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Analyzing the competitiveness of low-carbon drive-technologies in road-freight: A total cost of ownership analysis in Europe

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HIGHLIGHTS

- Road-freight TCO compared for 5 drive-technologies in 3 applications, 10 countries.
- A database of costs for road-freight TCO parameters is newly compiled.
- Low-carbon vehicles largely competitive in light- and medium-duty segments.
- Low-carbon vehicles competitive in heavy-duty segments in selected countries.
- Findings indicate three important TCO parameters to drive this competitiveness.

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ABSTRACT

In light of the Paris Agreement, road-freight represents a critically difficult-to-abate sector. In order to meet the ambitious European transport sector emissions reduction targets, a rapid transition to zero-carbon road-freight is necessary. However, limited policy assessments indicate where and how to appropriately intervene in this sector. To support policy-makers in accelerating the zero-carbon road-freight transition, this paper examines the relative cost competitiveness between commercial vehicles of varying alternative drive-technologies through a total cost of ownership (TCO) assessment. We identify key parameters that, when targeted, enable the uptake of these more sustainable niche technologies. The assessment is based on a newly compiled database of cost parameters which were triangulated through expert interviews. The results show that cost competitiveness for low- or zero-emission niche technologies in certain application segments and European countries is exhibited already today. In particular, we find battery electric vehicles to show great promise in the light- and medium-duty segments, but also in the heavy-duty long-haul segments in countries that have enacted targeted policy measures. Three TCO parameters drive this competitiveness: tolls, fuel costs, and CAPEX subsidies. Based on our analysis, we propose that policy-makers target OPEX before CAPEX parameters as well utilize a mix of policy interventions to ensure greater reach, increased efficiency, and increased policy flexibility.

1. Introduction

The transport sector, one of the largest energy consumers in the global economy, will have to play a crucial role in mitigating climate change. In 2018, the transport sector contributed 25% of total global CO_2 emissions from fuel combustion, of which 74% was attributed to road transport alone [1]. Road-freight, in particular, represents a critically difficult-to-abate sub-sector. It is heavily reliant upon high-carbon

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Abbreviations: BET, Battery electric truck; BEV, Battery electric vehicle; CAPEX, Capital expenditure; CNG, Compressed natural gas; EU, European Union; EV, Electric vehicle; FCET, Fuel cell electric truck; GVW, Gross vehicle weight; HDT, Heavy-duty truck; HET, Hybrid electric truck; ICE, Internal combustion engine; ICE-D, Internal Combustion Engine – Diesel; ICE-NG, Internal Combustion Engine – Natural Gas; IEA, International Energy Agency; LDT, Light-duty truck; LNG, Liquid natural gas; MDT, Medium-duty truck; O&M, Operation and maintenance; OEM, Original equipment manufacturer; OPEX, Operational expenditure; TCO, Total cost of ownership.

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energy carriers. Today, more than 95% of global road-freight vehicles run on fossil fuels, which poses a challenge for identifying pathways that diverge from the incumbent carbon-heavy system. By 2050, however, the International Energy Agency (IEA) projects this percentage to drop below 33% in a sustainable development scenario—diesel and gasoline vehicles will be replaced instead by low- or zero-carbon alternatives [2]. A mix of national and sub-national emissions reductions targets together with a shift in the manufacturing focus of major vehicle suppliers are required for this transition. The European Union has positioned itself at the forefront of global transport sector-related emissions reduction targets stating in its 2020 commission report on transport "we must shift the existing paradigm of incremental change to fundamental transformation" [3]. In line with the European Green Deal, transport sector emissions are to be reduced by 90% by 2050[1] as compared to current levels [4].

It is clear that the transition to zero-emission vehicles in the road transport sector is critical [5], though perhaps not straightforward, particularly as several low-carbon drive-technologies compete. Moreover, the appropriateness of certain drive-technologies in certain sector segments is unclear. In the passenger transport sector, considerable progress has been made towards a zero-emission fleet. Norway is one such example of a leading electric car society that has advanced the transition to electric road transport, making history in 2020 with battery electric vehicles (BEV) comprising 54% of all new car sales [6,7]. In Europe, the IEA estimates a 35% electric vehicle sales share by 2030 [8]. Battery electric vehicles have notably surfaced as the dominant drive-technology for passenger cars. In the commercial vehicle sector, however, progress is slower and the dominant technology or technologies are not so obvious. Light-duty commercial vehicles, such as vans or small flat-beds, have already begun to electrify, but medium- and heavy-duty trucks continue to run primarily on diesel. Still early in the game, battery electric and hydrogen-fueled drive-technologies vie for market position in the long-haul trucking segments. The major US based fuel-cell truck company Nikola has partnered with the Italian vehicle manufacturer IVECO to bring the latest battery electric and fuel-cell electric Nikola TRE models to market in 2021 and 2023 [9]. Daimler Truck AG and Volvo Group have launched the new joint venture 'cellcentric' as part of an industry first commitment to accelerate fuel-cells for long-haul trucks [10]. At the same time, Volkswagen Group-owned Scania has shifted their attention from hydrogen to battery-electric trucks. Natural gas powered trucks offer yet another option for road-freight and are touted in particular as an attractive transitional technology that will contribute to emissions reductions in the short term [11]. Beyond Europe, vehicle electrification in China has surged under heavy domestic policy support. In 2019, more than 25 times more electric trucks were sold in China than in the US and Europe combined [8]. However, OEMs in the US and Europe offer the majority of available medium- and heavy-duty truck models [12]. While original equipment manufacturers (OEM) ramp-up manufacturing and production of these various alternative drive-technology trucks, fleet owners and policy makers remain uncertain about which zero-carbon technology to transition to, in which segments, and when.

To asses this uncertainty, relative cost competitiveness between vehicles of varying alternative drive-technologies is often evaluated through total cost of ownership (TCO) assessments. In the literature, TCO analyses are far more prevalent in the passenger vehicle sector than they are in the commercial vehicle sector. A number of passenger vehicle studies examine and compare select technical variations within a given drive-technology (i.e. degrees of hybridization in hybrid-electric vehicles) [13–17]. Others have evaluated the TCO cost-benefits of hybrid vs. full electric vehicles as well as with 'regular' cars [18,19]. Results from these studies indicate that the TCO of electric passenger vehicles may become close to or even lower than that of conventional vehicles by 2025.

Comparative TCO studies for commercial vehicles, however, have only recently emerged. The earliest and most frequently referenced of which, is an EU commissioned study from consultancy firm CE Delft on zero-emission trucks that evaluates the TCO for two different truck classes and three or four different vehicle configurations across three selected years in Europe [20]. Following this analysis, subsequent studies have branched. A group of studies have focused on optimization of lifecycle costs for select alternative drive-technology designs as compared to internal combustion engines (ICE) [21,22]. Other studies have considered cost benefits of a mix of drive-technologies but only within an isolated region [23–26]. Considerable research has also been done by the University of California Davis Institute of Transport Studies on developments of zero-emission medium- and heavy-duty truck technologies, markets, and policy assessments, though mostly in the Californian context [27,28]. More broadly, larger TCO assessment studies have been conducted by international agencies, private consultancies, and energy companies alike [2,29–33] all with varied methodologies, boundary conditions and modelled input parameters.

In light of this review, we identify three key gaps present in the literature. Firstly, there is a lack of consolidated understanding of how drive-technology competitiveness for road-freight vehicles varies across countries and across applications. Studies and reports are dispersed in terms of cost estimates, methodological approaches, considered time-periods, as well as geographic scope. These inconsistencies make it difficult to compare results. Furthermore, as we have witnessed significant cost reductions for technologies that have rapidly matured in recent years, battery electric, fuel cell electric and liquid natural gas vehicles that were once missing from the commercial vehicle sector, now seem viable. However, we identify secondly that it remains obscure just how economically viable low-carbon drive-technologies have become in different contexts of the road-freight vehicle sector today. Thirdly, we find limited comparative policy assessments of the sector thereby making it difficult to pinpoint how and where it is most important to intervene with policy.

Given these findings, this paper addresses the gaps and contributes to the literature by first developing a consolidated and comparative TCO assessment framework for a variety of drive-technologies in a range of use-case applications and geographies. Detailed emphasis is placed on the defining characteristics of each of these three dimensions such that *relative cost competitiveness* between drive-technologies can be comparatively and holistically evaluated. Second, we provide a newly compiled database of costs for the TCO analysis, and third, we discuss how policy-makers can effectively intervene in the road-freight sector to accelerate its low-carbon transition.

To guide our study, we pose the following primary research question: which key TCO parameters drive cost competitiveness of low- or zero-emission commercial vehicle drive-technologies in which application segments? We then contextualize this question by introducing geographic variance to examine and compare a range of country-specific policies that impede or enable cost competition today. As a sub-question, we then ask: in which contexts are which policy tools most effective?

To address these questions, we stochastically evaluate and compare the TCO for five vehicle drive-technologies in three representative road-freight applications and ten European countries. We select Europe due to significant variance of policies relevant to road-freight activity but also because many countries adhere to national or EU decarbonization targets mentioned previously, and thus require defined pathways for reaching these goals. As many input data points were either contrasting or not readily available, we performed expert interviews to inform as well as cross compare collected cost values.

The remainder of this paper is structured as follows: Section 2 introduces the methodological framework for comparing TCO values for

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[1] This includes a target of at least 30 million zero-emission vehicles operable on European roads by 2030, and for nearly all cars, vans, buses as well as heavy-duty vehicles to be zero-emission by 2050.

different drive-technologies in different applications and geographies. Section 3 outlines modeling assumptions and data sources, including details on the expert interviews. Section 4 evaluates the results, while Section 5 provides a discussion of the results and considers policy implications. Finally, conclusions are drawn in Section 6.

2. Framework

Road-freight transport of goods is a complex socio-technical system [34,35]. A large variety of use-case applications exist to meet a range of consumer needs and preferences. It is therefore important to characterize the manner in which goods are transported to meet consumer preferences in a given geography when assessing suitable drive-technology options. In this study we introduce a consolidated framework in which three dimensions—drive-technology, application, and geography—characterize and differentiate the road-freight transport system. Importantly, this framework enables a comparative cost analysis of specific modeled drive-technologies in specific applications and geographies. The framework also provides policy-makers an organized structure to discuss where, how, and in what manor to potentially intervene.

- Drive-technology Dimension: Select drive-technologies are compared in each application segment. The drive-technology is defined by the vehicle's primary propulsion method and the paired fuel type. For example, a vehicle with an internal combustion engine powertrain fueled by diesel is different from a vehicle with the same powertrain fueled by natural gas.
- Application Dimension: This dimension structures the physical landscape of road-freight vehicles into a matrix of nine representative segments (Fig. 1). Commercial goods are transported in road-vehicles of varying gross vehicle weights (GVW), daily ranges, and vocational profiles. The application matrix therefore provides a structural framework to categorize and segment the manner in which specified masses of goods—light (LDT), medium (MDT), and heavy-duty (HDT) trucks—are transported over representative distances—urban, regional, and long-haul—with characteristic vocational profiles—payload, charge, and drive.
- Geography Dimension: Commercial goods are transported differently in different geographies. There are obvious qualitative physical differences (style of truck, tendency of payload loading, quality of the roads, driving patterns etc.) as well as quantitative economic differences (fuel and electricity prices, tolls, wages, etc.). Furthermore, policy measures, such as financial incentives, vehicle movement restrictions, or weight restrictions, vary significantly between geographic regions and even sub-regions. To include this variance, the framework specifies specific geographies as modeled inputs.

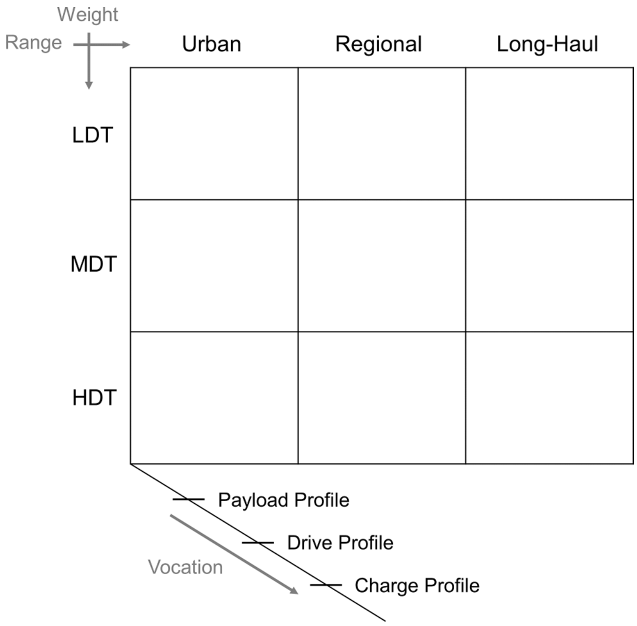

Fig. 1. The application matrix characterizes the road freight landscape along the weight, range and vocation dimensions. Light (LDT), medium (MDT), and heavy (HDT) duty trucks travel in the urban, regional and long-haul ranges. Each matrix segment is then further characterized by the vocational dimension for which the payload, drive and charge profiles are defined.

Alternative drive-technologies that lower or eliminate a vehicle's carbon emissions typically come at a cost. Like every new technology entering the market, initial capital cost competitiveness is difficult to assuage. In some contexts, however, while the initial expenditure of a new technology may be high, switching to a new technology may enable lower *long-term* costs. For example, an investor switching to a new technology may benefit from an increase in the operating efficiency of the technology's core functionality or a decrease in the annual costs required to power and maintain this technology. A TCO analysis therefore offers a fair assessment of the cost effectiveness of alternative vehicle drive-technologies over their complete lifetime by combining the initial purchase cost and annual operating expenditures.

In contrast to the passenger vehicle sector, the commercial vehicle sector is concertedly more attuned to the total cost of the vehicle over its full operational lifetime [36,37]. Commercial vehicles have a higher daily utilization rate, span longer lifetimes, and operate in predictable, often pre-determined routes that are strategically optimized. Fleet owners and commercial transport businesses, cognizant of high operating expenses, thus rely heavily on the TCO as a cost evaluation metric.

We therefore base our cost comparison on evaluated TCO values for specific drive-technologies in specific applications and geographies. We follow the TCO equation from Wu et al. [13] with some adjustments to parameter labels and addition or reconfiguration of select parameters. Formula (1) expresses the TCO as follows:

$$TCO_{t,a,g} = \frac{\left(CAPEX_{t,a} - SUB_{t,a,g} - \frac{SV_{t,a}}{\left(1+i_g\right)^N}\right) \cdot CRF + \frac{1}{N_{a,g}} \sum_{n=1}^{N} \frac{OPEX_{t,a,g}}{\left(1+i_g\right)^n}}{AKT_{a,g}} \tag{1}$$

where *TCO* is the total cost of ownership per kilometer (EUR/km), *CAPEX* is the capital expenditure or initial purchase cost of the vehicle (EUR), *SUB* is the subsidy on the initial vehicle purchase (EUR), *SV* is the scrappage value, *OPEX* is the operating expenditure or annual operating cost (EUR), *N* is the lifetime of the vehicle (years), and *AKT* is the annual kilometers travelled (km). For the discounting terms, *CRF* is the capital recovery factor $= (i(1+i)^N)/((1+i)^N - 1)$, and *i* is the discount rate. Subscripts *t*, *a*, and *g* refer to the drive-technology, application and geography dimensions respectively.

Each parameter uniquely influences the TCO. To analyze cost comparison results, it is important to understand not only how influential each parameter is, but also along which dimension(s) it is chiefly influential. Fig. 2 visualizes how the TCO parameters are broken down, and which parameters exhibit which dimensional dependencies.

The further sub-division of the CAPEX and OPEX parameters disaggregates the TCO so to understand better where and in what way policy efforts can be focused. For this study, we have selected the indicated sub-divisions, though alternative sub-parameters can be included depending on the geography to be assessed or the parameter to be affected through policy.

