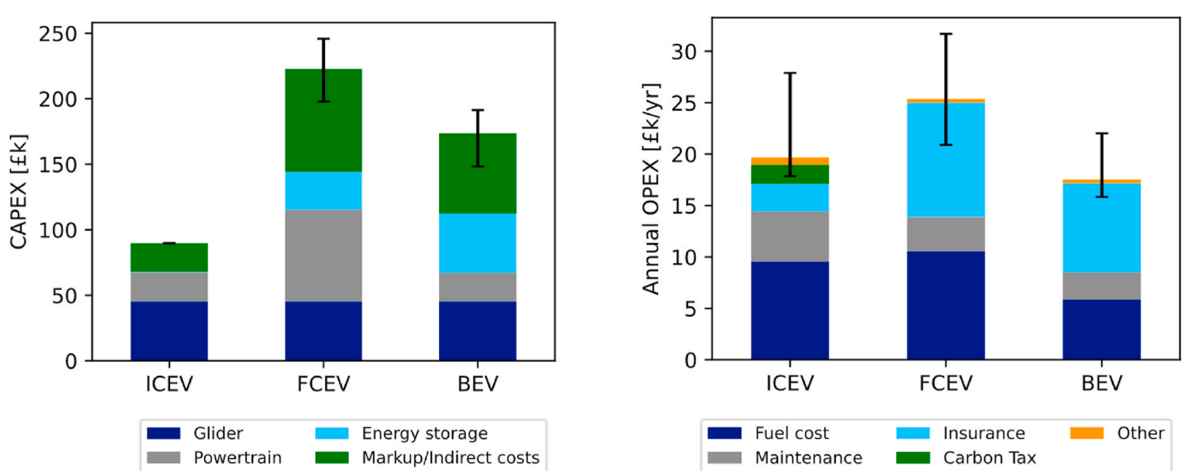

Fig. 5. Baseline MDT CAPEX and OPEX breakdown for Scenario 1, error bars show the 5th to 95th percentile.

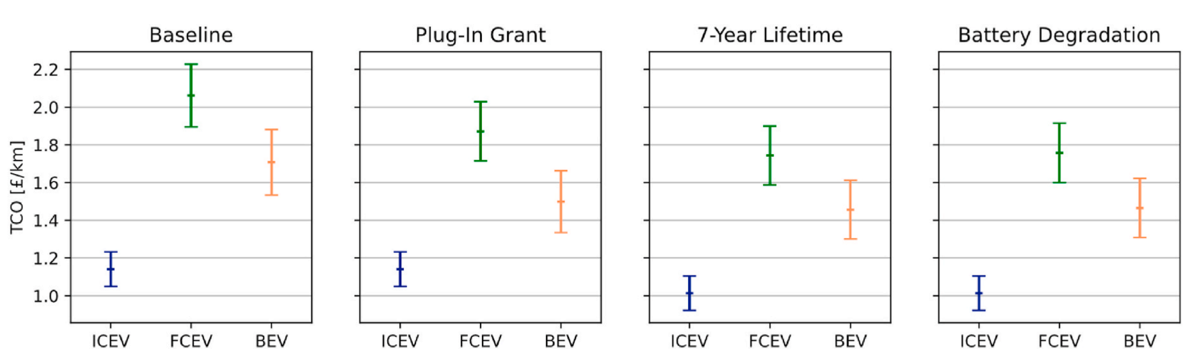

Fig. 6. MDT TCO/km values for the scenario analysis, error bars show ±2 standard deviations from the mean.

degradation over a 7-year lifetime (Scenario 4), negligible increases in TCO are observed, at 0.8% and 0.6% for FCEVs and BEVs; respectively. Although the FCEV does not use the Li-ion battery as its major energy storage, system degradation may cause a comparatively higher impact on its TCO than the BEV due to a lower fuel economy.