3. Model and data

Using the framework outlined in section 2, this study develops a

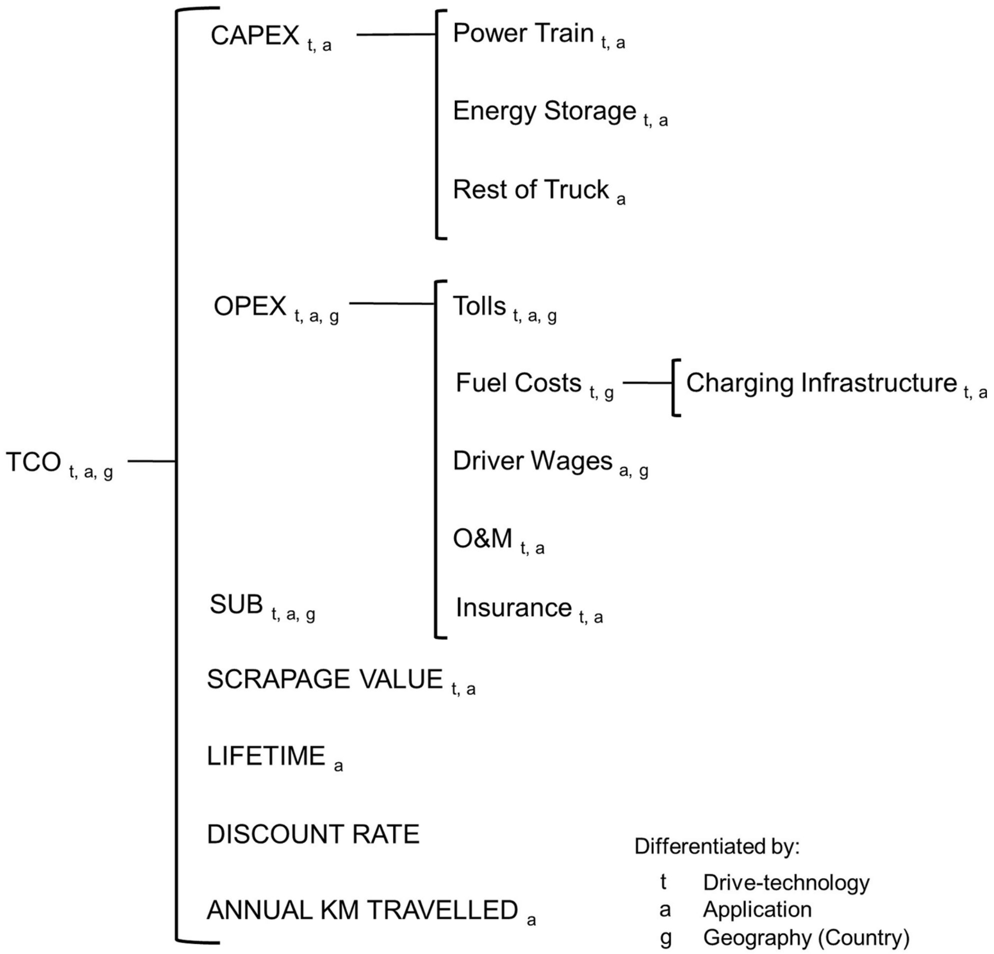

Fig. 2. A dimensional parameter tree that identifies which TCO parameters are differentiated along which framework dimensions. Subscripts defined in Equation (1) are used in the tree to differentiate TCO parameters.

model to stochastically evaluate and compare five drive-technology options in three representative application segments and ten countries (as the adjusted geography dimension). The following section first defines the case selection of each framework dimension (3.1), second, details how each TCO parameter is evaluated (3.2), third, presents model simulation techniques (3.3), and finally discusses data sources for the model's input parameters (3.4).

3.1. Case selection

We model five representative drive-technologies, in three distinct application segments, across ten representative European countries. Static TCO values are calculated for commercial vehicles in the year 2021 to demonstrate the current state of cost competitiveness for alternative drive-technologies.

3.1.1. Drive-technologies

Though internal combustion engines largely dominate the current road-freight vehicle market, a variety of alternative drive-technologies are surfacing as viable options for conversion. For this study, we select five drive-technologies that are most relevant as of 2021: internal combustion engine diesel truck (ICE-D), battery electric truck (BET), hybrid electric truck (HET), fuel cell electric truck (FCET), and internal combustion engine natural gas truck (ICE-NG).

We select ICE-D, ICE-NG and HET for their technological maturity and BET and FCET as drive-technology options that are seriously considered by policy-makers as options to lower road-freight related CO_2 emissions. Notably, we recognize that HET and ICE-NG vehicles do not allow for a zero-emission future, but are nonetheless considered important bridge technologies to meet this goal.

The HET is modeled as a range extending vehicle with a small battery that is not capable of running in pure electric mode. The natural gas truck is assumed to be a compressed natural gas (CNG) truck in the LDT weight segment and a liquid natural gas (ICE-NG) truck in the MDT and HDT weight segments. Table 2 details the drive-technology primary propulsion and fueling categorization. Further specifications for each drive-technology are included in Appendix 1.

3.1.2. Application segments

We model three representative road-freight vehicle segments along the diagonal of the application matrix in Fig. 1: LDT-Urban, MDT-Regional, and HDT-LongHaul. We select these segments as the typical application for each weight-range pairing, but also to cover the dimensional extremes of the application matrix.

3.1.3. Geography (Countries)

Ten European countries are modeled as the geographical case studies of the model (Table 1, Column 3). We model Europe as the representative geography because of its varied road freight related policies, varied country-specific TCO parameter costs, geographic proximity which allows for similarities within the region to be assumed such as vehicle dimensions and size and daily kilometers travelled, as well as for general accessibility to data. Furthermore, all analyzed countries have set decarbonization targets. Cost parameters in Europe, such as taxes, tolls, subsidies and fuel costs, depend highly on country-specific rates and policies. Modeling these costs at the country level allows for a

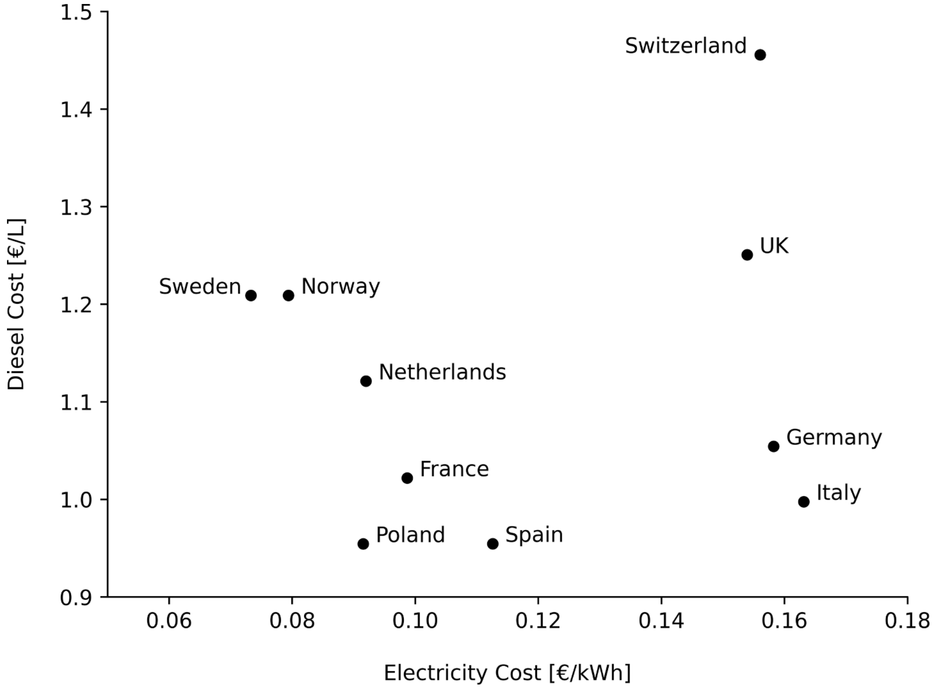

Fig. 3. Scatter plot of the average 2019 diesel vs. electricity prices for each of the ten modeled European countries. VAT as well as recoverable diesel excise duties for unique countries (Italy, France, Spain) are not included in the displayed costs. Electricity costs are for EUROSTAT Band IC consumption (500–2000 MWh/year) or equivalent.

Table 1
The three modeled dimension of the TCO. Each TCO parameter will depend on one or more of the drive-technology, application, or country dimensions. The percentage values in brackets below each drive-technology in the column on the left display the 2019 road-freight vehicle market prevalence of each specific drive-technology in the LDT segment followed by the combined MDT/HDT segments. These percentages represent the 2019 European average and are reported by European Automobile Manufacturing Association [38].

Drive-Technology	Application	Countries
• Battery Electric Truck (BET) [0.3% LDT; <0.1% MDT/HDT] • Fuel Cell Electric Truck (FCET) [<0.1% LDT; <0.1% MDT/HDT] • Hybrid Electric Truck (HET) [0.0% LDT; <0.1% MDT/HDT] • Internal Combustion Engine – Diesel (ICE-D) [89.5% LDT; 97.8% MDT/HDT] • Internal Combustion Engine – Natural gas (ICE-NG) [0.5% LDT; 0.4% MDT/HDT]	• Light-duty – Urban (LDT-Urban) • Medium-duty – Regional (MDT-Regional) • Heavy-duty – Long Haul (HDT-LongHaul)	• France • Germany • Italy • Netherlands • Norway • Poland • Spain • Sweden • Switzerland • UK

differentiated examination of policies that affect market competitiveness of alternative-drive vehicles.

We follow the case selection strategy proposed by Seawright and Gerring [39] and identify European countries by selecting (a) relevant cases and (b) diverse cases. For the relevant cases, Germany, France, the United Kingdom (UK), Spain, and Poland are selected as they represent the top five countries with the greatest annual tonnage of road freight transported (tonne-km) in 2019 [40]. Combined these five countries transport over 60% of road-freight goods in Europe. The remaining five countries are selected for diversity of key TCO parameters that differentiate drive-technology competitiveness. Italy holds the highest number of natural gas fueling stations as well as the lowest natural gas pump price [41]. The Netherlands hosts a large and presently increasing number of hydrogen filling stations [42]. Norway and Sweden exhibit the two lowest electricity prices for industrial consumers [43], and are on the higher end of diesel prices in all of Europe [44]. Switzerland stands as an extreme case as it has the highest diesel price in Europe, the highest electricity cost of the ten selected countries [45,46], and charges the highest heavy-duty vehicle toll per kilometer travelled in Europe.

3.2. *Model parameters*

3.2.1. *Capital expenditure (CAPEX) and subsidies*

We divide the CAPEX into three sub-parameters: powertrain, energy storage, and rest of truck. The *powertrain* component includes the costs of the vehicle's power source (such as combustion engine, fuel cell or motor), any auxiliaries necessary for operation, as well as the transmission. The *energy storage* component refers only to costs related to fuel tanks or batteries—the energy source of the vehicle. The *rest of truck* component represents costs associated with the vehicle glider, such as the body, wheels, cabin, etc. A unique feature of this TCO model is the calculation of performance parameters—power and energy—for each

Table 2
Key specifications for drive-technology categorizations.

	BET	FCET	HET	ICE-D	ICE-NG
Primary propulsion	E-motor	E-motor	Parallel (split ICE and E-motor configuration)	ICE	ICE
Fuel type	Electricity	Hydrogen	Diesel	Diesel	CNG/LNG

modeled vehicle (see Section 3.3.1). A bottom-up calculation of the CAPEX is thus formulated based on power and energy dependent cost values for pre-defined drive-train configurations (see Appendix 1.1) of each modeled drive-technology. This feature is introduced to a) allow the differentiation of CAPEX sub-parameters, which require power and energy dependent cost values, and b) enable simulation of vehicle performance as a function of modeled inputs for the application dimension—weight and daily range. The powertrain and energy storage costs are collected on a per-kW and per-kWh basis respectively. The rest of truck cost is a function of the vehicle weight and is therefore application dependent only—that is, glider costs are assumed to be irrespective of the drive-technology and collected on a per-vehicle basis. Further, a gross margin of 24.3% (sum of OEM margin, dealer margin, and logistics margin) is assumed for all drive-technologies [47]. The CAPEX is calculated irrespective of the country dimension and is therefore the same for each drive-technology in each application segment.

Subsidies for the initial purchase cost of the vehicle are dependent on the country issuing the subsidy, the application weight of the vehicle, and the drive-technology type. Vehicle subsidies are subtracted from the CAPEX once upon purchase.

$$CAPEX = Energy\ \ Storage + Powertrain + Rest\ \ of\ \ Truck \tag{2}$$

3.2.2. Operating expenditure (OPEX)

The OPEX is divided into five sub-parameters: tolls, fuel costs, driver wages, operation and maintenance costs (O&M), insurance fees, and infrastructure costs. Tolls is a function of the drive-technology, the application segment, and the country in which a vehicle is driven. Different units of measurement are recorded for each country as each country has its own system of tolling which can be recorded on per/km, per/year, or per-tonne/km basis. For example, the Netherlands, and Sweden both operate under the Eurovignette toll system which charges by time or on a per-year basis, Germany charges tolls on a per/km basis and Switzerland charges vehicles over 3.5 tonnes on a weighted per/km basis. Furthermore, toll rates are differentiated for vehicles with different emissions classes. As a baseline we assume EURO class VI for all emitting drive-technologies. If the toll system specifies exemptions for low or zero-emission vehicles, this is then taken into account. Fuel and infrastructure costs are discussed in the sub-section below. Driver wages is differentiated by application segment (more specifically weight class) and country. Within each segment, we take into account driver experience by introducing entry, mean and senior salaries. O&M costs comprise the annual monetary sum of total efforts for maintenance, repair and inspections of the vehicle. These costs have been found to correlate directly with vehicle drive-technology and application and are modeled accordingly. Based on the approach from Kleiner and Friedrich [48], we assume a baseline O&M cost for ICE-D vehicles in each application segment and then assume a relative cost percentage difference from the baseline for each of the remaining four drive-technologies. Insurance fees are assumed to be 2% of the CAPEX [20,49] and thus depend on both the drive-technology and application dimensions. The total OPEX is the sum of each sub-parameter as indicated in Equation (3) below.

$$OPEX = Tolls + Fuel\ \ Costs + Infrastructure\ \ Costs + Driver\ \ Wages + O\&M + Insurance \tag{3}$$

3.2.3. Fuel costs

Fuel costs are handled separately for each of the four fuel types: diesel, natural gas, electricity, and hydrogen. Projections of fuel prices, while necessary to estimating the annual fuel costs over a vehicle's operational lifetime, are inherently uncertain. This analysis thus takes a probabilistic approach to price projections for diesel, natural gas, electricity and hydrogen. We exclude 2020 in the collected historical values to avoid skewed averages from fuel volatility during the COVID-19 pandemic [50].

For diesel, we establish a normal distribution by first calculating average fuel costs of three-year periods prior to 2019 (2011–13, 2014–16, 2017–19), and second, calculating the standard deviation of these averages. For the projection, we take the most recent three-year period average (2017–2019) as the mean, and the standard deviation of the three, three-year period averages as the standard deviation of the normal distribution. For natural gas, given the limited number of vehicles and stations, and lack of publically available LNG or CNG pricing, it is not possible to provide a complete fuel price comparison for all ten selected European countries. However, natural gas prices have been shown to correlate closely with diesel price market fluctuations, just at a lower price point [51]. We therefore take price savings percentages vs. diesel as the natural gas price for select countries and follow the same methodology as diesel prices to establish an independent normal distribution for natural gas prices.[2] For electricity costs, we consider a commercial sector annual consumption level of 500-2000MWh (EUROSTAT Band IC), and perform the same projection methodology as for diesel.