4.1.3. *Heavy-duty trucks (HDT)*

As seen in Fig. 7, CAPEX requirements for FCEVs and BEVs are higher compared to ICEVs, with each technology being 156% and 144%, more expensive respectively. For HDT BEVs, energy storage costs are significant due to higher range requirements, but this effect is mitigated in the

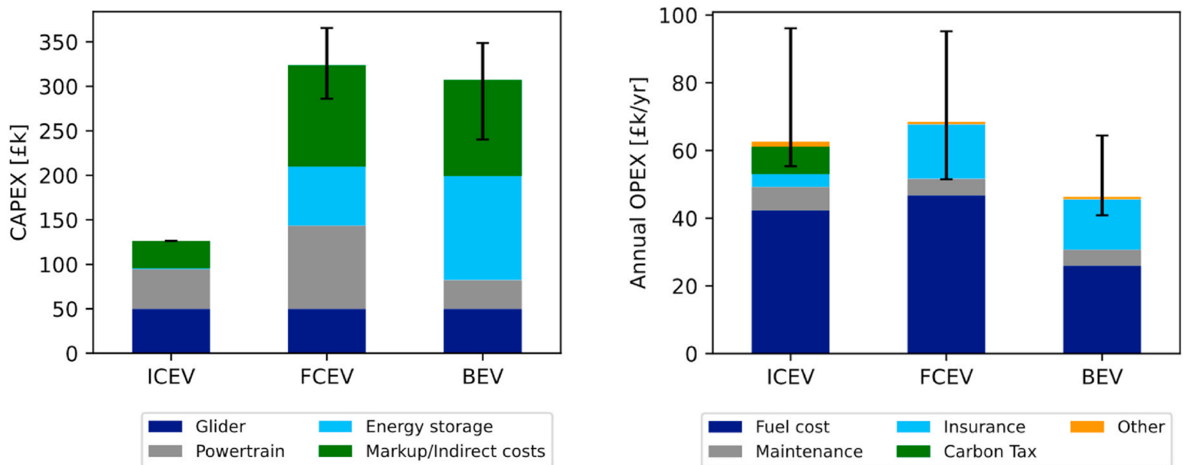

Fig. 7. Baseline HDT CAPEX and OPEX breakdown for Scenario 1, error bars show the 5th to 95th percentile.

lifetime TCO due to the relatively low fuel costs compared with ICEVs and FCEVs. The fuel cell system remains the most expensive component of the FCEV, although its energy storage cost is 43% lower than the BEV.

Fig. 8 reveals the TCO/km results of the scenario analysis for the heavy-duty sector. With the plug-in grant (Scenario 2), the cost gaps between ICEVs, FCEVs and BEVs are narrowed to £0.40/km and £0.17/km respectively, due to the former having higher CAPEX and OPEX. Results show that extending vehicle lifetime to 7 years (Scenario 3) the TCO/km of ICEVs, BEVs and FCEVs is lowered by 8%, 13% and 12% respectively, showing the clear benefit of increased asset utilisation for the more expensive BEV and FCEV technologies. Notably, with the increased 7-year lifetime, the TCO/km of FCEVs and BEVs are 50% and 23% higher than ICEVs; respectively. The higher vehicle mileage of HDTs also leads to a greater TCO impact because of battery degradation, as illustrated in the results for Scenario 4 in which the TCO/km of heavy-duty FCEVs and BEVs are increased by 2.4% and 1.7%; respectively.

4.2. GHG emissions

The resulting annual GHG emissions for HDTs are illustrated in Fig. 9. Of the various alternative pathways considered, FCEV using grey hydrogen (SMR) demonstrates the highest annual GHG emissions of 81 tCO_2/year, which is only 20% lower than that of ICEV. This highlights the clear need to source hydrogen sustainably to gain any emission reductions. This is followed by using hydrogen produced from grid electricity, which results in a further 17% emission reduction. In contrast, the BEV and blue hydrogen (SMR with CCS) pathways exhibit significantly lower GHG emissions, with reductions of 70% and 85%, respectively, compared with ICEV. The availability of these low-carbon supply routes is expected to further grow as the supply chains are being scaled up rapidly (Basma, 2021). Moreover, both BEV and FCEV have the promising potential of achieving net zero if using dedicated renewable energy sources.

4.3. Sensitivity analysis

This section presents the impact of a variability of ±30% in key parameters on the TCO value of MDT and HDT models. With regards to ICEVs, albeit the limited cost reduction potential of conventional fossil-driven powertrain components in the future (Basma et al., 2021), the TCO is largely influenced by the cost of the engine, particularly in the medium-duty weight class (9% change in TCO with a 30% change in engine cost), as shown in Fig. 10. The TCO may increase with increasing raw materials prices (König et al., 2021). Diesel price is the most influential cost parameter for ICEVs in the heavy-duty sector with a 30% change resulting in a 13.6% change in TCO, further ahead than the engine cost. In contrast, a 30% change in the carbon price is insignificant for both MDT and HDT, at around 1.3% and 2.5% change in TCO; respectively.