Finally, for hydrogen pump prices, we divert slightly from traditional methods as there is no clearly established market for hydrogen (for transport applications) in Europe. We assume a symmetric PERT distribution with a most likely value of ~8 €/kg-H_2, and +/−1 €/kg-H_2 as the minimum and maximum values, for all ten countries. This is the 2021 average hydrogen pump price in Germany (VAT exclusive), which currently has the highest number of H_2 filling stations in Europe. Similar pump prices are found in the UK, France, Denmark and Switzerland. Hydrogen pump stations remain sparse, despite both the EU and a number of individual member states having announcing commitments to long term hydrogen investment [52–54]. Optimistic cost reduction outlooks have been published by key industry players, including the Hydrogen Council Initiative, which estimates a 60% reduction in H_2 pump prices by 2030 [55]. These optimistic estimates, however, assume high station utilization rates as a result of high scale-up of demand for fuel cell vehicles. Hydrogen refueling stations are currently the highest cost element in the cost at the pump [55]. With uncertainty around fuel cell vehicle uptake and hydrogen station utilization rates, we maintain the current average pump price of 8 €/kg-H_2 in the PERT distribution over the lifetime of the vehicle, which is in-line with values reported in [55].

Commercial haulers may reclaim fuel VAT throughout the EU as well as in Norway and Switzerland [56]. Diesel, natural gas, hydrogen and electricity costs are therefore reflective of this VAT reduction. In some EU countries, commercial haulers may also reclaim excise duties on diesel for vehicles with a gross vehicle weight of at least 7.5 tonnes. This is the case in three of the ten countries examined in this study—Italy, France, and Spain—for which we have adjusted prices accordingly [57].

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[2] It should be noted that we assume the LNG and CNG price to be the same. This is the case in most European countries with higher numbers of natural gas fueling stations [51]. CNG pricing tends to be more stable than LNG on a whole, but the price savings percentages and thus the pump prices are comparable.

3.2.4. Infrastructure cost

Infrastructure costs for ICE-D, HET, FCET, and ICE-NG vehicles are included in the fuel cost of diesel, hydrogen and natural gas, as we refer to pump prices that include margins which cover the cost of the petrol station. For battery electric vehicles, the infrastructure costs are calculated separately. To model the cost for electric charging stations, we take a levelized cost of charging (LCOC) approach [58]. An electric commercial vehicle must pay, in addition to the electricity costs, the cost to use the charging infrastructure. An LCOC approach offers a few key advantages for modeling: the cost itself is computed on a per-kilowatt-hour basis and therefore scales with the amount of electricity charged per vehicle, the LCOC can be computed for different station powers and for different station utilizations, and the capital costs are amortized over the lifetime of the charging station, not the vehicle. We model the LCOC with the following equation:

$$LCOC = \frac{\left(C_{equipment} + C_{installation}\right) + \sum_{t=1}^{life} \frac{C_{O\&M_t}}{(1+i)^t}}{\sum_{t=1}^{life} \frac{E_{charging\quad station,\ t}}{(1+i)^t}} + C_{electricity} \tag{4}$$

where $C_{equipment}$ is the equipment cost, $C_{installation}$ is the installation cost, $C_{O\&M}$ is the annual operation and maintenance cost, $E_{chargingstation}$ is the total annual energy discharged per charging station, i is the discount rate, and *life* is the lifetime of the charging station. The electricity cost, though not part of the infrastructure cost, is modeled within the LCOC.

Equipment costs are primarily dependent on the power level of the charging station, where as installation costs depend on a variety of influencing factors such as the number of charging stations per site, the level of grid reinforcement required, which scales as a function of station utilization and the associated electricity demand, as well as the mechanical installation. The total annual energy discharged per charging station is a function of the daily station utilization. We assume this to be 50%, implying that each charger outputs power for the full 12-hour overnight period every working day of the year. We assume the annual operation and maintenance costs to be a fixed 1% of the equipment cost per year. Station lifetime, in line with similar studies and confirmed by expert interviews, is assumed to be 15 years for each power level. The cost of capital is assumed a constant 7%.

As a charging pattern baseline in each of the three modeled application segments, we assume strictly overnight depot charging for a maximum of 12 hours. Because each vehicle is designed with sufficient energy storage for its daily route, no on-road charging is required. We also assume that depot owners—commercial vehicle transport companies—invest in the least-cost commercially available charger to fulfil their needs. For the LDT-Urban, MDT-Regional, and HDT-LongHaul application segments, we assume 7 kW, 22 kW, and 150 kW power levels respectively. Key modeling assumptions and LCOC parameter costs are tabulated in Table 3.

Table 3
Key assumptions used for modeling the infrastructure cost to charge battery electric vehicles.

	7 kW	22 kW	150 kW
Application Segment	LDT-Urban	MDT-Regional	HDT-LongHaul
Equipment Cost (EUR)	800	10,000	150,000
Installation Cost (EUR)	400	3813	100,000
Total Annual Energy per Charging Station (MWh)	21	66	450
Total Annual Energy per Site[a] (MWh)	105	330	2250

[a] Assuming 5 charging stations per site charged 12 h a day for every work day.

3.2.5. Fuel consumption and payload profile

We model fuel consumption as a function of the vehicle weight. Using market available data for real world fuel consumption values of each considered drive-technology, we establish logarithmic fits to the collected data points. The fuel consumption is then stochastically modeled for different gross vehicle weights and with different payload capacities. Commercial vehicles rarely operate fully loaded—average payloads depend specifically on the application segment. In line with a number of studies that similarly model capacity utilization [56,59,60], we introduce a percentage of total payload capacity for each application segment as follows:

- LDT-Urban operates with 50% average load of a 1.5 tonne total carrying capacity
- MDT-Regional operates with a 75% average load of a 5 tonne total carrying capacity
- HDT-LongHaul operates with a 75% average load of a 14 tonne total carrying capacity

For a given vehicle weight, inclusive of average carrying capacity utilization assumptions, we establish a PERT distribution with the result from the vehicle weight specific logarithmic function as the most likely value, and a 10% error padding as the minimum and maximum values.

The annual kilometers travelled are a function of the vehicle's daily range (km/day) multiplied by the number of working days per year.

3.2.6. Scrappage value

Data on end-of-life scrappage value for road-freight vehicles of different vehicles sizes, weights and vehicle kilometers travelled is sparsely available. Furthermore, scrappage value data for vehicles outside of the conventional ICE-D drive-technology is unavailable as the alternative drive-technology vehicle market itself does not yet exist. However, a comprehensive study from Kleiner and Friedrich [48] that performed a regression analysis on real market data of dealer selling price, establishes scrappage values[3] in percentage of the initial purchase price as a function of vehicle weight and total lifetime kilometers travelled. In this study, we do not differentiate scrappage value by drive-technology. With a non-existent sale market for a number of alternative drive-technologies in our modeled application segments, we do not speculate differentiated costs on the resale market. Rather, we assume the scrappage value to be primarily a function of the material and production cost of the vehicle (CAPEX) and the lifetime vehicle mileage.

Based on the results from [48], for the LDT-Urban, MDT-Regional and HDT-LongHaul segments, we take a 25%, 11%, and 18% scrappage value percentage of the CAPEX respectively.

3.2.7. Discount rate and lifetime

We assume a constant discount rate of 7% for commercial investors across all select European countries and all technologies. We assume a 7-year lifetime for the LDT-Urban and MDT-Regional application segments, and an 8-year lifetime for the HDT-LongHaul segment. We model the lifetimes to be slightly shorter than European averages [61] for two reasons. First, to account for decline in vehicle activity during the later years of the vehicle's life, a shorter lifetime but consistent daily kilometers traveled throughout the lifetime is assumed. Second, we model shorter lifetimes to exclude the necessity of battery replacement. Based on feedback from expert interviews, we assume battery replacement for heavy-duty trucks to be between 7 and 8 years and battery warranty for light- and medium-duty trucks to be between 6 and 8 years, which is in line with reported OEM offerings for available battery electric models [62,63].

3.3. Simulation techniques

3.3.1. Power and energy calculation

Different power and energy values are required of a vehicle depending on its application segment, which specifies the vehicle's

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[3] Defined as the achievable selling price minus the dismantling and disposal costs.

weight and range as well as payload, drive and charge profile. To capture these differences, we model usage profiles from world harmonized vehicle drive cycles, to output total power and energy demands of the vehicle. These outputs provide the performance specifications for a bottom-up vehicle cost formulation. We assume the vehicle must be equipped with enough power to perform the assigned drive cycle fully laden and enough energy to complete the required daily range without refueling or recharging.

We derive the formula for vehicle propulsion power from the standard dynamic vehicle model [64] as follows:

$$P_{prop} = [\frac{1}{2}\cdot\rho_{air}\cdot c_D\cdot A_f\cdot v^2(t) + m\cdot g\cdot c_r + m\cdot\frac{dv(t)}{dt}]\cdot v(t) \tag{5}$$

where ρ_{air} is the air density, c_D is the coefficient of drag, A_f is the frontal area, m is the total mass of the vehicle (maximum payload included), g is the gravitational constant, c_r is the coefficient of tire rolling resistance, and $v(t)$ is the velocity as a function of time. The gravitational constant and air density are ambient properties, but all other parameters are vehicle specific and thus depend on the application segment. It is important to note that we ignore the road gradient term in the propulsive power formulation as it has been found, on average, to cancel out over the entirety of a given trip [65].

The formula for total energy is then derived by integrating the propulsive power over the specific drive cycle velocity profile [66]:

$$\begin{aligned} & E_{total} = \int_{Drive\ \ Cycle} \frac{P_{total}(t)}{v(t)}\ dt; \\ & where\ P_{total}(t) = H(P_{prop})P_{prop} + P_{aux} \end{aligned} \tag{6}$$

where H is the Heaviside step function and P_{aux} is the total auxiliary mechanical power demand of the various non-propulsive subsystems of the vehicle, such as air conditioning or steering. The auxiliary power is a constant term that depends on both the drive-technology and application segment. Purely dissipative breaking is assumed.

For the drive cycle, we model the World Harmonized Vehicle Cycle (WHVC) for the HDT-LongHaul application segment, and the World Harmonized Light-duty Test Cycle (WLTC) class 2 for the LDT-Urban and MDT-Regional segments. Both of these drive cycles are considered suitable approximations for their respective real-world applications in the literature.

3.3.2. Stochastic simulation

Cost uncertainty of CAPEX and OPEX parameters is modeled with a probabilistic Monte Carlo simulation. The following section will discuss for which parameters we introduce uncertainty and why, simulation methods, and types of distributions used.

We determine the stochastic nature of a TCO parameter based on variability of collected data, relative impact of the parameter on the sensitivity of the TCO, and relative uncertainty of the parameter itself. That is to say, parameters with rather certain or even constant cost data and parameters that minimally affect the TCO are not modeled stochastically.

For the CAPEX, all but three specific vehicle components that makeup the powertrain, energy storage and rest of truck sub-parameters are modeled stochastically. CAPEX sub-parameter costs are modeled with PERT distributions based on best estimates of minimum, maximum and most likely values from collected data. For the OPEX, uncertainty is introduced for driver wages as well as for fuel costs. We use a PERT distribution for driver wages and a normal or PERT distribution for projected fuel costs as per the methodology described in Section 3.2.3. Uncertainty is also introduced for fuel consumption—a highly variable technical parameter dependent on the vehicle make, model, payload as well as the on-road drive profile—as outlined in Section 3.2.5. Tolls are modeled as constants as they are fixed reported values from respective regulatory administrations. Insurance and O&M are also both modeled as constants primarily because their impact on the TCO sensitivity is small. Introducing additional uncertainty in these two parameters does not therefore affect the results. Subsidies on the vehicle CAPEX, similar to tolls, are fixed reported values. Scrappage value as a percentage of the vehicle CAPEX is not modelled stochastically, though the resulting monetary scrap value, a function of the CAPEX, is accordingly distributed. Other non-stochastic TCO parameters include the vehicle lifetime and cost of capital. Parameters that define the application segments, such as weight, daily range, as well as annual kilometers travelled which correspond directly to the range, are also non-stochastic. We assume constant weight and daily range values for each segment as indicated in Table 4.

Table 4
Key modeling parameters assumed constant in the model.

	LDT-Urban	MDT-Regional	HDT-LongHaul
Weight (metric tonnes)	3.5	7.5	32
Daily range (km/day)	75	200	600
Total Payload Capacity (metric tonnes)	1.5	5	14
Utilization Percentage of Total Payload (%)	50	75	75
Power (kW)			
BET	80	151	343
FCET	80	151	343
HET	80	151	343
ICE-D	80	151	343
ICE-NG	80	151	343
Energy (kWh)			
BET	34	168	1354
FCET	53	263	2116
HET	57	282	2275
ICE-D	65	322	2600
ICE-NG	67	332	2677
Lifetime (years)	7	7	8
Annual km travelled (km)	19,500	52,000	156,000

Finally, we introduce stochastic variance for two key identified vehicle performance characteristics—coefficient of drag and frontal surface area—as calculated power and energy values, which directly translate to vehicle CAPEX, are particularly sensitive to these two parameters. We assume again a PERT distribution for both parameters. See Appendix 5 for a full table of which TCO parameters are modelled stochastically and which are not.

A Monte Carlo method is then applied by repeated simulation of outputs with probabilistic inputs that have defined stochastic distributions. This study runs 10,000 simulations of each drive-technology in each application segment and each country for the base year 2021.

3.4. Data sources

CAPEX data is derived from four primary sources, though we cross-reference researched values with secondary sources, market available data, as well as with expert interviews. A full table of CAPEX cost assumptions with relevant sources can be found in Appendix 2.1.

Data for OPEX parameters are collected from a wider variety of sources as many of the OPEX sub-components are country dependent and therefore require country specific examination. Diesel price data and natural gas price data, modeled as a percentage savings of diesel prices, is sourced from the EU Commission Historical Oil Bulletin reports. Electricity data is sourced from EUROSTAT. For the two non-EU countries, Norway and Switzerland, we source the diesel price data from Statistics Norway [67] and AVENERGY Suisse [46], and electricity price data from EUROSTAT and the Swiss Federal Electricity Commission respectively. Toll data are collected from country specific regulatory authorities and informational websites. Driver wage data are collected from two primary studies [20,68] and adjusted for inflation. See Appendix 3 for collected OPEX data and associated references.

Vehicle subsidy data are collected from government reports and policy announcements for each of the ten European countries. See Appendix 2.2 for collected vehicle subsidy data.

Infrastructure cost data are sourced primarily from a study by the International Council on Clean Transport (ICCT) on infrastructure for zero-emission trucks [69], and two joint studies from the NGO European Climate Foundation and consulting company Cambridge Econometrics [31,70]. The LCOC methodology, however, is extrapolated from a study by the National Renewable Energy Lab (NREL) [58]. Notably, data for station installation costs, especially for high charging power sites, are lacking in both the literature and the field. We therefore take data from the above mentioned sources and cross compare with expert interviews. This supplies us with an informed understanding of how installation costs would scale with increasing power levels, despite the scarcity of operational high power level charging stations in the field.

Performance parameters data, such as coefficient of drag, frontal surface area, and coefficient of friction required for power and energy calculations are collected from representative vehicles in each application segment from brochures and vehicle specification documents of major European OEM's. These values are cross-compared with studies in the literature. In total 36 vehicles and 6 studies were sourced. The World Harmonized Vehicle Cycle (WHVC) and the World Harmonized Light-duty Test Cycle (WLTC) data are sourced from the United Nations Global Technical Regulations addendum No. 4 [71] and No. 15 [72] respectively. Appendix 4 details all parameter values assumed in the vehicle power and energy dimensioning.