The sensitivity analysis for BEV HGVs (Fig. 11) indicates that the impact of the variability in the MDT battery cost is the most significant, followed by electricity price, with 9.7% and 3.7% changes to TCO with a 30% variation; respectively. In the heavy-duty class, the sensitivity to electricity price is significantly higher than the MDT due to the higher lifetime mileage. The impact of battery price is more significant than electricity price for HDTs, with a change of 10.9% in TCO compared to 8.1%.

For the FCEV sensitivity, as illustrated in Fig. 12, the cost of the fuel cell system and the hydrogen fuel price are the two most relevant variables influencing the TCO of both MDT and HDT. Like ICEV, HDT cost is more sensitive to hydrogen price than MDT, due to higher mileage. Nevertheless, cost reduction on fuel cells and hydrogen storage would effectively improve especially in the MDT segment. These high sensitivities would contribute to amplifying the uncertainties in both CAPEX and OPEX parameters.

5. Discussion

5.1. Results

In this study, the CAPEX of MDTs is in line with the literature, and the vehicle purchase price of FCEVs can reach up to 150% more than that of ICEVs, while the BEV is in between, with a 90% on-cost. In contrast, the OPEX of FCEV is 45% higher than that of BEV largely due to the higher fuel cost of hydrogen. This analysis also indicates that the BEV is more economical than the FCEV even in the HDT sector. These results are different from a few other studies in the literature, *e.g.,* (Noll et al., 2022), this is attributed due to a lower battery storage capacity specified in such analysis. It was also found that the adoption of a uniform insurance-to-vehicle purchase price ratio would result in remarkably elevated insurance costs for BEV and FCEV, particularly in the MDT sector. This potential bias in the results necessitates the need for further investigations to unveil the real insurance costs of zero-emission trucks.

The results also reveal that the TCO gap between BEVs and ICEVs is remarkably larger for MDTs than for HDTs, at 33% and 11%; respectively. This implies that the high utilisation of the vehicle enhances the

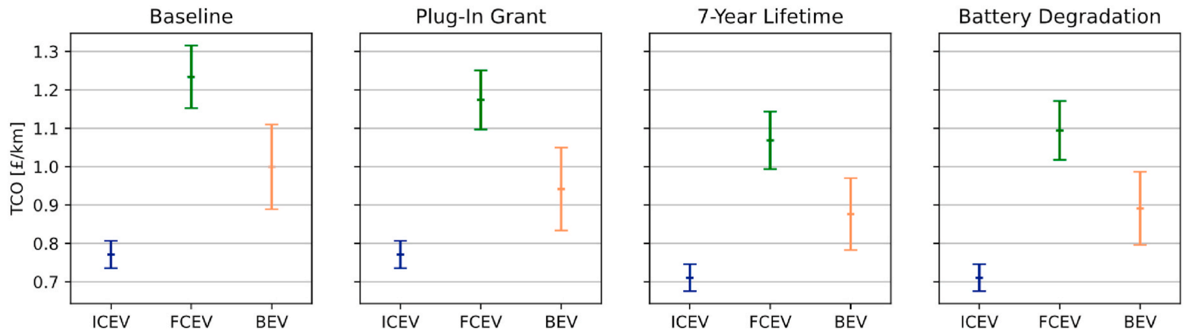

Fig. 8. HDT TCO/km values the scenario analysis, error bars show ±2 standard deviations from the mean.