3.4.1. Expert interviews

Secondary to the archival data collected from publically available literature and assessment studies, a number of expert interviews were conducted to inform cost assumptions, but also to inform the formulation of the commercial vehicle TCO model. In total, 17 interviews (see Table 5) were conducted throughout the course of 2020. All interviews were conducted under the "Chatham House Rule" and hence no references to interviewees or their affiliations are made.

Table 5
Interview sample.

	Organization	Expertise	Interviewee's Role(s)
1	International Agency	Freight transport landscape and modeling	Transport Analyst
2	International Agency	Freight transport landscape and modeling	Transport Analyst
3	International Agency	Freight transport landscape and modeling	Transport Modeler
4	International Agency	Freight transport expert, author, and analyst	Energy, Technology and Environmental Sustainability Advisor
5	Private Agency	Transport and urban research	Senior Research Associate
6	Public Agency	Mobility infrastructure	Research Analyst
7	Public Agency	Sustainable mobility, alternative fuels and charging infrastructure	Senior Advisor Sustainable Mobility
8	OEM	Product development and strategy for electric trucks and electric powertrain	Product Strategist for German Electric Mobility Group
9	OEM	Electric road systems	Head of Business and Development for German eHighway Company
10	OEM	Natural gas vehicle engineering	Senior Director of Engineering for US Manufacturing Company
11	OEM	Vehicle charging	Senior Project Manager & Business Developer for German Company
12	OEM	Vehicle charging	Head of eMobility Market for Swiss Company
13	University	Vehicle engineering and modeling	Researcher
14	University	Vehicle engineering and modeling	Researcher
15	Environmental Think-Tank	Carbon-free mobility	Principal
16	Consultancy	Policy-relevant econometric analysis	Associate Director
17	National Lab	Mobility infrastructure and impacts analysis	Research Analyst

4. Results

In the following section, we will examine first the results of the CAPEX for each drive-technology in each application segment, and second, the results of the TCO calculations for all drive-technologies in each application segment and country.

4.1. CAPEX results

To begin, we look at the results from the bottom-up cost formulation of each drive-technology in each application segment in Fig. 4. A CAPEX cost comparison reveals similar *relative* costs between drive-technologies in each application segment—BET and FCET vehicles compete for the most expensive option, and the three fossil fueled technologies observe the least expensive options. This trend scales aptly in the light- and medium-duty segments, but becomes acutely more exaggerated in the long-haul segment. This is due to the substantial increase in required energy storage for 600 km of daily range, which especially disadvantages the CAPEX of zero-emission drive-technologies. The battery cost alone amounts to over 63% of the total BET vehicle cost in this segment. Though not as pronounced, the 700 bar compressed hydrogen storage tank similarly makes up a large percentage (over 22%) of the total FCET cost. For FCETs in all segments, the powertrain assumes the largest sub-component cost. Fuel cell stack systems, the single most expensive cost from this sub-component, remain prohibitively costly for commercial vehicles. Interestingly, the powertrain cost of BET and FCET vehicles does not as noticeably increase *between* application segments as compared to ICE-D. For BET and FCET vehicles, the powertrain cost is between 15–22% and 53–56% of the total in all segments respectively. For ICE-D vehicles, however, the powertrain cost steadily increases from 20% of the total in the LDT-Urban segment to 48% of the total in the HDT-LongHaul segment. These trends highlight the importance of decreased energy storage and fuel cell stack costs, two relatively immature technologies in road-freight applications, in order for BET and FCET vehicles to demonstrate competitive capital costs.

Traditional ICE-D vehicles remain the least CAPEX option in both the MDT-Regional and HDT-LongHaul segments, but ICE-NG vehicles are in fact cheaper in the LDT-Urban segment. The ICE-NG vehicle is modeled with compressed natural gas (CNG) in the LDT-Urban segment, which exhibits comparatively lower tank costs. In the MDT-Regional and HDT-LongHaul segments, ICE-NG vehicles are modeled with liquid natural gas (LNG) storage, which must be stored at very low temperatures and very high pressures, making for a more expensive tank, though more volumetrically efficient consumption. For the HET, the parallel vehicle configuration assumes a 30% downsize of the internal combustion engine and insertion of a small range-extending battery that improves fuel consumption. Despite the battery inclusion and the associated powertrain accessories resulting in a higher CAPEX, Fig. 5 reveals how this high upfront cost is offset by lower annual fuel costs as the annual mileage increases.

Our data from traditional drive-technologies, such as ICE-D, ICE-NG and HET vehicles (in some applications segments), closely resembles market data. For zero-emission drive-technologies, however, the market is still in the very early stages of development and production. Particularly in the HDT-LongHaul segments, BET and FCET vehicles are simply unavailable for purchase, or available only as demonstrative test cases.

Additionally, it is difficult to compare market costs cleanly to the results of this study for two main reasons: 1) vehicle performance specifications for market available vehicles do not always match the

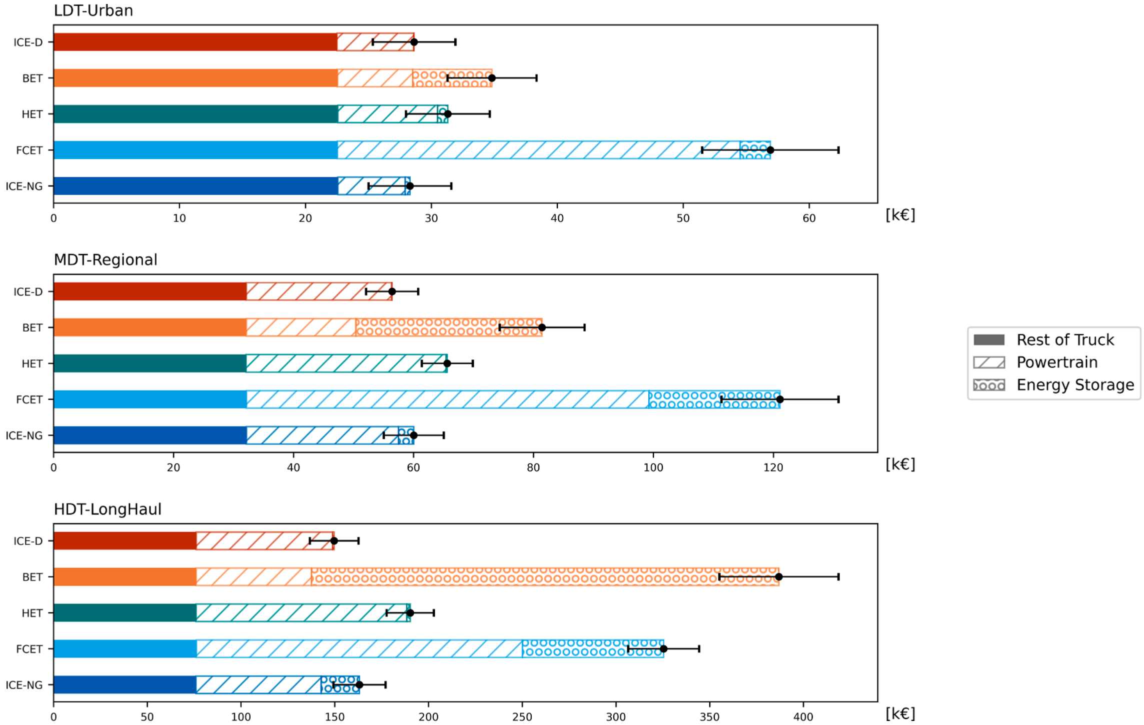

Fig. 4. CAPEX values for five drive-technologies in three application segments. The drive-technologies are separated by color and shown on the y-axis of each application sub-plot. We separate the CAPEX into its three sub-components: Rest of Truck (solid), Powertrain (dashed), Energy Storage (bubbled). The Rest of Truck sub-component does not differ between drive-technologies. The key differentiating sub-components are thus namely the Powertrain and Energy Storage. Note that we assume CAPEX values for all drive-technologies in all application segments do not differ between specific European countries. Considering the low-carbon drive-technologies on a CAPEX basis, we see that BETs are competitive in the LDT-Urban segment, but not in the MDT-Regional or HDT-LongHaul segments, and FCETs are uncompetive in all segments. Values are in thousands of Euros and based on bottom-up cost formulations of calculated power and energy ratings for each vehicle. VAT is not included, but a gross margin of 24.3% is included. The black error bars denote two standard deviations.

vehicle design methodology that this study follows, and 2) this study does not scale costs to production volumes. For drive-technologies that are mature such as ICE-D vehicles, the modelled cost results are comparable, but for BET and FCET vehicles, costs are not so easily comparable as the options are not only in pre-production but the market for these drive-technologies has not had time to converge to preferred vehicle designs. Expert interviews have confirmed these ballpark CAPEX values, in particular for the zero-emission vehicles.

In the HDT-LongHaul segment, the cost of the BET appears wildly high, but again, this analysis assumes the truck is designed for 600-km of daily range without charge. This gives a battery capacity of over 1200kWh, thus the nearly €400,000 CAPEX. We acknowledge this battery capacity to be quite high—a number of heavy-duty battery-electric truck OEMs have indicated a capacity range of closer to 600–900 kWh. However, we model this extreme to specifically show what the cost *would* be, should a BET require this maximal range.

Lastly, the model in this study does not suppose the CAPEX results to be highly indicative of what European fleet-owners should expect at a dealership. Rather, the model proposes CAPEX values that we expect to see on the market in the coming years for vehicles of similar technical performances.

4.2. TCO results

While the CAPEX accounts for only a part of lifecycle costs, the TCO provides a holistic picture. Fig. 5 presents the primary results from this study. TCO values for each drive-technology are displayed for each studied European country in each of the three application segments.

4.2.1. Light- and medium-duty application segments

In the LDT-Urban segment, competition between drive-technologies is high. Furthermore, drive-technology TCO values in most countries follow the same comparative trend: ICE-D, ICE-NG and BET vehicles compete for the most economical option, HET vehicles follow closely behind and FCET vehicles are decidedly more expensive. However, the per-km spread in TCO values between drive-technologies in each country, with the exception of the UK and Spain, is comparably negligible. Disregarding FCET vehicles which are outliers in all segments, no one drive-technology stands out as the clear low-cost choice. This indicates that the selection of one drive-technology over another would likely depend on a given investor’s purchasing conditions and needs. In ten out of ten countries, BET vehicles have the lowest average TCO value and FCET vehicles have the highest. Given the current price point for fuel cell stack systems and high cost of hydrogen, this is unsurprising. What is perhaps most notable in the LDT-Urban segment is the absolute TCO difference between countries. This is due to the variation of country-specific wages, which comprise on average over 60% of the TCO. In later application segments, this trend becomes less apparent as wages contribute a smaller percentage of the TCO.

In the MDT-Regional segment we begin to see a bit more differentiation in TCO between drive-technologies. BET vehicles stand out as the least cost option in nearly all ten countries and even distinguish themselves, in certain countries such as Switzerland or Norway, as the obvious favorite. ICE-D, HET, and ICE-NG vehicles exhibit approximately the same relative difference in many countries. Interestingly in this application segment, Switzerland surfaces as an anomaly. Two important insights are observed in Switzerland: one, the TCO value of all drive-technologies are significantly higher than those in all other countries, and two, FCET vehicles are relatively competitive in the MDT-Regional segment and especially competitive in the HDT-LongHaul segment. Both of these observations are attributed to the Swiss “Leistungsabhängige Schwerverkehrsabgabe” (LSVA) toll system that

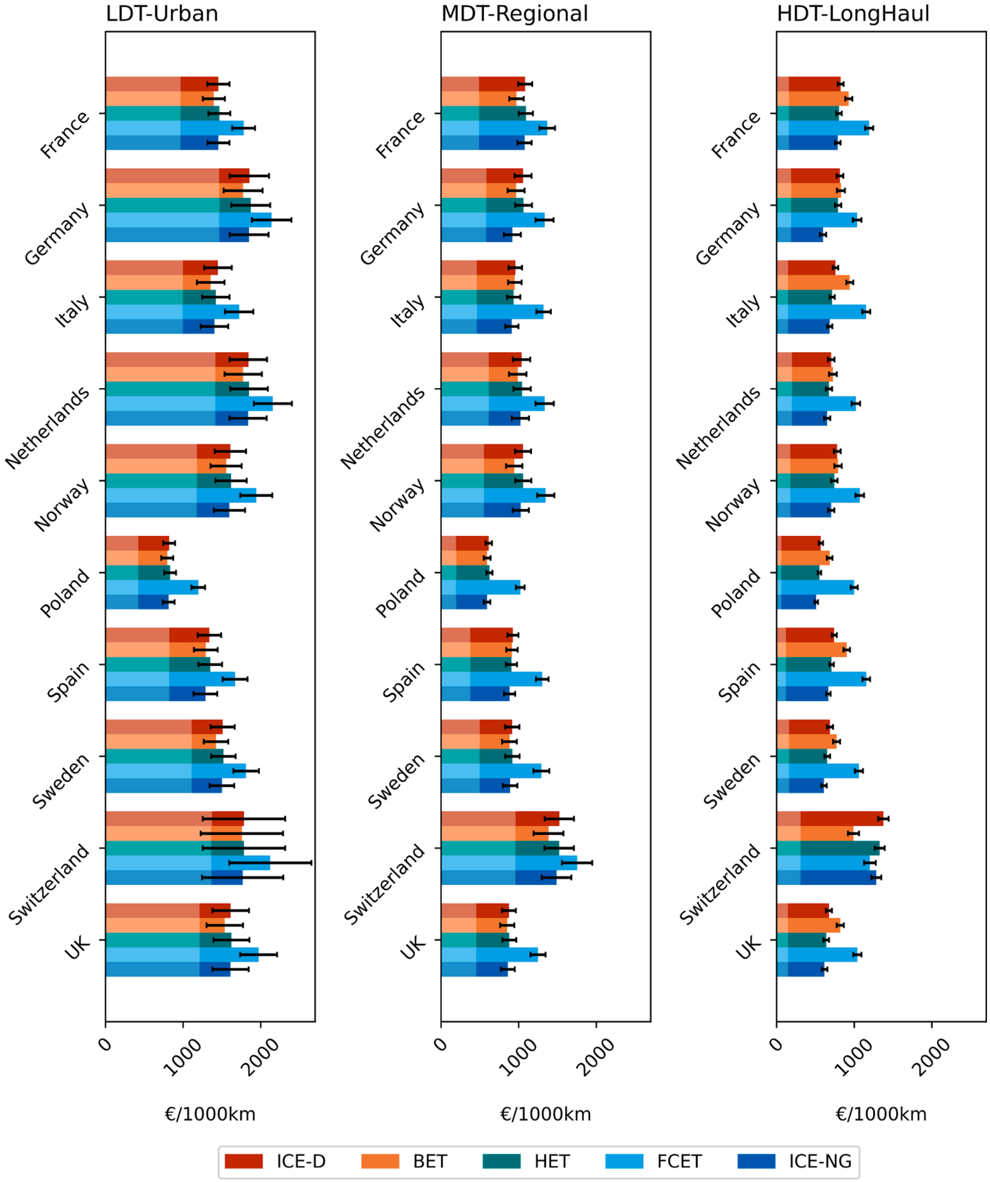

Fig. 5. The TCO results for each drive-technology in each application segment and country. The drive-technologies are grouped by color for each country on the y-axis. The TCO value is displayed in €/1000 km on the x-axis. Drive-technology competitiveness is assessed by comparing the relative TCO values within a specific application and country. For a commercial vehicle investor, drive-technologies with low TCO values (shorter bars) thus indicate more attractive options than drive-technologies with high TCO values (longer bars) which are less attractive options. As a reading example, we take Switzerland. In the LDT-Urban segment, ICE-D, BET, HET and ICE-NG all display relatively similar TCO values—only the FCET drive-technology is uncompetitive in this segment with a TCO value much higher than all others. In the MDT-Regional segment, BETs distinguish themselves as the most economical (least TCO) drive-technology on average, but compete closely with ICE-NG as well as ICE-D and HET vehicles. FCETs remain uncompetitive in this segment as well. Finally, in the HDT-LongHaul segment, BETs stand out as the clear least-cost option, followed next by FCETs. ICE-D vehicles are the highest cost option in this segment, and HET and ICE-NG vehicles sit in-between. Error bars are included in black at the end of each colored bar graph and indicate two standard deviations. The lighter shaded portion of the bar indicates the driver wages portion of the TCO.

uniquely charges all vehicles over 3.5 tonnes based on their total weight, emissions class and kilometers driven. Switzerland is the only country in Europe[4] that charges permissible weight of heavy-duty vehicles thus resulting comparatively in a much higher toll. Zero-emission vehicles, however, are exempt from this toll, which explains the unexpected competitiveness of FCET vehicles in this segment. The LSVA toll thus constitutes a key policy tool that induces competition of low- or zero-emission trucks. The effectiveness of vehicle tolls as a mechanism for policymakers to facilitate such competition is even more accentuated in the HDT-LongHaul segment.