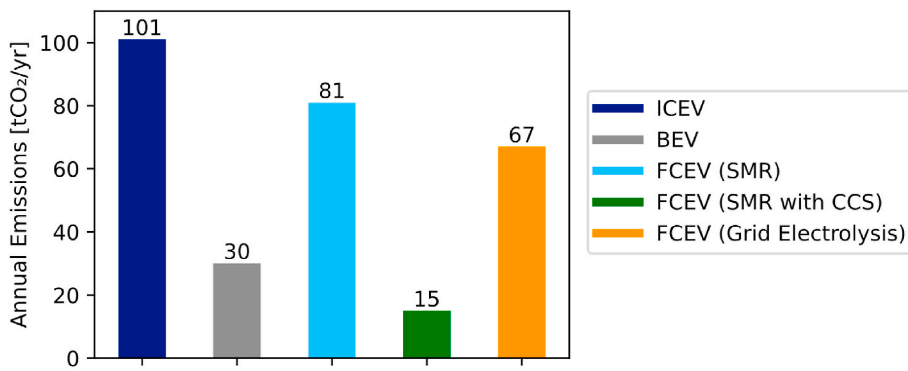

Fig. 9. HDT annual well-to-wheels GHG emissions for the five fuel pathways.

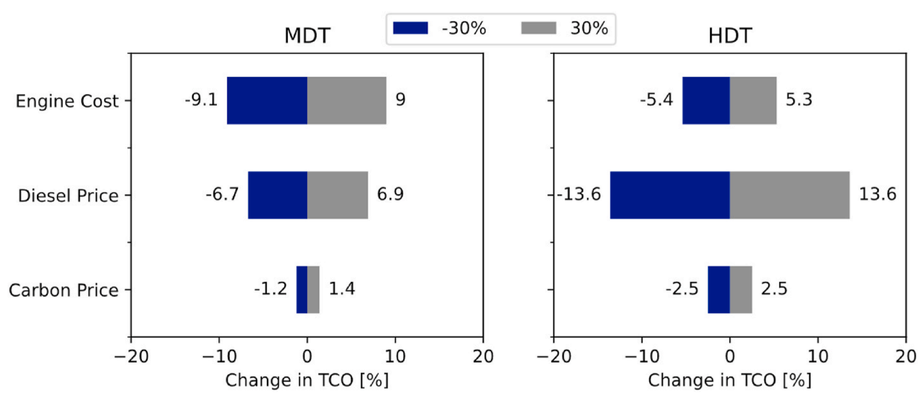

Fig. 10. Sensitivity tornado charts for ICEV HGVs.

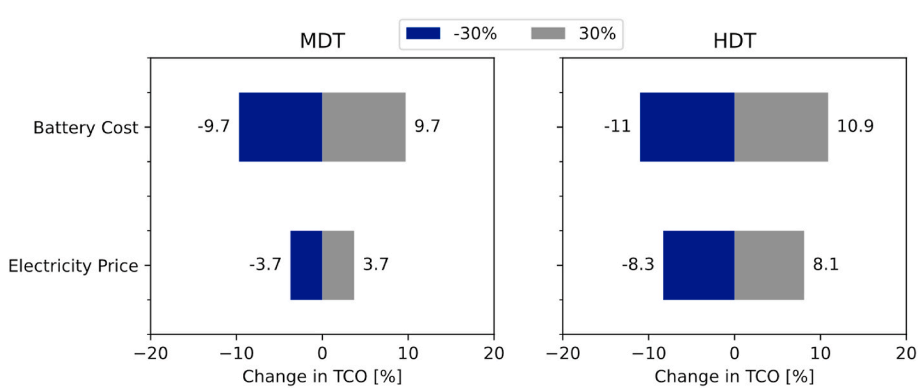

Fig. 11. Sensitivity tornado charts for BEV HGVs.

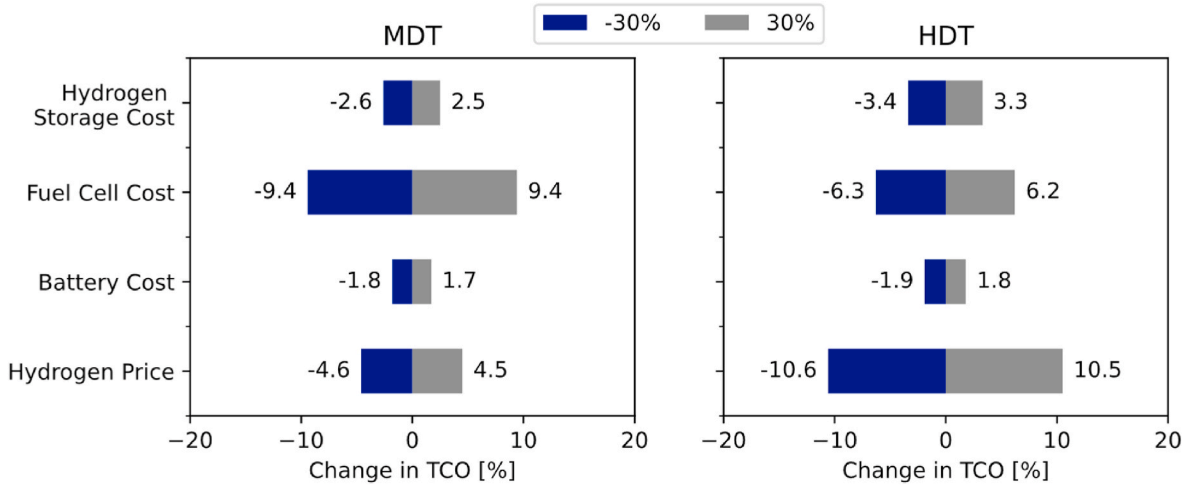

Fig. 12. Sensitivity tornado charts for FCEV HGVs.

benefits of BEV's better fuel economy, hence offsetting the high CAPEX of the battery. As for FCEVs, the higher fuel cost of hydrogen remains the major reason for the high TCO, along with the high cost of fuel cell components. It is to be noted that a flat gross profit margin of 24.3% is applied to all vehicles would lower the TCO of the alternative technologies by 8% to 12%, which however, could not significantly tighten the gaps.

In Scenario 2, it is evident that the £25k plug-in grant reduces the TCO gap for BEVs by 30% to 40% but its effect on FCEVs is not significant, due to its higher CAPEX. Scenario 3 demonstrates that adopting a longer vehicle lifetime increases the asset utilisation of BEV and FCEV technologies and reduces costs as they spread the CAPEX over a longer period. Scenario 4 demonstrates that the increases in lifetime fuel costs caused by battery efficiency degradation are very limited. A progressive estimation of a 3% TCO increase for both types of zero emission vehicles can be adopted and applied to other studies in the literature which omit battery degradation. The results of the sensitivity analysis overall align with the literature. Diesel and hydrogen cost are the key indicators for ICEV and FCEV especially in the HDT sector, whereas battery cost is the determinant factor for the BEV TCO in both weight classes.

5.2. Performance gaps

Currently, FCEV has a competitive advantage over BEV in fulfilling demanding driving range requirements without carrying as much additional weight onboard. The 700-kWh battery pack alone contributes 4,286 kg to the gross weight of the BEV HDT (17% of max. payload capacity), whereas the entire FCEV system offers 30% extra driving range and its payload penalty is 54% less than BEV's. Powertrain system efficiency is identified as another determining performance metric because it is directly linked to lifetime fuel costs and GHG emissions so improvements in efficiencies are equally as important as fuel price reductions. According to (Basma, 2021; Earl et al., 2018), the average pack-level specific energy of Li-ion batteries and efficiencies of electrified powertrain technologies are expected to increase by 60% and 20%, respectively, by 2030 compared to the current level, which would greatly reduce the payload penalty for BEV technologies. The charging rates present an additional limitation for BEVs, as they could potentially experience downtime between double shifts due to the extended time required for recharging. Consequently, fleet managers might need to deploy supplementary vehicles to fulfil the demands of intensive operations.

5.3. Policy implications & recommendations

In light of the study, OPEX accounts for a higher share of TCO than anticipated, particularly in the heavy-duty segment. The high upfront cost of zero emission vehicles remains one of the main impediments to market entry for zero emission alternatives.

Therefore, this paper proposes that policy measures should prioritise supporting the roll-out of zero emission MDTs in the short term. CAPEX incentives such as the plug-in grant for vehicle purchases and infrastructure development may help to narrow the gap. Meanwhile, a mode shift strategy can be adopted to shift the demand for ultra-long-haul goods transport to less carbon-intensive freight modes. This could include a nationwide distance-based road tolling for fossil-driven HGVs which discourages long-distance road freight activities. Alternatively, a rebate for the cost of electricity and hydrogen used for HGVs can be adopted as a significant OPEX incentive. In the long term, scaling the BEV and FCEV markets of light- and medium-duty vehicles could substantially reduce the cost of critical components including Li-ion batteries and fuel cell systems, etc. At this nascent stage, policymakers could shift their focus to OPEX incentives, *e.g.,* subsidies on charging and refuelling using renewable electricity and hydrogen.