The exhibited competitiveness of low- and zero-emission vehicles in the light- and medium-duty segments has been widely anticipated in recent years by OEMs, fleet owners, and other relevant transport players. In particular, the trend towards BET development is in line with the results of this study. With current passenger vehicle models overwhelmingly shifting to battery electric drive-trains, it is expected that light and even medium sized commercial vehicles will shortly follow suit. Outcomes in the heavy-duty commercial vehicle segment, however, are not as pronounced. The following section thus specifically addresses the uncertainty of such outcomes in the HDT-LongHaul segment and examines key parameters that critically affect comparative TCO results.

4.2.2. *Heavy-duty application segment*

In the HDT-LongHaul segment, drive-technology competition varies significantly between countries—no clear trend is visualized. Predominantly, ICE-D and ICE-NG vehicles demonstrate the lowest TCO values with HET vehicles closely behind. More notably, the country-level variance in competition of the two zero-emission vehicles, BET and FCET, is stark. Except in Switzerland, FCET vehicles are largely too expensive to consider in this segment. The current fuel cell stack and hydrogen fueling costs prove again to be prohibitively high. For the most part, BET vehicles are equally uneconomical, though not always. In fact, three countries show highly competitive BET TCO values as compared to the incumbent ICE-D vehicles. This result is quite surprising. Especially given the high daily range this model assumes for the HDT-LongHaul segment. While discussions regarding the shift of heavy-duty long-haul commercial vehicles away from internal combustion drive-trains towards cleaner alternatives are trending, the timeframe for this shift has remained uncertain. The current understanding is that battery costs and

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[4] And one of only three countries in the world [109].

thus vehicle CAPEX is, today, still too high. The results of this TCO analysis in certain countries prove otherwise. To better discern this contradiction, we specifically examine select countries that both do and do not display BET competitiveness as compared to ICE-D by breaking down the components of the TCO to identify key influencing parameters.

To begin, we examine Switzerland as the anomaly case. In the HDT-LongHaul segment of Fig. 5, we see that the BET TCO value is not only abnormally lower than its fossil fuel counterparts, but also that Switzerland is the sole country in this segment that displays ICE-D vehicles as the least economical option. Nevertheless, we know from Fig. 4 that BET CAPEX values in the HDT-LongHaul segment are more than double ICE-D CAPEX values. A waterfall chart of summed TCO components in Fig. 6 reveals how this high BET CAPEX is offset. While reduced fuel and O&M costs as well as a slight advantage in scrappage value for BET vehicles certainly contribute, the true driving parameter is tolls. Nearly 40% of the ICE-D TCO in Switzerland comes from tolls. As previously indicated, Switzerland has a unique tolling scheme that charges per-km fees based on gross vehicle weight and emissions class. This policy tool, more specifically the inclusion of a vehicle weight based toll, has strikingly enabled TCO competition of BET vehicles that are exempt from this toll.

To further understand key TCO driver parameters, we next examine the comparative TCO results of BET and ICE-D vehicles for two pairs of countries that exhibit high diesel and low electricity costs and vice versa. Fuel costs are a large component of the TCO and are markedly varied for each of the ten studied European countries. For this reason, we select and compare country pairs with fuel costs that both advantage and disadvantage ICE-D over BET vehicles. The first pair, Sweden and

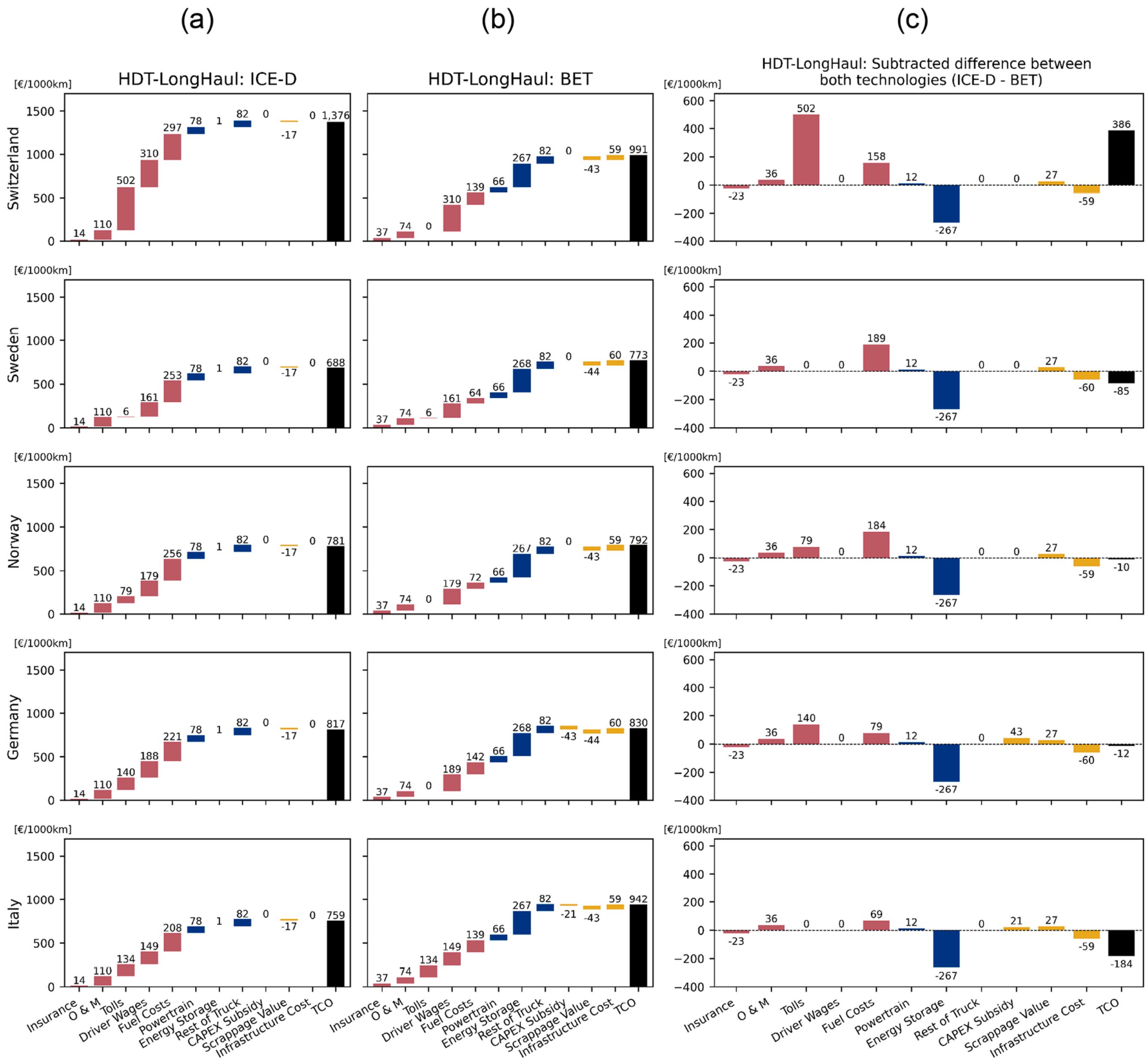

Fig. 6. Waterfall charts of drive-technology TCOs for five selected countries: Switzerland, Sweden, Norway, Germany, and Italy. ICE-D waterfall charts are shown in column (a), and BET waterfall charts are show in column (b), both for the HDT-LongHaul segment. TCO components are differentiated on the x-axis and summed to the total TCO value. OPEX components are shown furthest to the left in dark pink, CAPEX components follow next in dark blue, and the remaining components are in gold. The TCO result is displayed in black. Column (c) displays zero-line delta plots—the subtracted difference between the two technologies of each individual TCO component (i.e. ICE-D components minus BET components). Positive values indicate parameters that are more expensive for ICE-D vehicles and negative values indicate parameters that are more expensive for BET vehicles.

Norway, exhibit relatively high diesel costs as well as the two lowest electricity costs of the country case selections (see Fig. 3). The second pair, Germany and Italy, display relatively low diesel costs matched with high electricity costs. Though we might expect these comparative results to favor BET vehicles for Sweden and Norway and disfavor BET vehicles for Germany and Italy, an alternate outcome is in fact observed.

We first compare Sweden and Norway. In Fig. 6 (a) and (b), the black TCO bar at the right of each waterfall chart reveals ICE-D vehicles as the clear least cost option in Sweden, though in Norway, BET vehicles are only 2% more expensive than ICE-D vehicles. Despite both countries displaying nearly identical fuel costs for each drive-technology, one country clearly favors the zero-emission vehicle option over the other. In order to distinguish why this is the case, it is crucial to recognize which TCO parameters to compare along the country dimension and which to compare along the drive-technology dimension. As some parameters, such as tolls, fuel costs, and CAPEX subsidies, depend on both

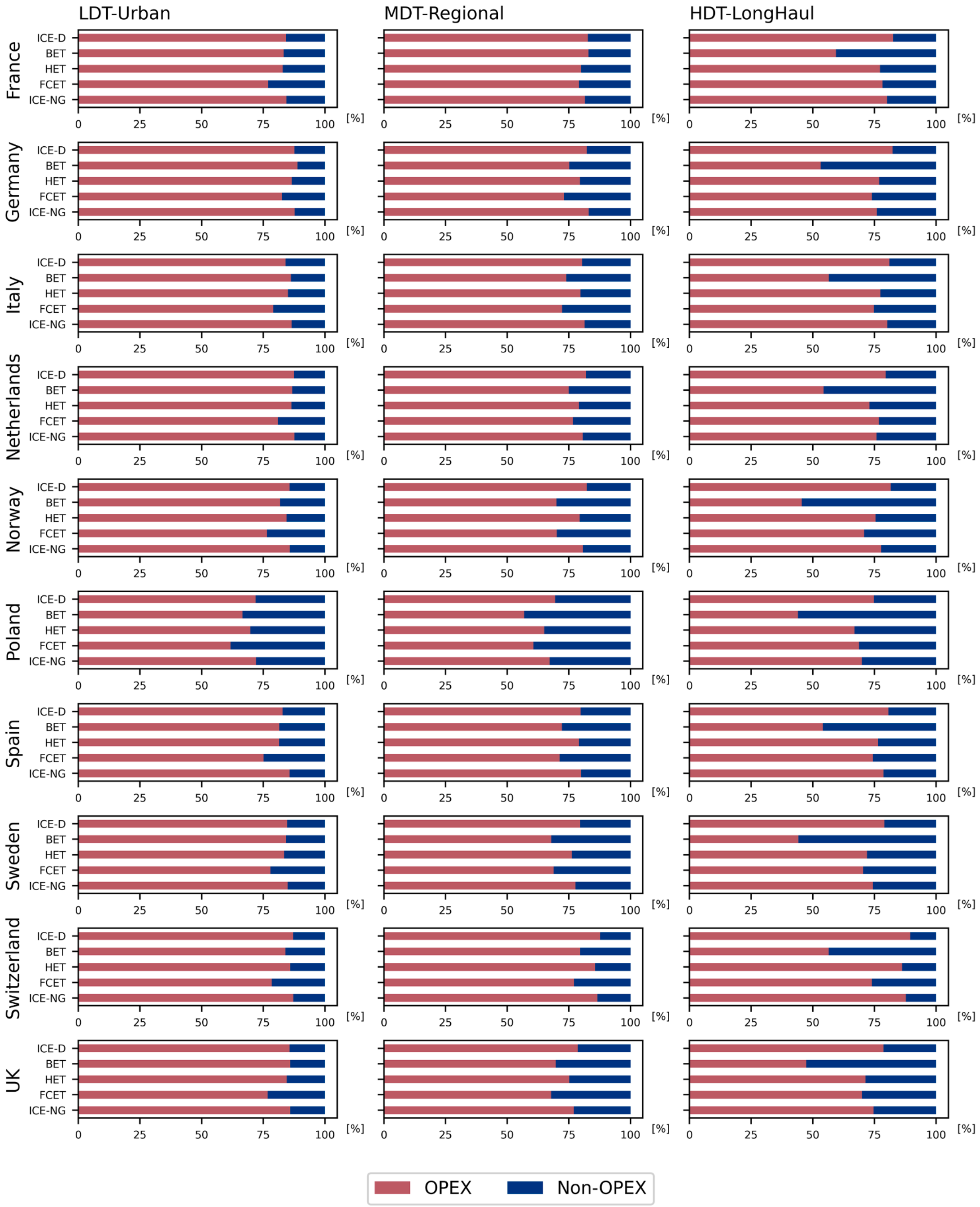

Fig. 7. Comparison of the percentage makeup of OPEX and non-OPEX parameters in the TCO for each drive-technology in each application segment and in each country. OPEX parameters (Insurance, O & M, Tolls, Driver Wages, Fuel Costs) are shown to the left in dark pink and non-OPEX parameters (CAPEX, CAPEX Subsidy, Scrappage Value, Infrastructure Cost) are shown to the right in dark blue. Overall, we see high pink and low blue percentages in most countries and application segments. Only the BET drive-technology in the HDT-LongHaul segment shows nearly even pink to blue ratios. This indicates the importance of OPEX parameters as key determinants of commercial vehicle TCO competitiveness.

dimensions, it is helpful to eliminate one dimension by plotting the difference of each TCO parameter as is done in the zero-line delta plot in Fig. 6 (c). Here, the toll parameter is again identified as the key influencing factor. Similar to, though not as pronounced as the Swiss case, Norway's toll exemption for BET vehicles advantages the zero-emission drive-technology over the conventional one.

Next, we compare Germany and Italy. The TCO results for the low diesel, high electricity cost country pair show high and low competitiveness of BET vehicles in Germany and Italy respectively. Looking at Fig. 6 (c) for these two countries, three parameters determine this result: tolls, fuel costs, and CAPEX subsidy. The 10 €/1000 km difference in fuel costs and 22 €/1000 km difference in CAPEX subsidy between the two countries, though minor, contribute slightly to BET competitiveness in Germany as compared to Italy. The 140 €/1000 km difference in tolls, however, is the deciding factor. With this example, we see how a combination of differences in certain TCO parameters enables zero-emission vehicle cost competitiveness, but also how policies that target certain parameters are more effective than others.

The zero-line delta plots in Fig. 6 (c) pointedly visualize the magnitude of the energy storage cost when comparing BET with ICE-D vehicles. Identification of key driving factors that enable TCO competitiveness of BET vehicles in the HDT-LongHaul segment thus becomes a discussion of which parameters most effectively offset the high sunk cost of the battery. From this application-focused, comparative drive-technology analysis, we ascertain three such parameters: tolls, fuel costs and CAPEX subsidies. Countries that are able to offset the high battery cost with targeted policies that affect these particular parameters effectively enable HDT-LongHaul BET vehicle competition.