The availability of charging and refuelling facilities remains the critical challenge for fleet operation, given the low availability of public EV charging points to HGVs. Assuming a representative scenario for a commercial BEV fleet consisting of 80 MDTs and 40 HDTs, 75% of which must be charged overnight with an 80-kW charger on-site (Earl et al., 2018). If all the vehicles were to be charged during the same period, a 7.2 MW connection to a medium voltage grid would be required. Such requirements imposes significant financial and technical challenges to deliver robust on-site charging facilities alongside a reliable substation and low voltage network infrastructure that ensures an efficient operation (Acha et al., 2011). For this to take place adequately it is paramount for integrated master planning of land use, road transport and power networks to be conducted (Bustos-Turu et al., 2015).

Currently, UK businesses can benefit from a 100% first-year tax allowance while purchasing new and unused zero emission HGVs and equipment for hydrogen storage and electric vehicle charging points (GOV.UK, 2021). The benefit allows for a deduction of the cost of qualifying capital expenditures made during the year in which the equipment was purchased. However, as the pillar to support a full-scale fleet transformation, additional investment in charging infrastructure development is required and in this area is where efforts need to be placed as well.

Overall, this paper finds on cost BEVs as a more promising pathway for the HGV sector across all weight classes. As TCO parity is still far from being achieved, the breakthrough points for each technology are given below as a reference for fleet operators to decide when to commence a full-scale fleet transition. These are based on Scenario 3 where zero emission HGVs are assumed to have a lifetime of 7 years. These breakthrough points may however vary with changes in diesel prices.

BEV

- Pack-level battery cost drops from £160 to £70 per kWh.
- Pack-level battery energy density improves from 0.17 to 0.24 kW h/kg.

FCEV

- Hydrogen pump price drops from £5.8 to £2.5 per kg.
- Fuel cell system cost drops from £267 to £110 per kW_e.

5.4. Methodology discussion

As of today, there is widespread availability of static TCO frameworks for HGVs. Nevertheless, the time domain should be factored in to develop a dynamic TCO model, the benchmarking of which also requires extensive cost data and technical parameters to be provided by industry and academia. The results may better inform timelines for cost parity for each technology in each application segment. Developing such information would enable supporting the energy transition of HGV fleets by minimising its financial and technical risks.

6. Conclusions

This paper provides a streamlined framework to evaluate the cost competitiveness of zero emission powertrain technologies in the UK's HGV sector, for both medium and heavy-duty vehicles. The capital and operational costs for FCEVs and BEVs are calculated using a TCO model under a range of scenarios, to allow comparison with existing ICEV costs. In this study, the first TCO model which considers the capacity and efficiency degradation of Li-ion batteries is established. It also contributes by presenting a robust method to calculate environmental GHG emissions based on real-world fuel consumption while factoring the resale value differences across different technologies. Finally, a sensitivity analysis is conducted to assess the relative importance of key input parameters on the cost-effectiveness of ICEV, BEV and FCEV technologies.

In the medium-duty and heavy-duty sectors, the modelled TCO of BEVs and FCEVs are 9% to 34% and 37% to 80% higher than ICEVs; respectively. This study corroborates existing literature from the UK, which suggests that BEVs are currently more economically viable than FCEVs in the HGV sector. Nonetheless, significant cost reductions are expected for both BEVs and FCEVs in the next 5 to 10 years from the time of writing (Sharpe and Basma, 2022). This study projects that TCO parity to ICEV can be achieved when battery cost is reduced by 56% to £70 per kWh for BEV, or if the fuel cell system cost drops by 60% to £110 per kWe for FCEV. However, considering that this TCO study does not consider the costs of charging infrastructure, the gap between these two technologies could be narrowed if FCEVs can offer a more inexpensive and faster refuelling solution. Another key finding of this work is that battery efficiency degradation has a minimal impact on the TCO. The sensitivity analysis implies that although fuel cell and battery costs remain the most influential cost parameters for MDT FCEVs and BEVs, the TCO of HDTs is significantly more sensitive to OPEX parameters, particularly fuel prices, because of the heavier payload and longer travel distances these vehicles incur.

Future work to improve the modelling and analysis of TCO fleets includes developing an integrated TCO model for recharging and refuelling infrastructure considering a range of funding approaches and commercial agreements. Such framework and a relevant case study that considers the impact on daily operational performance would provide a more holistic perspective on the viability of alternative HGV fleets. In addition, we would recommend that researchers conduct a comprehensive environmental assessment that accounts for the diesel fuel production emissions, as well as any non-GHG pollutants. Lastly, developing comprehensive techno-economic and environmental roadmaps for HGV fleets via optimal investment strategies would facilitate decision-making to undertake a successful transition as demonstrated previously for other carbon intensive sectors Hart et al. (2020) and Ayoub et al. (2020).

CRediT authorship contribution statement

Zixian Wang: Conceptualization, Software, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Salvador Acha:** Conceptualization, Methodology, Validation, Investigation, Resources, Writing – review & editing, Visualization, Project administration, Supervision. **Max Bird:** Conceptualization, Methodology, Validation, Investigation, Writing – review & editing, Visualization, Supervision. **Nixon Sunny:** Conceptualization, Methodology, Validation, Resources, Writing – review & editing, Supervision. **Marc E.J. Stettler:** Conceptualization, Methodology, Validation, Resources, Writing – review & editing, Supervision. **Billy Wu:** Conceptualization, Methodology, Validation, Resources, Writing – review & editing, Supervision. **Nilay Shah:** Writing – review & editing, Validation, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix

Table A1
CAPEX cost data inputs used to run the TCO model.

	Category	£ per kW	£ per kg curb weight	£ per vehicle	£ per kWh
ICE for MDT		45.9	/	/	/
ICE for HDT		60.3	/	/	/
Power electronics		/	0.673	/	/
Aftertreatment		/	0.614	/	/
Transmission for MDT		/	/	3469	/
Transmission for HDT		/	/	4820	/
Additional FCEV system		19.13	/	/	/
Additional BEV system		17.22	/	/	/
Fuel cell system	Max	303.0	/	/	/
	Most likely	267.2	/	/	/
	Min	201.7	/	/	/
Glider for MDT		/	/	45,240	/
Glider for HDT		/	/	50,000	/
Diesel fuel tank		/	/	/	0.19
Onboard charger		/	/	598	/
Li-ion battery pack	Max	/	/	/	200.0
	Most likely	/	/	/	159.0
	Min	/	/	/	100.0
H_2 storage (350 bar)	Max	/	/	/	37.5
	Most likely	/	/	/	26.3
	Min	/	/	/	22.0

Sources: (den Boer et al., 2013; Eaton Cummins, 2021; Hill et al., 2012; Kleiner and Friedrich, 2017a; König et al., 2021; Noll et al., 2022; Rout et al., 2022; Transport, 2020)

Table A2
OPEX cost data inputs used to run the TCO model.

	Category	£ per L	£ per kg	£ per kWh	£ per vehicle per year
Diesel fuel price	Max	1.99	/	0.186*	/
	Most likely	1.46	/	0.137*	/
	Min	1.20	/	0.112*	/
Electricity Price	Max	/	/	0.287	/
	Most likely	/	/	0.177	/
	Min	/	/	0.148	/
H_2 Price	Max	/	9.12	0.184*	/
	Most likely	/	5.80	0.174*	/
	Min	/	3.72	0.112*	/
AdBlue price		0.20	/	/	/
Carbon price	Max	150	/	/	/
	Most likely	100	/	/	/
	Min	50	/	/	/
Maintenance & repair ICEV MDT		/	/	/	4,880
Maintenance & repair ICEV HDT		/	/	/	6,964
Maintenance & repair BEV MDT		/	/	/	2,635
Maintenance & repair BEV HDT		/	/	/	4,666
Maintenance & repair FCEV MDT		/	/	/	3,318
Maintenance & repair FCEV HDT		/	/	/	4,875

Sources: (Department for Business Energy & Industrial Strategy, 2020a, 2020b; Gray et al., 2022; Kleiner and Friedrich, 2017b; Langshaw et al., 2020; Noll et al., 2022; Transport, 2020)

Table A3
Depreciation of the vehicle types (percentage of remaining value in reference to the initial purchase price).