5. Discussion and policy implications

5.1. *OPEX vs. CAPEX parameter subsidies*

A key finding of this study is the strong influence of OPEX parameters on commercial vehicle TCO results. Fig. 7 demonstrates this succinctly by showing what percentage of the TCO is comprised of OPEX parameters. When we consider all three dimensions detailed in this study, OPEX parameters make up on average close to 75% of the TCO for all drive-technologies in all application segments and countries, baring BET vehicles in the HDT-LongHaul segment. Thus far, the conventional wisdom of how to increase uptake of alternative-drive vehicles has primarily revolved around CAPEX subsidies. While this may be appropriate for passenger vehicles, it is not so for commercial vehicles. Policy instruments that target OPEX parameters are considerably more effective than instruments that target CAPEX parameters in enabling competitiveness of zero-emission commercial vehicles. Examination of the HDT-LongHaul segment distinctly shows that countries who display cost competitiveness of BET vehicles manage to counterbalance high battery costs, not by subsidizing the CAPEX itself, but by introducing targeted OPEX subsidies.

Switzerland is a prime example of this. The high LSVA toll for heavy-duty vehicles substantially preferences zero-emission drive-technologies over all others in an application segment that has thus far been designated too expensive to decarbonize. Norway has similarly brought about BET commercial vehicle competitiveness through a combination of toll exemptions for zero-emission vehicles and high diesel costs. Contrastingly, Italy and France display low economic competitiveness of zero-emission drive-technologies in the HDT-LongHaul segment. Both countries target CAPEX subsidies, which barely affect the TCO, while ignoring OPEX subsidies for tolls and conversely advantaging carbon-intensive drive-technologies by offering a refund on diesel excise duties. As far as the clean-transport transition is concerned, these are misplaced subsidies.

The importance of OPEX parameter subsidies in reducing the cost of zero-emission commercial vehicles has been emphasized in previous TCO studies, but not to this level of comparative country-level detail and, to our knowledge, not to the extent that economic competitiveness of BET vehicles in heavy-duty applications is demonstrated for countries that establish targeted OPEX subsidies.

5.2. *Targeting effective TCO parameters*

We identify secondly that certain key policy influencing parameters, such as tolls, fuel costs, and CAPEX subsidies, more effectively alter TCO results. Of these three parameters we observe the two OPEX parameters, tolls and fuel costs, to most efficiently affect the TCO. Policy makers intending to increase the prevalence of zero-emission road-freight vehicles on the road would be wise to address these parameters first and foremost. However, coordinated policy designs that employ a combination of the three parameters offer additional options to enabling drive-technology competition.

Individually, tolls is the single most effective policy parameter in facilitating zero-emission drive-technology competition for road-freight vehicles with high annual kilometers travelled. This is not only the case in Switzerland, where the heavy-duty vehicle LSVA is decisively influential, but also in Norway and Germany where zero-emission vehicle toll exemptions make BETs comparatively economical. As a fundamental policy design, tail-pipe emissions based tolls have traditionally promoted both the manufacturing and acquisition of cleaner combustion engine technologies that have improved gradually with each newly instated EURO class rating (i.e. emitted pollutant allowance). Accordingly, zero-emission drive-technologies should be charged in line with their tail-pipe emissions profile—which is non-existent. Full toll exemption for zero-emission road-freight vehicles is thus mechanistically appropriate and a surefire way to spark zero-emission road-freight vehicle adoption. It does however, pose problems should the entire commercial fleet become zero-emission, in which case toll revenues would cease. This concern, however, is far from realization. So long as zero-emission road-freight drive-technologies remain niche, complete toll exemption could support their emergence to mass. As a second toll design element, calibration of the toll itself (how high you set the toll) can deliver pronounced differences in comparative TCO costs. Switzerland implements the high LSVA toll—based on vehicle weight as well as emission's class—in large part because the toll is designed to discourage high volumes of long-haul trucking that could instead be transported by rail [73]. Thus, the levy not only covers traditional costs incurred directly from road wear, but also internalizes the negative externalities of favoring road over rail shipments. In sum, we find carefully planned policy design of tolling mechanisms to be essential in enabling a swift transition to zero-emission road-freight vehicles particularly in the MDT-Regional and HDT-LongHaul segments.

Fuel costs can similarly have high influencing effects on comparative drive-technology TCOs. We see this again in the Swiss case, but also in Norway and Sweden where high diesel and gasoline costs discourage the use of traditional fossil fuel technologies favoring instead zero-emission alternatives. Targeting carbon-intensive fuel costs at the country level, though effective and of course environmentally shrewd, evoke the most push-back both from commercial industry as well as the general populous who are often vehemently opposed to increased station pump prices. Tackling policy measures with high political and institutional resistance is difficult on the country level let alone at the EU level. A minimum excise duty of 0.33 €/L on diesel is imposed at the EU level for motor vehicles, while the remaining duty is charged at the member-state level. The problem with this member-state skewed duty structure is that motor fuel in the EU is taxed where it is purchased and not where it is consumed. Truckers thus have an incentive to refuel where the duties are lowest. In France, for example, the excise duty on diesel is one of the highest in the EU (0.609 €/L) as compared to neighboring countries of Luxemburg, Germany and Spain where the excise duties are comparatively much lower (0.335 €/L, 0.470 €/L, and 0.379 €/L respectively). Member-states looking to autonomously increase excise duties as a targeted policy measure intended to enable domestic uptake of zero-emission vehicles are heavily undercut by the taxed-where-purchased-not-consumed standard. The EU has identified the diversity of excise duties to be the root of the problem—thus the original impetus for the minimum duty rate—and have encouraged convergence of diesel duties across member-states. However, a simpler solution would be to tax motor fuel where it is purchased. The comparative TCO results from this study do not assume interstate transport—each individual states' policies are therefore directly reflected in the TCO. In reality, interstate transport is a major factor in the EU. If fuel costs are to be used effectively as a policy instrument to promote low- or zero-carbon road-freight vehicles, a reconsidering of coordinated EU policies may be required.

CAPEX subsidies is a demand-side policy instrument that both reduces vehicle costs and signals to industry players a government's preference for zero-emission drive-technologies. These subsidies can be effective in theory, so long as the incentive is considerable and the method of refund is transparent to fleet-owners and other interested investors. In reality, however, this policy instrument applies more to the passenger vehicle sector where purchasing decisions are largely influenced by the CAPEX. While we currently see 26 out of the 27 EU countries offering stimuli for electric vehicle purchases (mostly for passenger cars), only 20 of these states offer direct incentives such as bonus payments or premiums as opposed to the six remaining states that offer mere tax reductions or exemptions [74]. Furthermore, these subsidies are disproportionately available for cars and light vans and are not as available for commercial trucks. In this study, 8 out of 10 countries offer CAPEX subsidies in certain application segments (see Appendix 2). While the Netherlands offers the highest refund for zero-emission vehicles, particularly in the HDT-LongHaul segment, many other European countries have introduced comprehensive CAPEX subsidy programs across a variety of drive-technologies and application segments. Direct CAPEX subsidy is an area where we might see increased activity as zero-emission trucks become more prevalent. Though in line with the findings of this study, CAPEX subsidies appear to be most effective when implemented in the LDT-Urban application. With a lower annual mileage and a lower energy storage requirement in this segment, CAPEX subsidies more efficiently offset the sunk battery cost than they do in the HDT-LongHaul segment.

This conclusion is perhaps best illustrated with an example, for which we take Germany. As discussed in the results section 4.2.2, enabling TCO competitiveness of BETs is primarily a question of how to offset the high sunk cost of the battery. In Germany, all application segments display BET cost competitiveness with ICE-D, though this is obtained by way of different targeted parameters. In the LDT-Urban segment, BETs overcome a 60 €/1000 km sunk energy storage cost by way of an 86 €/1000 km CAPEX subsidy (see Appendix 6). In the HDT-LongHaul segment, BETs overcome a 267 €/1000 km sunk energy storage cost by way of a primary 140 €/1000 km toll exemption and secondary 43 €/1000 km CAPEX subsidy. Despite the absolute monetary value of the CAPEX subsidy in the HDT-LongHaul segment being almost 4.5 times greater than that of the LDT-Urban segment, the later segment's TCO is more influenced by the CAPEX subsidy parameter.

Combined policy measures that address multiple TCO cost parameters in appropriate application segments, as is the case in Germany and Norway, are shown in the results of this study to be just as effective in enabling BET drive-technology competitiveness as policy measures that heavily target a single TCO parameter, as is the case in Switzerland. Importantly, different combinations of the three discussed policies are specifically effective in different application segments. HDT-LongHaul requires a more coordinated effort with multiple targeted parameters, but must, at the very least, have zero-emission vehicle advantaging toll policies for BETs to be competitive. In the MDT-Regional segment, a combination of fuel costs and CAPEX subsidies are enough to advantage BET over ICE-D vehicles as is the case in Sweden, Italy, the UK, and Spain (see Appendix 6). For some countries in the LDT-Urban segment, a BET cost advantage is gained through offset fuel costs alone (i.e. Switzerland, Norway). Policy-makers should therefore be cognizant of these application specific tradeoffs when deciding where (i.e. which application segments and which TCO parameters) and how much to subsidize zero-emission road-freight vehicles.

5.3. *Areas for further research and data collection*

5.3.1. *TCO parameter sensitivities*

The outputs of this study, and thus the analysis, are only as good as the modelled inputs. In particular, we identify three TCO parameters that warrant further study beyond the scope of this paper: lifetime, infrastructure costs, and scrappage value.

Lifetime, in this study, is modelled as the full operational period of a vehicle. We find this assumption to be essential in communicating comparative results for a *total* cost of ownership study. However, other TCO studies have rather considered the ownership payback period as the lifetime of the vehicle. Payback periods typically range from 3 to 5 years depending on an investor or fleet owner's preference. The lifetime parameter exhibits high sensitivity in the TCO results as it shifts the cost focus from CAPEX to OPEX. High lifetime assumptions imply more operational kilometers travelled thus rendering vehicles with low kilometer-based operating costs, such as zero-emission vehicles, competitive. While this model takes a total operational period approach, a further analysis of comparative costs under payback period assumptions would expand the understanding of drive-technology competition for conditions perhaps more tailored to an investor's decision making criterion.

Infrastructure cost is a highly sensitive parameter as it varies significantly with utilization assumptions. With the LCOC approach used in this study, station utilization affects both the total annual energy charged as well as the installation cost, which scales significantly, but not linearly, for higher power-level stations. Cost data for these high power stations are thin and only a few studies offer assessments on how to properly scale production and installation costs from low to high power stations. Ultimately, this lack of data stems from a lack of demonstrated projects, but further research on cost scaling for higher power-level stations would greatly enhance comparative models such as the one proposed in this study. Furthermore, country level differences in production or installation costs for charging stations of varying power-levels and use-profiles is lacking in the literature. Such a differentiation would aptly contribute to analyzing country-level differences in comparative TCO results.

Scrappage values for commercial vehicles of varying drive-technologies, as indicated previously, has thus far not been systematically evaluated. This is in large part due to the immature market. Nonetheless, a categorical evaluation of the resale value of powertrain and energy storage components of alternative drive-technologies could be further researched. For example, the opportunity for second-life applications of vehicle batteries following the retirement of the vehicle may very well increase the resale value of BET vehicles, should the battery be sold or operated in second-life applications such as wholesale arbitrage or frequency containment reserve. Similar parallels could be drawn for fuel cell stacks following FCET vehicle retirements. Understanding these potential differences in resale opportunities for various alternative drive-technologies is important for comparative cost evaluations.

5.3.2. *Policy design tools for identified multi-dimensional parameters*

Section 5.2 describes a guideline for identifying key parameters that influence the TCO. More specifically, it allows policy-makers to prioritize and then target parameters that more effectively increase the competitiveness of low- or zero-emission drive-technologies. However, this analysis does not propose or evaluate specific policy design elements for the key parameters identified. Further research could, for example, investigate how the design, or combination of designs, of a policy tool or tools that target certain parameters may affect TCO results in the three application segments and ten representative European countries. The framework has been set—policy proposals should follow thereafter.

5.3.3. *Dynamic modelling*

Lastly, while this study offers a static "snap-shot" approach to comparative TCO analysis of differing drive-technologies, a dynamic approach would capture feedback effects of expected technology cost reductions as a function of the experiential learning rate of the technology. Batteries in particular exhibit high rates of experiential learning [75]. In further studies, it will be important to project TCO results that both consider and endogenize these cost reductions.

6. Conclusion

This paper proposes a consolidated framework with which to evaluate comparative TCOs of alternative-drive vehicles in the road-freight sector in different applications and countries. We model and compare five drive-technologies in three representative application segments and ten European countries in order to identify which key TCO parameters drive cost-competitiveness of low- and zero-emission commercial vehicles. Support policies for the electrification of the commercial vehicle sector in Europe have multiplied in recent years, though many of these policies focus on subsidizing the upfront cost of the vehicle. Our results show that this may be neither the most efficient nor the most appropriate policy instrument to target in this sector.

Overall, we find that cost competitiveness for low- or zero-emission drive-technologies in certain application segments and European countries is exhibited already today. In particular, battery electric vehicles show great promise in the light- and medium-duty segments, but also in the heavy-duty long-haul segments for countries that have enabled their competitiveness through specific targeted policy measures. Though zero-emission vehicles currently show low percentages of new vehicle sales in all commercial vehicle segments in Europe, a number of market developments have signaled the transition away from this carbon-heavy reality. OEMs are increasing the number of available commercial EV models offered as well as setting stringent timelines for full product-line electrification targets. We see these production trends in Europe, but also in other major markets such as in China and the US. In addition to market offerings, strong policy support is required to accelerate the low-carbon commercial vehicle transition. Particularly for medium- and heavy-duty vehicles, which have faced slower adoption rates as compared to the light-duty sector, policy support is crucial. From our results, we identify three main TCO parameters that drive TCO competitiveness for zero-emission vehicles: tolls, fuel costs, and CAPEX subsidies. In line with these findings, we propose that policy-makers target OPEX before CAPEX parameters as well as target an appropriate mix of parameters to ensure greater reach, efficiency, and flexibility of policy design.

Finally, we hope this framework and model will serve as a tool for fleet owners, policy-makers and OEM's to use when evaluating their own preferences, goals, or perspectives. We offer this model, as it is itself flexible and repeatable for different input conditions, as a starting point that can and should be improved, extended and built upon. Importantly, this framework should be applied to other geographies and can be helpful particularly in rapidly growing road-freight markets such as China, to understand cost competitiveness of commercial vehicle drive-technologies in such dynamic regions.

CRediT authorship contribution statement

Bessie Noll: Conceptualization, Data curation, Formal analysis, Visualization, Software, Writing – original draft. **Santiago del Val:** Data curation, Formal analysis, Visualization. **Tobias S. Schmidt:** Conceptualization, Writing – original draft, Supervision, Funding acquisition. **Bjarne Steffen:** Conceptualization, Writing – original draft, Supervision, 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.

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Appendix

1 Drive-technology Specifications

1.1 Drive-technology configuration schematics

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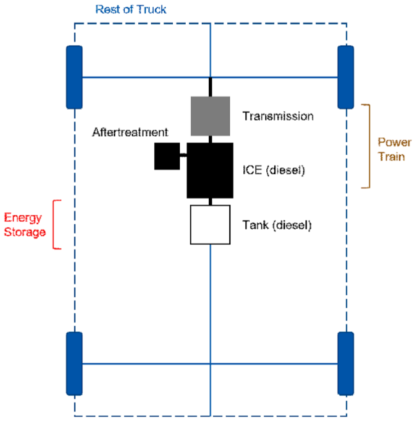
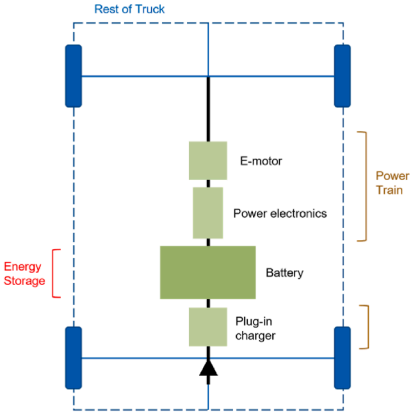
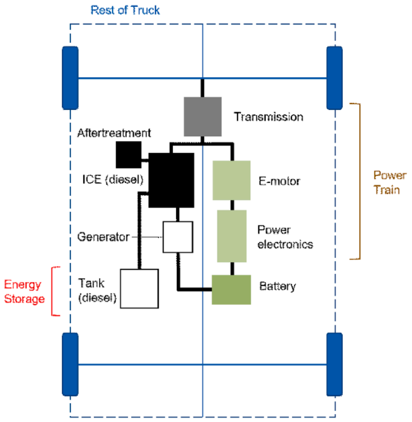
1.1.1 Internal combustion engine - diesel (ICE-D)



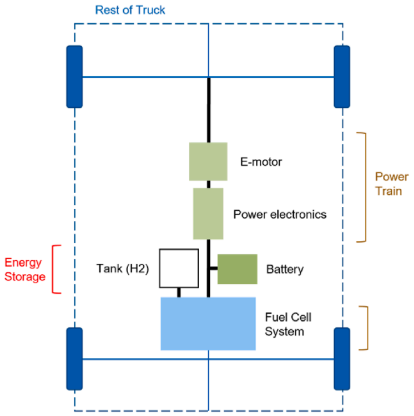
1.1.2 Battery electric truck (BET)



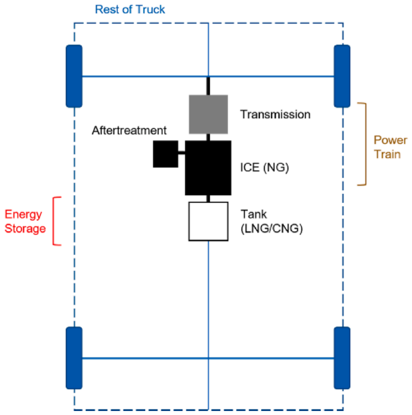
1.1.3 Hybrid electric truck (HET)



1.1.4 Fuel cell electric truck (FCET)



1.1.5 Internal combustion engine – natural gas (ICE-NG)



1.2 Tank-to-wheel efficiencies

Drive-technology		Source
BET	0.84	[64,76]
FCET	0.43	[76]
HET	0.40	[76]
ICE-D	0.35	[76]
ICE-NG	0.34	[76]

1.3 Power and energy ratios

Drive-technology	Power Ratio	Energy Ratio[6]		
		LDT	MDT	HDT
BET	–	–	–	–
FCET	1.0[7]	11.5	17	17
HET	0.3[8]	12.3	550	343
ICE-D	–	–	–	–
ICE-NG	–	–	–	–

[6] Energy ratio is defined as the ratio of fuel energy storage to battery energy storage.
[7] Power ratio for FCET is defined as the ratio of power rating of the electric motor to power rating of the fuel cell stack.
[8] Power ratio for HET is defined as the ratio of power supplied by the electric motor to power supplied by the ICE. 30% is a semi-hybrid.

1.4. Energy ratio reference vehicles

Drive-technology	Energy Ratio Reference Vehicles		
	LDT	MDT	HDT
BET	–	–	–
FCET	Hyundai H350	UPS fuel cell delivery truck prototype	Hyundai XCIENT
HET	Ford Transit Custom Plug-in Hybrid	FUSO Canter 7C15 Eco Hybrid	Volvo FE 340 6×2
ICE-D	–	–	–
ICE-NG	–	–	–

2. CAPEX data

2.1 CAPEX cost data

Component Group	Component Specification	Variable Type	Uncertainty	Cost Value	Unit	Source
Energy Storage	Li-ion battery pack	Distributed	Most likely	139.34	€$_{2020}$/kWh	[77], expert interview
		(PERT)	Min	118.44	€$_{2020}$/kWh	+20%
			Max	160.24	€$_{2020}$/kWh	−20%
	Fuel tank (diesel)	Distributed	Most likely	0.21	€$_{2019}$/kWh	[76]
		(PERT)	Min	0.15	€$_{2019}$/kWh	[76]
			Max	0.26	€$_{2019}$/kWh	[76]
	Fuel tank (LNG)	Distributed	Most likely	5.76	€$_{2019}$/kWh	[76]
	@ −162°C	(PERT)	Min	4.61	€$_{2019}$/kWh	+20%
			Max	6.91	€$_{2019}$/kWh	−20%
	Fuel tank (CNG)	Distributed	Most likely	4.18	€$_{2019}$/kWh	[76]
	@ 200 bar	(PERT)	Min	3.34	€$_{2019}$/kWh	+20%
			Max	5.01	€$_{2019}$/kWh	−20%
	Fuel tank (H_2)	Distributed	Most likely	24.75	€$_{2019}$/kWh	[47], expert interview
	@ 700 bar	(PERT)	Min	22.50	€$_{2019}$/kWh	[47], expert interview
			Max	27.00	€$_{2019}$/kWh	[47], expert interview
	LDT					
	Fuel tank (H_2)	Distributed	Most likely	14,962	€$_{2020}$/vehicle	[110], expert interview
	@ 700 bar	(PERT)	Min	12,034	€$_{2020}$/vehicle	[110], expert interview
			Max	20,123	€$_{2020}$/vehicle	[110], expert interview
	MDT					
	Fuel tank (H_2)	Distributed	Most likely	41,988	€$_{2020}$/vehicle	[110], expert interview
	@ 700 bar	(PERT)	Min	33,773	€$_{2020}$/vehicle	[110], expert interview
			Max	56,473	€$_{2020}$/vehicle	[110], expert interview
	HDT					
Powertrain	Engine (diesel)	Distributed	Most likely	40.77	€$_{2019}$/kW	[47]
		(PERT)	Min	39.50	€$_{2019}$/kW	[47]
	LDT		Max	41.90	€$_{2019}$/kW	[47]
	Engine (diesel)	Distributed	Most likely	59.89	€$_{2019}$/kW	[47]
		(PERT)	Min	53.61	€$_{2019}$/kW	[47]
	MDT		Max	66.09	€$_{2019}$/kW	[47]
	Engine (diesel)	Distributed	Most likely	79.00	€$_{2019}$/kW	[47]
		(PERT)	Min	67.72	€$_{2019}$/kW	[47]
	HDT		Max	90.29	€$_{2019}$/kW	[47]
	Engine (NG)	Distributed	Most likely	32.87	€$_{2019}$/kW	[47]
		(PERT)	Min	31.88	€$_{2019}$/kW	[47]
	LDT		Max	39.50	€$_{2019}$/kW	[47]
	Engine (NG)	Distributed	Most likely	63.62	€$_{2019}$/kW	[47]
		(PERT)	Min	54.59	€$_{2019}$/kW	[47]
	MDT/HDT		Max	85.06	€$_{2019}$/kW	[47]
	Electric motor	Distributed	Most likely	32.50	€$_{2019}$/kW	Expert interview
		(PERT)	Min	30.00	€$_{2019}$/kW	Expert interview
			Max	35.00	€$_{2019}$/kW	Expert interview

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Component Group	Component Specification	Variable Type	Uncertainty	Cost Value	Unit	Source
	Fuel cell stack system LDT/MDT/HDT	Distributed (PERT)	Most likely	250	€$_{2019}$/kW(net)	[110], Expert interview
			Min	225	€$_{2019}$/kW(net)	+10%
			Max	275	€$_{2019}$/kW(net)	−10%
	Aftertreatment LDT	Constant	–	996.0	€$_{2019}$/vehicle	[47]
	Aftertreatment MDT/HDT	Constant	–	0.71	€$_{2019}$/tonne kerb weight	[47]
	Generator LDT/MDT/HDT	Constant	–	60.00	€$_{2019}$/vehicle	[47]
	Power electronics LDT	Constant	–	1523.62	€$_{2019}$/vehicle	[47]
	Power electronics MDT/HDT	Constant	–	1.08	€$_{2019}$/tonne kerb weight	[47]
	Plug-in charger LDT	Constant	–	393.60	€$_{2019}$/vehicle	[47]
	Plug-in charger MDT/HDT	Constant	–	787.21	€$_{2019}$/vehicle	[47]
	Automated transmission LDT	Constant	–	338.58	€$_{2019}$/vehicle	[47]
	Automated transmission MDT	Constant	–	3950.14	€$_{2019}$/vehicle	[47]
	Automated transmission HDT	Constant	–	5322.81	€$_{2019}$/vehicle	[47]
Rest of truck	LDT	Distributed (PERT)	Most likely	17070.24	€$_{2019}$/vehicle	[76]
			Min	13825.49	€$_{2019}$/vehicle	[76]
			Max	20315.00	€$_{2019}$/vehicle	[76]
	MDT	Distributed (PERT)	Most likely	24336.24	€$_{2019}$/vehicle	[76]
			Min	20315.00	€$_{2019}$/vehicle	[76]
			Max	28356.35	€$_{2019}$/vehicle	[76]
	HDT	Distributed (PERT)	Most likely	57559.16	€$_{2019}$/vehicle	[76]
			Min	45144.44	€$_{2019}$/vehicle	[76]
			Max	69973.89	€$_{2019}$/vehicle	[76]

2.2 CAPEX subsidy data

Country	Application Segment	Drive-technology					Source
		ICE-D	ICE-NG	HET	BET	FCET	
France	LDT-Urban	0	0	0	5000	5000	[79]
	MDT-Regional	0	0	0	40% of acquisition cost; max €50,000	40% of acquisition cost; max €50,000	
	HDT-LongHaul	0	0	0	40% of acquisition cost; max €50,000	40% of acquisition cost; max €50,000	
Germany	LDT-Urban	0	0	0	9000	9000	[80,81]
	MDT-Regional	0	12,000	0	12,000	12,000	
	HDT-LongHaul	0	12,000	0	40,000	40,000	
Italy	LDT-Urban	0	4000	4000	10,000	10,000	[82]
	MDT-Regional	0	8000	8000	10,000	10,000	
	HDT-LongHaul	0	20,000	20,000	20,000	20,000	
Netherlands	LDT-Urban	0	0	0	5000	5000	[83,84]
	MDT-Regional	0	0	0	40% of price difference with ICE-D	40% of price difference with ICE-D	
	HDT-LongHaul	0	0	0	40% of price difference with ICE-D	40% of price difference with ICE-D	
Norway	LDT-Urban	0	0	0	0	0	[80]
	MDT-Regional	0	0	0	0	0	
	HDT-LongHaul	0	0	0	0	0	
Poland	LDT-Urban	0	30% of price difference with ICE-D; max €6654	0	30% of price difference with ICE-D; max €15,526	0	[85]
	MDT-Regional	0	30% of price difference with ICE-D; max €7763	0	30% of price difference with ICE-D; max €33,270	0	
	HDT-LongHaul	0	30% of price difference with ICE-D; max €22,180	0	30% of price difference with ICE-D; max €45,000	0	
Spain	LDT-Urban	0	4500	0	4400	4400	[86]
	MDT-Regional	0	6300	8000	8000	8000	
	HDT-LongHaul	0	13,500	15,000	15,000	15,000	
Sweden	LDT-Urban	0	0	0	6000	6000	[87]
	MDT-Regional	0	0	0	0	0	
	HDT-LongHaul	0	0	0	0	0	
Switzerland	LDT-Urban	0	0	0	0	0	[88]
	MDT-Regional	0	0	0	0	0	
	HDT-LongHaul	0	0	0	0	0	
UK	LDT-Urban	0	0	0	6900	0	[89]
	MDT-Regional	0	0	0	6900	0	
	HDT-LongHaul	0	0	0	0	0	

*All subsidy values are reported in €/vehicle.

3. OPEX data

3.1 Toll data[9]

Country	Weight Segment	Unit	Drive-technology					Source
			ICE-D	ICE-NG	HET	BET	FCET	
France[10]	LDT	€/km	0.13	0.13	0.13	0.13	0.13	[90]
	MDT	€/km	0.26	0.26	0.26	0.26	0.26	
	HDT	€/km	0.26	0.26	0.26	0.26	0.26	
Germany	LDT	€/km	0	0	0	0	0	[91]
	MDT	€/km	0.093	0	0.093	0	0	
	HDT	€/km	0.187	0	0.187	0	0	
Italy[11]	LDT	€/km	0.08	0.08	0.08	0.08	0.08	[92]
	MDT	€/km	0.13	0.13	0.13	0.13	0.13	
	HDT	€/km	0.18	0.18	0.18	0.18	0.18	
Netherlands	LDT	€/year	750	750	750	750	750	[93]
	MDT	€/year	1000	1000	1000	1000	1000	
	HDT	€/year	1250	1250	1250	1250	1250	
Norway[12]	LDT	€/km	0.038	0.038	0.038	0.007	0.007	[94–96]
	MDT	€/km	0.106	0.106	0.106	0	0	
	HDT	€/km	0.106	0.106	0.106	0	0	
Poland	LDT	€/km	0.02	0.02	0.02	0.02	0.02	[97]
	MDT	€/km	0.04	0.04	0.04	0.04	0.04	
	HDT	€/km	0.06	0.06	0.06	0.06	0.06	
Spain[13]	LDT	€/km	0.17	0.17	0.17	0.17	0.17	[98]
	MDT	€/km	0.21	0.21	0.21	0.21	0.21	
	HDT	€/km	0.21	0.21	0.21	0.21	0.21	
Sweden	LDT	€/year	0	0	0	0	0	[93,99]
	MDT	€/year	0	0	0	0	0	
	HDT	€/year	1250	1250	1250	1250	1250	
Switzerland	LDT	€/year	37.23	37.23	37.23	37.23	37.23	[100]
	MDT	(€*tonne)/km	0.021	0.021	0.021	0	0	
	HDT	(€*tonne)/km	0.021	0.021	0.021	0	0	
UK[14]	LDT	€/year	0	0	0	0	0	[101]
	MDT	€/year	0	0	0	0	0	
	HDT	€/year	616	616	616	616	616	

[9] We assume EURO 6 class for all emissions emitting drive-technologies.

[10] Values come from the route Montpellier-Paris, connections through highways A9,A7 and A6. The length of the trajectory is 764 km and vehicle categories considerer are 2 and 4.

[11] Values picked from the route Milano sud-Napoli, for a total length of 776 km.

[12] Values are the average of four separate trips between: Bergen-Oslo, Bergen-Tromso, Oslo-Trondheim, Bergen-Trondheim

[13] Vales obtained from highway AP-7 connecting La Junquera-Parets. The length of it is 136 km. No seasonal or time related prices have been considered.

[14] Values are the results of an average of categories D, E and E(T).