	ICEV (Diesel)		FCEV		BEV	
Weight Class	MDT	HDT	MDT	HDT	MDT	HDT
Scrappage value/Vehicle purchase price (5-year lifetime)	35%	30%	25%	20%	25%	20%
Scrappage value/Vehicle purchase price (7-year lifetime)	30%	25%	20%	15%	20%	15%

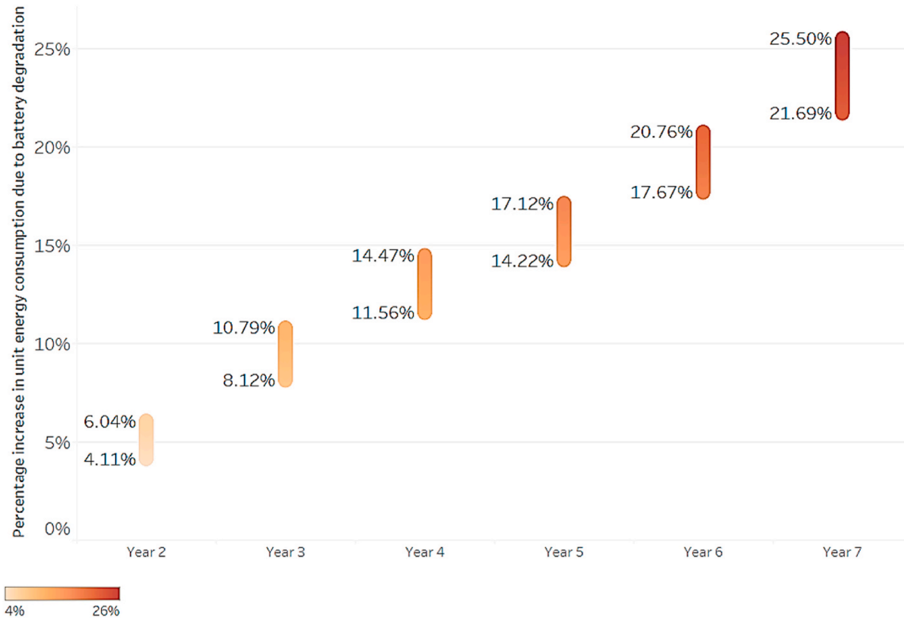

Fig. A1. The battery degradation performance data used to simulate the increased energy use across time (Yang et al., 2019).

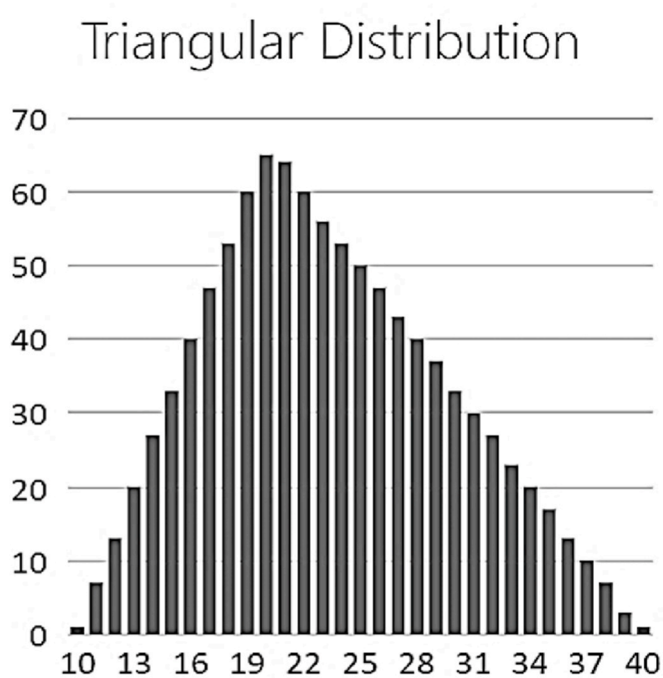

Fig. A2. An example of the probability distribution function of a triangular distribution.

Table A4
Fuel energy characteristics used to run the TCO model.

	Compressed hydrogen	Diesel fuel
Gravimetric density (kWh/kg) Lower heating value	33.33	/
Gravimetric density (MJ/kg)	120	/
Volumetric density (MJ/L)	/	38.51
Volumetric density (kWh/L)	/	10.70

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