3.2 Fuel cost data

Country	Fuel type	Distribution Type	Uncertainty	Cost Value	Unit	Source
France	Diesel	Normal	Mean	0.9633	€/L	[44]
			Std	0.0874	€/L	
	Natural gas	Normal	Mean	0.8498	€/kg	[44]
			Std	0.0651	€/kg	
	Electricity	Normal	Mean	0.0957	€/kWh	[43]
			Std	0.0042	€/kWh	
	Hydrogen	PERT	Most likely	7.98	€/kg	[102,55]
			Min	6.98	€/kg	+1
			Max	8.98	€/kg	−1
Germany	Diesel	Normal	Mean	1.0357	€/L	[44]
			Std	0.1050	€/L	
	Natural gas	Normal	Mean	0.7861	€/kg	[44]
			Std	0.0797	€/kg	
	Electricity	Normal	Mean	0.1536	€/kWh	[43]
			Std	0.0097	€/kWh	
	Hydrogen	PERT	Most likely	7.98	€/kg	[102,55]
			Min	6.98	€/kg	+1
			Max	8.98	€/kg	−1
Italy	Diesel	Normal	Mean	0.9747	€/L	[44]
			Std	0.0754	€/L	
	Natural gas	Normal	Mean	0.7876	€/kg	[44]
			Std	0.0500	€/kg	
	Electricity	Normal	Mean	0.1508	€/kWh	[43]
			Std	0.0068	€/kWh	
	Hydrogen	PERT	Most likely	7.98	€/kg	[102,55]

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Country	Fuel type	Distribution Type	Uncertainty	Cost Value	Unit	Source
			Min	6.98	€/kg	+1
			Max	8.98	€/kg	−1
Netherlands	Diesel	Normal	Mean	1.0790	€/L	[44]
			Std	0.0617	€/L	
	Natural gas	Normal	Mean	0.9083	€/kg	[44]
			Std	0.0520	€/kg	
	Electricity	Normal	Mean	0.0850	€/kWh	[43]
			Std	0.0048	€/kWh	
	Hydrogen	PERT	Most likely	7.98	€/kg	[102,55]
			Min	6.98	€/kg	+1
			Max	8.98	€/kg	−1
Norway	Diesel	Normal	Mean	1.2001	€/L	[67]
			Std	0.1282	€/L	
	Natural gas	Normal	Mean	0.9108	€/kg	[67]
			Std	0.0973	€/kg	
	Electricity	Normal	Mean	0.0775	€/kWh	[43]
			Std	0.0078	€/kWh	
	Hydrogen	PERT	Most likely	7.98	€/kg	[102,55]
			Min	6.98	€/kg	+1
			Max	8.98	€/kg	−1
Poland	Diesel	Normal	Mean	0.9123	€/L	[44]
			Std	0.0895	€/L	
	Natural gas	Normal	Mean	0.6924	€/kg	[44]
			Std	0.0679	€/kg	
	Electricity	Normal	Mean	0.0887	€/kWh	[43]
			Std	0.0042	€/kWh	
	Hydrogen	PERT	Most likely	7.98	€/kg	[102,55]
			Min	6.98	€/kg	+1
			Max	8.98	€/kg	−1
Spain	Diesel	Normal	Mean	0.9207	€/L	[44]
			Std	0.0815	€/L	
	Natural gas	Normal	Mean	0.6824	€/kg	[44]
			Std	0.0574	€/kg	
	Electricity	Normal	Mean	0.1084	€/kWh	[43]
			Std	0.0043	€/kWh	
	Hydrogen	PERT	Most likely	7.98	€/kg	[102,55]
			Min	6.98	€/kg	+1
			Max	8.98	€/kg	−1
Sweden	Diesel	Normal	Mean	1.1862	€/L	[44]
			Std	0.0774	€/L	
	Natural gas	Normal	Mean	0.9004	€/kg	[44]
			Std	0.0587	€/kg	
	Electricity	Normal	Mean	0.0695	€/kWh	[43]
			Std	0.0070	€/kWh	
	Hydrogen	PERT	Most likely	7.98	€/kg	[102,55]
			Min	6.98	€/kg	+1
			Max	8.98	€/kg	−1
Switzerland	Diesel	Normal	Mean	1.3900	€/L	[46]
			Std	0.0561	€/L	
	Natural gas	Normal	Mean	1.0550	€/kg	[46]
			Std	0.0425	€/kg	
	Electricity	Normal	Mean	0.1502	€/kWh	[45]
			Std	0.0059	€/kWh	
	Hydrogen	PERT	Most likely	7.98	€/kg	[102,55]
			Min	6.98	€/kg	+1
			Max	8.98	€/kg	−1
UK	Diesel	Normal	Mean	1.2064	€/L	[44]
			Std	0.0938	€/L	
	Natural gas	Normal	Mean	1.0322	€/kg	[44]
			Std	0.0803	€/kg	
	Electricity	Normal	Mean	0.1392	€/kWh	[43]
			Std	0.0126	€/kWh	
	Hydrogen	PERT	Most likely	7.98	€/kg	[102,55]
			Min	6.98	€/kg	+1
			Max	8.98	€/kg	−1

3.3 LNG Cost Savings Percentages

Country	LNG Cost Savings [%]	Source
France	46	[51]
Germany	45	[51]
Italy	52	[51]
Netherlands	39	[51]
Norway	45	[51]

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Country	LNG Cost Savings [%]	Source
Poland	45	[51]
Spain	49	[51]
Sweden	45	[51]
Switzerland	45	[51]
UK	38	[51]

3.4 Driver wages data

Country	Application Segment	Annual salary (€)			Source
		Entry	Mean	Senior	
France	LDT	20,012	24,402	29,226	[20,68]
	MDT/HDT	24,523	33,314	40,612	
Germany	LDT	28,173	37,372	44,978	[20,68]
	MDT/HDT	29,215	39,665	48,383	
Italy	LDT	18,968	25,425	30,753	[20,68]
	MDT/HDT	23,054	31,328	38,179	
Netherlands	LDT	27,320	36,117	43,368	[20,68]
	MDT/HDT	31,201	41,923	50,808	
Norway	LDT	22,708	30,002	36,046	[20,68]
	MDT/HDT	27,709	37,621	45,889	
Poland	LDT	8133	10,718	12,881	[20,68]
	MDT/HDT	9819	13,310	16,226	
Spain	LDT	15,410	20,960	25,520	[20,68]
	MDT/HDT	18,793	25,561	31,122	
Sweden	LDT	23,099	27,986	33,519	[20,68]
	MDT/HDT	24,884	33,804	41,210	
Switzerland	LDT	18,321	33,852	53,940	[20,68]
	MDT/HDT	47,597	64,803	81,368	
UK	LDT	22,400	30,908	38,080	[20,68]
	MDT/HDT	22,400	30,908	38080[15]	

[15] Salaries for the UK were obtained from Salary Expert powered by the Economic Research Institute (ERI). https://www.salaryexpert.com/.

3.5 Fuel consumption logarithmic fit variables

Fuel Type	a	b	Output Units (y)
BET	0.3814	−2.6735	kWh/km
FCET	0.01973	−0.1233	kg-H_2/km
ICE-D	0.0903	−0.6404	L-diesel/km
ICE-NG	0.0694	−0.4650	kg-LNG/km

$$y = a\ln(x) + b$$

where x is the input vehicle weight and y is the output fuel consumption in the respective output units.

4. Vehicle performance data

4.1 Vehicle performance parameter values.

Parameter	Distribution	Unit	Application Segment		
			LDT-Urban	MDT-Regional	HDT-LongHaul
m	–	kg	3500	7500	32,000
A_f	Most likely	m^2	4.73	5.37	8.29
	Min		3.97	3.11	6.90
	Max		5.54	7.64	8.30
c_D	Most likely	–	0.41	0.55	0.62
	Min		0.30	0.45	0.47
	Max		0.55	0.62	0.70
c_r	–	–	0.0075	0.0070	0.0063
ρ_{air}	–	kg/m^3	1.225	1.225	1.225
g	–	m/s^2	9.81	9.81	9.81

4.2 Coefficient of drag and frontal surface-area data references.

As noted in Section 3.4, average, minimum and maximum values for the frontal surface-area and the coefficient of drag were collected from 36 representative European vehicles and 6 studies.

Application Segment	Source	Vehicle	Type	A_f	c_D
LDT-Urban	Renault	Master	van	4.66	–
	VW	Caddy Pannel	van	3.28	–
	VW	Transporter 6.1 Pannel	van	3.79	–
	VW	Transporter 6.1 Kombi	van	4.72	–
	VW	Crafter Pannel	van	5.43	–
	VW	Transporter 6.1 Chassis	utility	4.72	–
	IVECO	Daily	van	5.43	–
	[103]	New Iveco Daily 4100 Pannel	van	5.85	0.550
MDT-Regional	MB	Atego	rigid	5.85	0.549
	DAF	LF	rigid	5.81	–
	Renault	Maxity	rigid/utility	3.91	–
	MAN	TGL	rigid	5.85	–
	IVECO	Eurocargo (narrow)	rigid	5.59	–
	IVECO	Eurocargo (wide)	rigid	7.04	–
	[103]	MB Atego	rigid	8.80	0.549
	[104]	Baseline MD Truck – 11 t GVW	rigid	5.50	0.45
	[105]	Delivery Truck – 12 t	rigid		0.62
HDT-LongHaul	MB	Actros	articulated	9.60	–
	Renault	D	rigid	4.64	–
	Renault	D (wide, daily)	rigid	5.28	–
	Renault	D (wide, sleeper)	rigid	6.34	–
	Renault	T (night and day)	articulated	7.99	–
	Renault	T (sleeper)	articulated	9.06	–
	Renault	T (high sleeper)	articulated	9.60	–
	Volvo	FM (min height)	rigid or articulated	6.92	–
	Volvo	FM (mid height)	rigid or articulated	7.45	–
	Volvo	FM (max height)	rigid or articulated	7.79	–
	Volvo	FH (sleeper)	rigid or articulated	7.13	–
	Volvo	FH (globetrotter)	rigid or articulated	7.98	–
	MAN	TGX (low)	rigid or articulated	9.37	–
	MAN	TGX (hight)	rigid or articulated	9.78	–
	MAN	TGS (low)	rigid or articulated	8.14	–
	MAN	TGS (high)	rigid or articulated	8.64	–
	Scania	P Series (low)	rigid or articulated	7.27	–
	Scania	P Series (high)	rigid or articulated	8.76	–
	Scania	G Series (low)	rigid or articulated	7.49	–
	Scania	G Series (high)	rigid or articulated	8.99	–
	Scania	R Series (low)	rigid or articulated	7.72	–
	Scania	R Series (high)	rigid or articulated	9.44	–
	IVECO	Stralis (low)	rigid or articulated	7.03	–
	IVECO	Stralis (high)	rigid or articulated	9.12	–
	[103]	MB Actros LS 4x2	articulated	10.2	0.617
	[103]	EU Economy Vehicle	articulated	9.50	0.700
	[103]	EU Average Vehicle	articulated	10.2	0.617
	[103]	EU Premium Vehicle	articulated	9.50	0.473
	[106]	EU Average Vehicle	articulated	10.00	0.630
	[104]	Baseline HD Truck – 40 t GVW	articulated	7.70	0.600
	[105]	Long Haul 40 t Truck	articulated	–	0.600
	[107]	Average Heavy Duty Truck – 40 t (HIGH Cd)	articulated	–	0.630
	[107]	Average Heavy Duty Truck – 40 t (LOW Cd)	articulated	–	0.480
	[108]	Average European Truck (HD)	rigid or articulated	–	0.700

5. Stochastic model variables

5.1. Stochastically modelled variables from the TCO equation

Parameter	Distribution Modelled
CAPEX	
Energy storage	PERT
Powertrain	PERT
Rest of truck	PERT
OPEX	
Tolls	(no distribution)
Fuel costs	
Diesel	Normal
LNG/CNG	Normal
Electricity	Normal
Hydrogen	PERT
(Fuel consumption)	PERT
Driver Wages	PERT
O&M	(no distribution)
Insurance	(no distribution)

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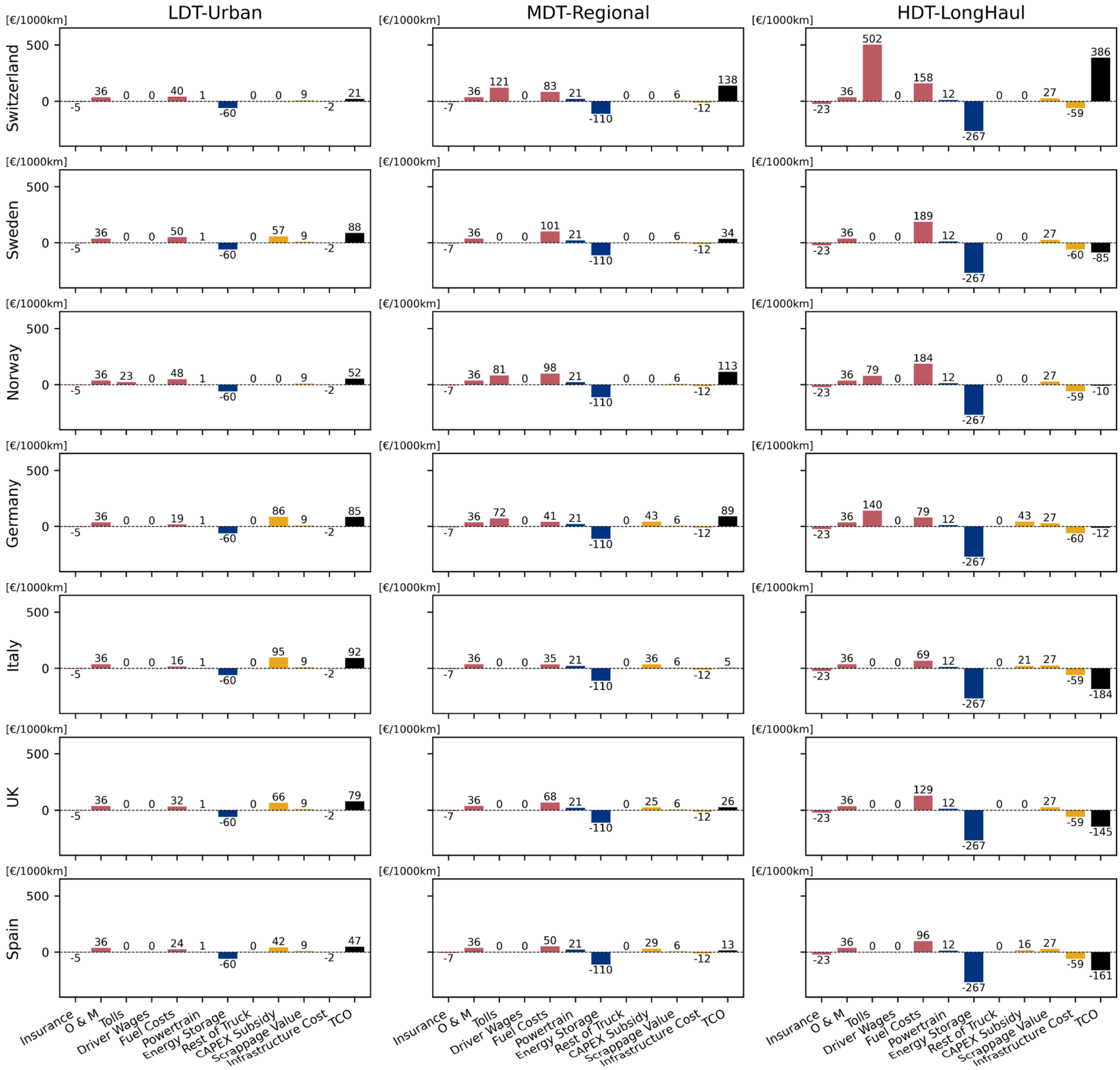
Parameter	Distribution Modelled
Subsidies	(no distribution)
Scrappage value (%)	(no distribution)
Lifetime	(no distribution)
Cost of capital	(no distribution)
Annual km travelled	(no distribution)

6. *Zero-line delta results figure – selected countries*

6.1 Zero-line delta plots for selected countries showing the subtracted difference between ICE-D and BET technologies of each individual TCO component (i.e. ICE-D components minus BET components). Positive values indicate parameters that are more expensive for ICE-D vehicles and negative values indicate parameters that are more expensive for BET vehicles.



7. *Code availability*

The Python model used in this comparative TCO analysis is available upon reasonable request of the authors.

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